Study on Interior Ballistic Characteristics of the Multi-gas Sources Ejection Power System

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Abstract. In this paper, the internal ballistics model of the multi-gas sources ejection power system is established, the internal ballistics characteristics are studied, and the launch process of a certain missile is calculated by using the internal ballistics equation, and the important parameters such as velocity and acceleration of the missile, pressure and temperature in the launch cylinder are obtained. Compared with the pure gas single power launch scheme, the multi-gas sources ejection power system can effectively reduce the missile overload, reduce the pressure in the launching cylinder and improve the energy utilization efficiency. The maximum acceleration of the missile is reduced by more than 50%, which makes the movement process of the missile more stable and the interior ballistic trajectory more accurate; the maximum pressure in the launch cylinder is reduced by more than 45%, which greatly improves the launch safety, and also provides conditions for the lightweight of the launch device.

1. Introduction

Gas-generator, as a power source, is widely used in attitude control of aviation and aerospace field. In the missile ejection, the charge of the gas-generator is designed according to the design requirements, and gas is obtained to meet certain parameters such as flow rate, speed, pressure and temperature.

In the launching technology, the device that uses the power other than the missile itself to launch the missile is called the ejection power system. Energy management techniques with different emission power systems have different schemes. Taking the underwater launch of a submarine-launched missile as an example, the energy management schemes are summarized as follows [1,2]:

a) Pure gas single power emission scheme [3]. The power system of the scheme remains unchanged at different launch depths, and the velocity of missile discharge is only controlled by the launch depth. The velocity of missile discharge decreases with the increase of launch depth. This scheme is actually a fixed energy emission scheme. The Poseidon missile in the United States adopts this scheme. The scheme is simple in structure, but has little energy management capability, and the missile needs to have strong adaptability.

b) Gas-steam emission scheme [4,5]. By injecting different cooling water into different launch depth areas, the scheme can adjust its useful energy to meet the requirements of exit velocity of variable depth launch missile. In other words, when transmitting large depth, less cooling water sprayed into; shallow when transmitting, the cooling water sprayed into more. The amount of water...
injected can be achieved by changing the number of spray holes. The US Trident II D5 submarine-launched missile uses this scheme [6]. The scheme automatically forms a pressure difference on both sides of the water injection hole during the work process, the cooling water enters the gas flow under the effect of the pressure difference to achieve the purpose of energy management. However, the energy adjustment range of the scheme is limited, and the regulation control device structure is relatively complex.

c) The emission scheme of variable throat diameter flow regulation [7]. The scheme is to add a regulating cone at the nozzle of the combustion chamber of the gas-generator to change the throat ventilation area. By adjusting the pressure in the combustion chamber to control the burning rate of the charge, the energy management is performed by adjusting the pressure in the combustion chamber to control the burning rate of the charge, and ultimately transmitted variable depth needs. The scheme requires an additional throat adjustment mechanism, which makes the system more complex and less reliable.

The multi-gas sources ejection power system is a new type of ejection power system. According to the missile, launch platform parameters and launch constraints, multi-gas sources ejection power technology can intelligently select the combination scheme and loading scheme of gas-generator, and determine the working timing sequence of gas-generators according to the actual missile launch parameters, so as to make the gas flow match with the missile movement rule and ensure the missile launch load and the missile discharge velocity are highly accurate and controllable.

In this paper, by studying the energy characteristics of the multi-gas sources ejection power system, a multi-gas sources ejection internal ballistic calculation model is established, and then the results obtained by the calculation are compared with the calculation results of the pure gas single power emission scheme. The results show that, on the premise of ensuring the launch load to meet the requirements of the missile discharge velocity, the multi-gas sources ejection power system can effectively reduce the maximum acceleration overload and the maximum pressure in the launch cylinder during the launch process, so as to provide a reliable theoretical basis for the further study of the multi-gas sources ejection power system.

2. Model

2.1. Structure and composition

The multi-gas sources ejection power system is mainly composed of: a set of modular gas sources, intelligent energy management system and integrated system, among which the intelligent energy management system is composed of energy adaptive matching system and high reliable ignition system.

![Figure 1. The Structure and Composition of the Multi-gas Sources Ejection System.](image-url)
According to the parameters of missile, launch platform and launch constraints, the multi-gas sources ejection power system can intelligently select the combination and loading scheme of gas-generators, and determine the working sequence of gas-generators according to the actual launch parameters, so as to match the gas flow with the missile motion rules and ensure the high precision and controllable launch load and the velocity of missile discharge.

