Calculation Method for Equivalent Ejection Mass of Variable Thrust in the Internal Ballistic Equation of Pyrotechnic Folding Rudder

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Abstract. In order to solve the calculation of actuator ejection mass in pyrotechnic folding rudder, this paper investigates the calculation method for equivalent ejection mass of variable thrust in the Internal ballistic equations of pyrotechnic folding rudder, and obtains the fitting curves of equivalent ejection mass and gunpowder thrust in the case of variable forces and calculates the gunpowder thrust curves during the unfolding process by establishing the dynamic simulation model of the pyrotechnic folding rudder. After test verification, the test results are consistent withe the simulation results, indicating that the method is accurate and effective, and provides a theoretical basis for the design of the pyrotechnic folding rudder.

Keywords: gunpowder thrust calculation; ejection mass; pyrotechnic actuator; internal ballistic equation; folding rudder

1. Introduction

1.1 Research status and trend analysis

The traditional gunpowder thrust calculation is generally based on the calculation of internal ballistics equations for solving, which is modeled as a simple actuator, including the igniter, gunpowder, actuator shell, piston rod, etc., and its system of equations is in the following form [1]:

$$\frac{dP}{dt}=\frac{(f_0\omega-P\omega(1/\rho-\alpha_0))\frac{d\Psi}{dt}-f_0cP-(PS+(k-1)\Sigma F)\frac{dl}{dt}-(k-1)\varphi mv\frac{dv}{dt}}{V_0-\omega(1-\Psi)/\rho-\alpha_0\omega\Psi+Sl} \tag{1}$$

$$\frac{d\Psi}{dt}=\frac{1}{e_1}\chi(1+2\lambda Z+3\mu Z^2)\frac{de}{dt} \tag{2}$$

$$\frac{de}{dt}=a_0P^n \tag{3}$$

$$\frac{dv}{dt}=\frac{SP-\Sigma F}{\varphi m} \tag{4}$$

$$\frac{dl}{dt}=v \tag{5}$$

Where P stands for the combustion chamber pressure; Ψ stands for the combustion rate which is a description of the progress of the gunpowder combustion quantity. When the gunpowder is all burned out the value is 1; e stands for the main charge combustion thickness, on behalf of the gunpowder extended arc thick direction of how much combustion whose unit is mm; v stands for the piston rod movement speed; l stands for the piston rod movement stroke; V_0 stands for the combustion chamber initial capacity; f_0 for the powder force of the main charge gunpowder , the meaning is the energy released by combustion of every kg of gunpowder and the unit is J / kg; ω stands for the main charge residual capacity, which means that the volume of the remaining dregs each kg of gunpowder after burning left, in units of m^3/kg; the main charge mass, in units of kg; ρ stands for the main charge density; χ , λ , μ stands for the main charge shape coefficients, of which $\chi=1+\alpha+\beta$, $\lambda=-\frac{\alpha+\beta+\alpha\beta}{1+\alpha+\beta}$, $\mu=\frac{\alpha\beta}{1+\alpha+\beta}$, $\alpha=\frac{e_1}{b}$, $\beta=\frac{e_1}{c}$; e_1 , b, c respectively represents the half of the arc thickness of the gunpowder, half of the width of the gunpowder ,half of the length of the gunpowder ; a_0 stands for the main charge shape burning speed coefficients, obtained generally through the test; n stands for the main charge shape burning speed pressure index, also generally obtained by the test; m stands for the piston rod mass; S stands for the piston rod area of stress; c stands for the gas leakage coefficient, generally considered as 0 in the good sealing conditions or very fast combustion process; k stands for the gas adiabatic index, generally taken as 1.237 in black powder combustion ; F stands for the external resistance and load; e_1 stands for the main charge of the initial thickness; φ stands for the correction coefficient to the correct of the experimental data; t stands for the time.

1.2 Literature Review

In the United States, with the successful development of technologies such as the Apollo program and the Space Shuttle, pyrotechnic technology has been greatly developed and continually improved, and appropriate product specifications and testing standards have been developed. Karl O. Brauer's Handbook of Pyrotechnics [2] provides a comprehensive introduction to the principles, material properties, structural composition, and applications of pyrotechnic devices, with numerous charts and figures, and the book virtually covers all pyrotechnic actuators developed in the aerospace field, some of which are still in use today. However, the book focuses more on introducing the structural components and practical applications of pyrotechnic power units, without systematically presenting the corresponding design standards and specifications, and some of the calculation formulas are empirical estimation formulas.

