Simulation and Calculation of Interior Ballistic of A Large Caliber Artillery

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Abstract. Based on the classical interior ballistic model, the model is improved according to the actual situation. Relying on the newly established model, the related software is compiled. The maximum bore pressure, muzzle velocity and detonation temperature of a 155mm caliber gun are simulated by using relevant software. The maximum bore pressure is 338.2748 MPa, muzzle velocity is 855.1096 m/s and detonation temperature is 3468.402 K. After comparing the calculated results with the experimental data, it is found that the software is more practical and can be applied in engineering practice.

1. Introduction
The calculation of interior ballistic model is the core of interior ballistic theory, which plays an important role in gun design, improvement and problem solving. The traditional interior trajectory solution methods include empirical method, analytical method, tabular method and graphic method, which are simple but limited. With the application of computer in ballistics, numerical methods have appeared. Although they are approximate solutions, the accuracy of calculation can meet the actual needs, especially some softwares such as MATLAB, FLUENT, CFD (Computational Fluid Dynamics), which provide more possibilities for numerical calculation. For example, LUO Qiao and Zhang Xiao-bing applied FLUENT software to Interior Ballistic Analysis of Ultrahigh Firing Rate Guns artillery.[¹] Liu Lin and Fan Cheng-jun used Simulink to simulate the interior trajectory of mixed charge, and the results met the actual engineering requirements.[²]

In this paper, the interior ballistic simulation model is built and calculated based on relevant software. Comparing the calculated values with the experimental results, the feasibility of this method in interior ballistic calculation is verified.

2. Establishment of Interior Ballistic Model
2.1 Basic Assumptions
Internal ballistic calculation is developed on the basis of classical interior ballistic theory, so it has certain similarity and inheritance in the construction of interior ballistic model. Based on the classical theory of interior ballistics, this paper establishes relevant models. Based on the classical theory of interior ballistics, the following basic assumptions are put forward:

a) The combustion of propellant obeys the law of geometric combustion.
b) The combustion of propellant and the movement of projectile are carried out under the condition of average pressure, and the flow of gas in bore follows Lagrange hypothesis.
c) The combustion of propellant obeys the law of exponential combustion.
d) During and after combustion, the combustion products of propellant remain unchanged, i.e. the propellant power f and the residual volume of propellant gas α are treated as constants.
e) When the projectile moves in the bore, it is well sealed and there is no air leakage.
f) When the projectile shoots out of the muzzle, the gunpowder gas is continuously flowing out and the gas pressure in the bore is constantly changing. The process of flowing out is carried out under the adiabatic condition.

2.2 Fundamental Equations

a) The commonly used interior ballistic model is the case of porous propellant, and its shape functions of gunpowder is as follows:

$$\psi_i = \begin{cases} \chi_i Z_i \left(1 + \lambda_i Z_i + \mu_i Z_i^2 \right) & (Z_i < 1) \\ \chi_i Z_i \left(1 + \hat{\lambda}_i Z_i \right) & (1 \leq Z_i < Z_k) \\ 1 & (Z_i \geq Z_k) \end{cases}$$

Among that, ψ is the burned percentage of fast burning propellant; Z is the relative thickness of burning propellant; $\chi_i$,$\lambda_i$,$\mu_i$,$\hat{\lambda}_i$ and $Z_k$ are the shape characteristic quantity of the main charge propellant; $Z_k$ is the relative thickness of burned propellant after burning.

b) Burning Rate Equation

$$\frac{dZ_i}{dt} = \begin{cases} \frac{u_i}{e_i} p_i^n & (Z_i < Z_k) \\ 0 & (Z_i \geq Z_k) \end{cases}$$

Among that, t is time, $u_i$ is burning rate coefficient, $e_i$ is arc thickness of the main charge propellant, $p$ is pressure, and n is burning rate-pressure exponent.

c) Travel Equation

$$v_i = \frac{dl_i}{dt}.$$  

Among that, v is the velocity of the projectile and l is the travel of the projectile in the controlling tube.

d) Motion Equations of The Projectile

$$\varphi m \frac{dv}{dt} = Sp.$$  

Among that, S is the maximum cross-section area of the projectile, $\varphi$ is the secondary work coefficient, m is the mass of the projectile, $p$ is the pressure in the chamber.

e) Energy Balance Equation

$$Sp(l_v + l) = f \omega \psi - \frac{\theta}{2} \varphi mv^2.$$  


Among that, $l_\varphi$ is equivalent length of the free volume of the first stage, $f$ is the gunpowder force, By combining the above equations, we can get:

$$
\begin{align*}
\psi_i &= \begin{cases} 
\chi Z_i (1 + \lambda Z_i + \mu Z_i^2) & (Z_i < 1) \\
\chi Z_i (1 + \lambda Z_i) & (1 \leq Z_i < Z_k) \\
1 & (Z_i \geq Z_k)
\end{cases} \\
\frac{dZ_i}{dt} &= \begin{cases} 
\frac{\mu_i}{e_{ij}} p_i^b & (Z_i < Z_k) \\
0 & (Z_i \geq Z_k)
\end{cases} \\
v_i &= \frac{dl_i}{dt} \\
\varphi m \frac{dv}{dt} &= Sp \\
Sp(l_\varphi + l) &= f \omega \psi - \frac{\theta}{2} \varphi m v^2 
\end{align*}
$$

(6)

Eq. 6 is the classical interior ballistic equations used in this paper.\cite{4}

3. Calculation of Simulation Parameters of Interior Ballistics

In this paper, a 155mm large caliber gun is taken as the calculation object, and the propellant of 23/19 propellant is used to simulate. Next, the relevant parameters are calculated.