The working process of the multi-gas sources ejection power system is as follows: detecting the transmitting load, calculating and optimizing the ignition timing, binding the ignition timing information to the energy adaptive matching system; The energy adaptive matching system gives the ignition signal according to the ignition timing information and activates the distributed igniter to ignite the gas source. Gas source produces high temperature and high pressure gas which flows into thrust chamber through nozzle. When the thrust force in the thrust chamber is greater than the resistance of the launch load, the launch load starts to move and ejects the barrel according to the preset launch internal ballistic law.

2.2. Basic assumptions

The actual launch process of the multi-gas sources ejection power system is a very complex physical and chemical process. In the process of establishing the multi-gas sources ejection internal ballistic calculation model, certain assumptions were made and some minor factors were simplified:

a) Both gas and air are treated as ideal gas, and the condensed phase composition in gas is ignored;

b) The gas flow is a frozen flow, regardless of the changes in its composition and properties, nor the chemical interaction between the gas and air;

c) Without considering the variation of parameters of the working gas flow along the pipeline, the flow of the working gas flow along the pipeline is regarded as the transmission process of the working gas energy from the launching power system to the launching cylinder;

d) The fuel gas continuously entering the launching cylinder and the air in the launching cylinder can be mixed under equal pressure at every instant to exchange energy to form a mixture with uniform state parameters at all points;

e) For heat loss and other energy loss, the energy coefficient is used, and its value is assumed to be a constant in the whole process;

f) The energy depreciation caused by the irreversibility of the process and the mass loss caused by air leakage are considered by the pressure coefficient;

g) The amount of gas generated by the gas source is equal to the amount of gas flowing out through the nozzle;

h) Due to the macroscopic kinetic energy of the working gas in the launch cylinder, the kinetic energy coefficient is introduced for consideration, and its value is assumed to be a constant throughout the launch process;

i) The amount of gas produced by the ignition powder is ignored.

2.3. Calculation model

The gas-generator is the gas source and energy source for launching missiles. The pressure change law of gas-generator plays an important role in interior ballistics, because it not only affects the burning rate and burning time of charge, but also directly affects the gas mass flow of gas into the launching cylinder, thus affecting the pressure change law in the launching cylinder. Therefore, it is an important basis for the calculation of the interior ballistics of the launch to provide the accurate mass flow of the generated gas through the calculation of the interior ballistics of the gas-generator.

In fact, the gas-generator is very similar to the solid rocket motor, but there are some differences between the gas-generator and the solid rocket motor due to different purposes. The calculation method of internal ballistic of the solid rocket motor can be used for reference. The calculation method of internal ballistic of the solid rocket motor has been relatively mature, and on this basis, the adaptability can be improved [8].
2.3.1. Internal pressure equation of gas-generator. The internal pressure calculation equation of the gas-generator is [9]:

\[ P_c = \left( \rho_P \cdot u_0 / P_0^2 \cdot \left[ 1 + \alpha_T (T_s - T_0) \right] \cdot C^* \cdot A_b / \sigma_f A_t \right]^{\frac{1}{\nu-1}} \]  

(1)

Where \( P_c \) is the working pressure of the gas-generator; \( \rho_P \) is the charge density; \( u_0 \) is the burning rate of the charge at the factory, that is, the combustion rate under temperature \( T_0 \) and pressure \( P_0 \); \( \alpha_T \) is the temperature sensitivity coefficient of the charge; \( T_s \) is the initial temperature of the charge; \( C^* \) is the characteristic velocity of the charge; \( A_b \) is the burning surface; \( \sigma_f \) is the total pressure recovery coefficient; \( A_t \) is the nozzle throat cross-sectional area; \( \nu \) is the charge pressure index.

2.3.2. Gas mass flow equation. The amount of gas entering the launching cylinder by a single gas-generator is calculated as follows:

\[ m_{ph} = \frac{A_t \mu \sigma_f}{C^*} \int_0^t P_c \, dt + m_{g0} \]  

(2)

Where \( C^* \) is the characteristic velocity of the charge, \( A_t \) is the nozzle throat cross-sectional area of the gas-generator.

For the combination of multiple gas-generators, the calculation formula of mass of gas is as follows [10]:

If \( t_i < t < t_{i+1} \),

\[ m_g = m_{g0} (t - t_i) \]  

(3)

If \( t_{i+1} < t < t_{i+2} \),

\[ m_g = m_{g0} (t - t_i) + m_{g0} (t - t_{i+1}) \]  

(4)

If \( t_{i+2} < t < t_{i+3} \),

\[ m_g = m_{g0} (t - t_i) + m_{g0} (t - t_{i+1}) + m_{g0} (t - t_{i+2}) \]  

(5)

If \( t_{i+n} < t < t_{i+(n+1)} \),

\[ m_g = m_{g0} (t - t_i) + m_{g0} (t - t_{i+1}) + m_{g0} (t - t_{i+2}) + \cdots + m_{g0} (t - t_{i+n}) \]  

(6)

In formula (3) to formula (6), \( t_i \) indicates that the \( i \)-th gas-generator starts to work, and \( t_f \) indicates the complete working time of a single gas-generator. And if \( t - t_i > t_f \), \( m_{g0} (t - t_i) = m_{g0} t_f \) in all the above.