Literature [3] points out that the design of pyrotechnic devices has been regarded as a skill rather than a subject. Bement , a specialist in NASA Langley Center , investigated the failures of the U.S. space pyrotechnic propulsion system, which resulted in a total of 84 accidents, of which 56 were due to insufficient knowledge of pyrotechnic technology and design errors. In 1991, in order to improve the technological level and reliability of space pyrotechnic devices, the NASA began a pyrotechnic device system planning program that focused on improved design methods, standards, and specifications for pyrotechnic devices and systems to reduce pyrotechnic device risks and improve product quality. Under the support of this program, technical studies of aerospace pyrotechnic devices have been conducted. These researches mainly focus on two aspects, one is the technical analysis and performance simulation of pyrotechnic devices, and the other is the reliability design and analysis of pyrotechnic devices.

The domestic pyrotechnic actuator has been applied for more than 40 years, and is developed independently on the basis of borrowing from American and Russian technologies. In terms of standards, based on U.S. military standards, QJ1075A "General Specification for Aerospace Pyrotechnic Devices" and GJB2034 "Aerospace Electro-explosive Subsystems Safety Requirements and Test Methods" and other basic standards are formulated. But for a long time, the technical research of pyrotechnic actuators has been based on specific models of products and tasks, and some pyrotechnic professional research institutions focus only on the research of gunpowder and deflagration theory, and the calculation of the gunpowder thrust There are relatively few specialized researches on the calculation of pyrotechnic thrust. The book "Spacecraft Entry and Return Technology" edited by Wang Xiji provides a comprehensive introduction to the design of the pyrotechnic actuator used in the recovery system [4] , which provides an engineering method for the calculation of the gunpowder thrust. Jiao Shaoqiu et al of the National University of Defense Technology (NUDT) conducted an internal ballistic modeling simulation of the working process of the piston connected separation device, and the theoretical calculations of the combustion pressure and the separation velocity were in agreement with the experimental data [5]. Gao Bin of the NUDT established the performance study of the pyrotechnic devices on the traditional internal ballistic equations [6]. With the completion of the model products, many of the research work was put aside and failed to get in-depth research and refinement, and at present, there is no comprehensive literature on the calculation, testing, and application of the pyrotechnic thrust, and there is limited research on specific topics.

2. Research Content

2.1 Establishment of internal ballistic simulation model

Establish the kinematic coupling equation of the gunpowder combustion and pyrotechnic actuator based on the internal ballistic equations, and parameterize the initial volume, the piston rod force area, the piston rod movement stroke, and the amount of drug in the model. The expressions of the internal ballistic equation of the pyrotechnic actuator are equations (1)~(5).

2.2 Simulation model based on the dynamic simulation software

Simplify the three-dimensional model, ignore the part of the folded rudder that is not involved in the rotation, and only convert the rotational inertia of the rotating part into the ejection mass of the piston rod in the linear direction.

The folded rudder unfolding dynamics simulation geometric model includes the outer rudder, inner rudder and spiral mechanism; the spiral mechanism includes the screw and the screw sleeve, the outer rudder is fixedly connected with the screw sleeve. The inner rudder and the screw are limited with the relative rotation. The gunpowder thrust acts on the screw, and the screw moves in a straight line, which is converted into the rotational motion of the screw sleeve, and the screw sleeve drives the outer rudder to rotate.

The geometric model is imported into the dynamic simulation software, and the geometric model is assigned with mass characteristics, constraints, and boundary conditions, so as to establish the simulation model of the folding rudder unfolding process. The inner and outer rudders, the screw sleeve, and the screw are all made of steel, and the density is assigned to 7800 kg/m^3, and the constraints are that the outer rudder and the sleeve rotate around the rotating axis, and at the same time, the piston rod moves linearly under the effect of the gas of the actuator. The boundary condition is that the inner rudder is fixedly connected with the earth.

2.3 Equivalent ejection mass calculation

In the the dynamic simulation model, a constant force is applied behind the piston rod st to push the piston rod to move in a straight line, and the outer rudder is rotated by the action of the screw and the screw sleeve, and the initial constant force used is 1800N.