3.1 Secondary Work Coefficient

$$\varphi = K + \frac{1}{3} \frac{a}{m} .$$

(7)

Among that, K is a constant related to weapons. The experience shows that the secondary work coefficient of the large caliber gun is 1.02.

3.2 The Gunpowder Force

For propellant composed of C, H, O and N, and the unit mass element is $C_a H_b O_c N_d$. The combustion reaction formula of propellant can be expressed as follows:

$$C_a H_b O_c N_d \rightarrow x CO_2 + y CO + z H_2 O + u H_2 + v N_2$$

The formulas for calculating specific heat, detonation heat, detonation temperature and the gunpowder force are as follows:

$$W_i = 22.41 a + 22.41 (a + \frac{b}{2} + \frac{d}{2}) = 22.41 (x + y + z + u + v) .$$

(8)

$$Q_v = x q_{CO_2} + y q_{CO} + z q_{H_2 O} - q + (x + y + z + u + v) RT_0 .$$

(9)

$$T_v = \frac{Q_v}{\sum nC_v} + T_0 .$$

(10)

$$f = nRT_v = \frac{PW_i}{273} T_v = \frac{103.3 W_i}{273} T_v .$$

(11)

Based on the above equation, the calculation results are as Table 1 shows.
Table 1. Parameters of Artillery Charge

| Name                  | Symbol | Value  | Unit   |
|-----------------------|--------|--------|--------|
| force capacity        | \( f \) | 1040000| J/kg   |
| Specific volume       | \( W_i \) | 0.9484 | m³/kg  |
| detonation heat       | \( Q_r \) | 4407000| J/kg   |
| explosion temperature | \( T_e \) | 3071   | K      |

3.3 Covolume

The residual volume is the incompressible volume (m³/kg) of the gas molecule of 1 kg propellant. The residual capacity of gunpowder is:

\[ \alpha = \sum_i y_i \alpha_i. \]  

(12)

According to experience, we take \( \alpha = 1 \) in the calculation.\(^{[6]}\)

3.4 Other Relevant Parameters

Referring to the relevant information, other parameters of interior ballistics are obtained as shown in Table 2 below.

Table 2. Other Relevant Parameters of Internal Ballistic

| Name                  | Symbol | Value  | Unit   |
|-----------------------|--------|--------|--------|
| Projectile Quality    | \( m \) | 45.0   | kg     |
| caliber               | \( d \) | 0.155  | m      |
| density               | \( \delta \) | 1.65  | g/cm³ |
| charge                | \( \omega \) | 15.6 | kg     |
| burning rate coefficient | \( u \) | 2.3e-10 | m³/(s·kg) |
| Burning Rate Index    | \( n \) | 0.921  |        |
| Secondary work        | \( \varphi \) | 1.02  |        |
| coefficient           |        |        |        |
| chamber volume        | \( V_0 \) | 0.02398| m³     |
| projectile trip       | \( l_i \) | 7.6   | m      |
| Characteristic Quantity of Powder Shape | \( \mu \) | 0 |        |
| \( \chi \)            | 0.75   |        |        |
| \( \lambda \)         | 0.12   |        |        |
| propellant web size   | \( e_i \) | 2.3   | mm     |

4. Result

By substituting the above values into the program, the data simulation results are shown in Table 3, and the output interior ballistic performance curves are shown in Fig. 1 to Fig. 3.

Table 3. Simulation Results of Interior Ballistic Performance of Artillery

| \( T \) [s] | \( p \) [MPa] | \( v \) [m·s⁻¹] | \( T \) [K] |
|-----------|-------------|---------------|------------|
| 0.00005   | 31.07375    | 0.6244        | 3468.402   |
| Time (s) | P (MPa) | V (m/s) | T (K) |
|---------|---------|---------|-------|
| 0.00025 | 35.61718| 3.3476  | 3467.982|
| 0.0053  | 327.5129| 355.8887| 3164.382|
| 0.0605  | 338.2748| 459.3889| 3075.322|
| 0.0097  | 165.3699| 855.1019| 2573.933|

Fig. 1. Simulation Curve for Calculating the Maximum Bore Pressure of Artillery

Fig. 2. Muzzle Velocity Calculating Simulation Curve

Fig. 3. Simulation Curve of Gun Gas Temperature Calculation
5. **Comparisons between calculation results and experiments**

In order to verify the correctness of the simulation results, the results are compared with the experimental data. The results are shown in Table 4 below.

|                          | Calculated | Experiment | Error% |
|--------------------------|------------|------------|--------|
| the Maximum Bore Pressure $p_M$ [Mpa] | 338.2748   | 340        | 0.507  |
| Muzzle Velocity $v_0$ [m s$^{-1}$]       | 855.1096   | 458        | 86.705 |
| detonation temperature $T_D$ [K]          | 3468.402   | 3071       | 12.940 |

6. **Conclusions**

Comparing the simulation results with the experimental data, it can be found that the fitting results of the maximum bore pressure are better and the error is less than 1%. However, the fitting results of muzzle velocity are much larger than the actual measurement results, which may be due to the friction resistance between projectile launching and internal ballistic in the actual measurement process or the decrease of muzzle velocity due to the increasing pressure and air resistance.

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