2.3.3. Energy conservation equation. The working gas in the multi-gas sources ejection power system is fuel gas and air. The heating process satisfies the energy conservation equation as follows:

\[ t_i = \frac{x_c m_g c_{vg} t_{vg} + m_a c_{va} t_a - \left( \frac{1}{2} M v^2 + \int_0^t F \, dl \right)}{m_g c_{vg} + m_a c_{va}} \]  

(7)

Where \( t_i \) is temperature in the launch cylinder, \( x_c \) is the energy coefficient, \( m_g \) is the mass of gas entering the launch cylinder, \( c_{vg} \) is the specific heat at constant volume of gas entering the launch cylinder, \( t_{vg} \) is temperature of gas entering the launch cylinder, \( m_a \) is the mass of air in the launch cylinder, \( c_{va} \) is the specific heat at constant volume of air in the launch cylinder, \( t_a \) is environment temperature, \( M \) is missile launching mass, \( v \) is velocity of the missile, \( F \) is the total drag acting on the missile.

2.3.4. Ideal gas equation of state. Based on the assumption of ideal gas, the gas and air in the launch cylinder meet ideal gas equation of state:
\[ P_t = \frac{x_p (R_g m_g + R_a m_a) T_i}{S_t (l_0 + l)} \]  

(8)

Where \( P_t \) is pressure in the launch cylinder, \( x_p \) is the pressure coefficient, \( R_g \) and \( R_a \) are the gas constants of gas and air respectively, \( T_i = t_i + 273.15 \), \( t_i \) is obtained from equation (7), \( S_t \) is the cross-sectional area of the launch cylinder, \( l_0 \) is the equivalent length of the initial volume at the bottom of the cylinder, \( l \) is the movement displacement of the missile.

2.3.5. Missile motion equation. The motion equation of the missile under the action of working gas meets the following formula:

\[ Ma = (1 + x_k) P_t S_t - F \]  

(9)

Where \( Ma \) is the combined external force of the missile in the launching cylinder, \( a \) is the acceleration of the missile, \( x_k \) is the kinetic energy coefficient, \( F \) is the total drag acting on the missile.

The movement displacement and velocity of the missile are calculated with the decomposed formula of Tailor progression:

\[ l_n = l_{n-1} + \Delta t \cdot v_{n-1} + \frac{1}{2} \Delta t^2 a_{n-1} + \frac{1}{6} \Delta t^3 a_{n-1} \]  

(10)

\[ v_n = v_{n-1} + \Delta t \cdot a_{n-1} + \frac{1}{2} \Delta t^2 a_{n-1} \]  

(11)

\[ \dot{a} = \frac{a_n - a_{n-1}}{\Delta t} \]  

(12)

The resistance of missile movement is:

\[ F = (1 + z) M g + P_o S_t \]  

(13)

\[ z = \frac{F_z}{M \cdot g} \]  

(14)

Where \( z \) is the friction coefficient of missile loading, \( F_z \) is the friction of missile loading.

The above equations together constitute the interior ballistic model of multi-gas sources ejection power system, from which the pressure and temperature of the working gas in the launching cylinder, the velocity, acceleration and displacement of the missile in the launching process can be calculated.

3. Results

The ejection internal ballistic design is to preliminarily determine the basic design parameters of the ejection power system device under the given internal projectile design requirements and known projectile parameters, barrel parameters, launching environmental condition parameters, etc. Then the interior ballistic equations are used to check the main design indexes of interior ballistic, and the structural parameters and loading conditions are modified until the design requirements are met.

The basic requirements of missile ejection interior ballistic design are as follows:

a) The ejection power system must guarantee the required velocity of missile discharge \( v_e \);

b) The acceleration of the missile moving in the cylinder shall not be greater than the allowable value \( a_{\text{max}} \), and the movement of the missile shall be stable as far as possible;

c) The pressure of the working gas in the launching cylinder shall not be greater than the allowable value \( P_{\text{max}} \);

d) The average temperature of the working gas in the launching cylinder shall not be greater than the allowable value of \( T_{\text{max}} \).

In this paper, for the launching process of a certain missile, the interior ballistics are calculated by the pure gas single power scheme and the multi-gas sources ejection power scheme respectively. Three gas modules are used in the multi-gas sources ejection power scheme, and two different ignition timing schemes are adopted. The temperature and pressure in the launching cylinder, velocity and
acceleration of the missile are calculated. The displacement of the missile in the launching cylinder is 16 meters. The comparison charts of the obtained missile movement displacement-time curve, missile speed-time curve, acceleration-time curve and pressure-time curve in the launching cylinder under different schemes are shown in Figure 2 to Figure 5. In the figures, scheme 1 represents the pure gas single power scheme, scheme 2 and scheme 3 are both multi-gas sources ejection power schemes. The ignition timing of scheme 2 is \( t_1 = 0 \text{ s}, t_2 = 0.22 \text{ s} \) and \( t_3 = 0.31 \text{ s} \). The ignition timing of scheme 3 is \( t_1 = 0 \text{ s}, t_2 = 0.19 \text{ s} \) and \( t_3 = 0.54 \text{ s} \).

![Figure 2. Comparison Chart of the Displacement-Time Curve](image)

![Figure 3. Comparison Chart of the Velocity-Time Curve](image)

![Figure 4. Comparison Chart of the Acceleration-Time Curve](image)

![Figure 5. Comparison Chart of the Pressure-Time Curve](image)

4. Analysis

The characteristics values extracted from the interior ballistic calculation results are shown in Table 1. It can be seen from Table 1 that, under the premise of ensuring the requirements of the velocity of missile discharge, the multi-gas sources ejection power system with reasonable ignition timing scheme can reduce the maximum acceleration of the missile by more than 50%, and the maximum pressure in the launch cylinder by more than 45%. This shows that the multi-gas sources ejection power system can effectively reduce the missile overload, reduce the pressure inside the launcher, improve the energy utilization efficiency, make the missile movement process more stable, internal trajectory more accurate, launch safety greatly improved. And the decrease of the pressure in the launch cylinder also provides theoretical support for the design of launcher weight reduction and provides conditions for the lightening of the launcher.
Table 1. Comparison table of characteristic values of different schemes.

| Scheme                      | Scheme 1 | Scheme 2 | Scheme 3 |
|-----------------------------|----------|----------|----------|
| Ignition timing             | pure gas single power | t₁ = 0s, t₂ = 0.22s and t₃ = 0.31s | t₁ = 0s, t₂ = 0.1979s and t₃ = |
| Displacement of the missile (m) | 16       | 16       | 16       |
| Velocity of missile discharge (m/s) | 40.03    | 35.93    | 32.00    |
| Maximum acceleration of missile (m/s²) | 109.64   | 54.16    | 55.17    |
| Maximum pressure in the launching cylinder (MPa) | 21.49    | 11.67    | 11.85    |

5. Conclusion

Aiming at the launching process of a certain type of missile, this paper constructs the internal ballistic calculation model of the multi-gas sources ejection power system. This paper builds a multi-gas sources ejection power system internal trajectory calculation model, using numerical calculation method and applying internal trajectory equation to study the launching parameters such as the velocity and acceleration of a certain missile, temperature and pressure in the launch cylinder during the launching process, and the calculation results are compared with pure gas single power scheme. The main conclusions are as follows:

Compared with the pure gas single power scheme, the multi-gas sources ejection power system has the following technical advantages:

a) The intelligent control of pulse ignition timing sequence is adopted, and the ignition timing sequence is adjusted according to the change of launch parameters, so as to make the gas generation rule of the whole launch process match with the corresponding functional requirements and realize the optimal control of gas flow.

b) By using the multi parameter control technology of missile launching, the reverse solution technology of gas flow law and the optimization technology of pulse ignition timing, a solution model of obtaining the gas flow law and gas flow optimal distribution according to the parameters of missile, launch platform, launch constraints and gas generator is proposed, and the optimal combination scheme and ignition timing are calculated quickly and accurately so as to match the gas flow with the launching process, and provide the missile with low impact load environment and high-quality launching trajectory.

In addition, according to the parameters of missile, launch platform and launch constraints, the actual timing control scheme may need real-time adjustment of launch parameters after determining the combination of gas-generator and ignition timing scheme, so as to achieve high-precision control of missile launch load and barrel exit speed. This puts forward strict requirements for the feedback, response speed and matching accuracy of the system. This is also the direction that the multi-gas sources ejection power system needs to break through in the future.

Acknowledgments

This work was supported by our task group. The author gratefully acknowledges the help of Pro. Taikun Wang, Pro. Xinwei Qiang, Mr. Jiuling Sui and Mr. Pengyong Li with this study.

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