According to the above model simulation results, extract the displacement of the piston rod in the linear direction with the time curve. The data is imported into mathematical analysis software for quadratic function fitting. According to kinematics relationships, the coefficient in front of the quadratic term of the fitting function is half of the acceleration of the piston rod. The piston rod linear displacement with time curve changes as Fig. 1 The acceleration of the piston rod in the linear direction is analyzed to be 27.42m/s^2 .

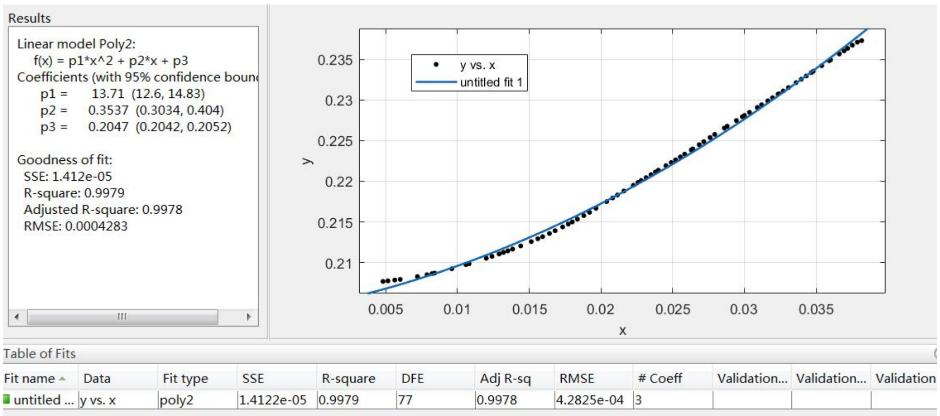

Fig. 1 Piston rod linear displacement curve over time

According to Newton's second law of motion, the equivalent ejected mass is 65.65kg under the constant force of 1800N.

Considering the role of different forces applied to the piston rod, change the value of the constant force to repeat the simulation calculation, and finally get the equivalent ejection mass with the change of force by the fitting curve as shown in Fig. 2, and the equation of the fitted curve is $M_{eq} = -8.588 \times 10^{-8}x^3 + 6.203 \times 10^{-4}x^2 + 1.512x + 1279$

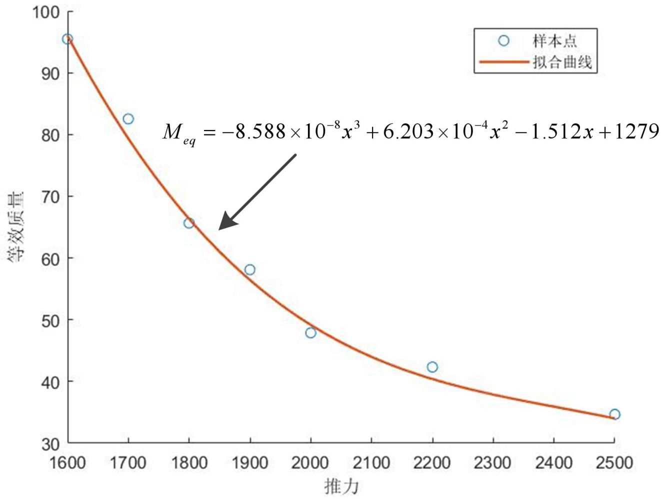

Fig. 2 Equivalent ejection mass curve over force

It can be seen that the equivalent ejection mass is larger when the force is smaller, and the equivalent ejection mass tends to be a constant when the force is larger.

2.4 Dynamics Simulation after Equivalent Ejection Mass Correction

The equation of equivalent ejection mass and force is input into the mathematical analysis software function, so that in each iteration of the differential equation, a new gunpowder thrust and equivalent ejection mass are calculated, and then will be input into next iteration, so that the effect of the equivalent ejection mass generated by the variable gunpowder thrust is taken into account in the calculation of the gunpowder thrust. After that, the gunpowder thrust over time curve is obtained. Then input the gunpowder thrust curve input into the dynamic simulation software for the simulation, and it is found that after introducing the effect of the change of gunpowder thrust on the equivalent ejection mass, the time to unfold the rudder is longer than the time not considering the change of equivalent ejection mass. This is due to the fact that the equivalent ejection mass is very large in the case of small initial gunpowder thrust, resulting in a small initial acceleration, which makes the acceleration process of the piston rod shifted backward, resulting in an increase of the unfolding time. The angle over time curves of the simulation are shown in Fig. 3 and Fig. 4.

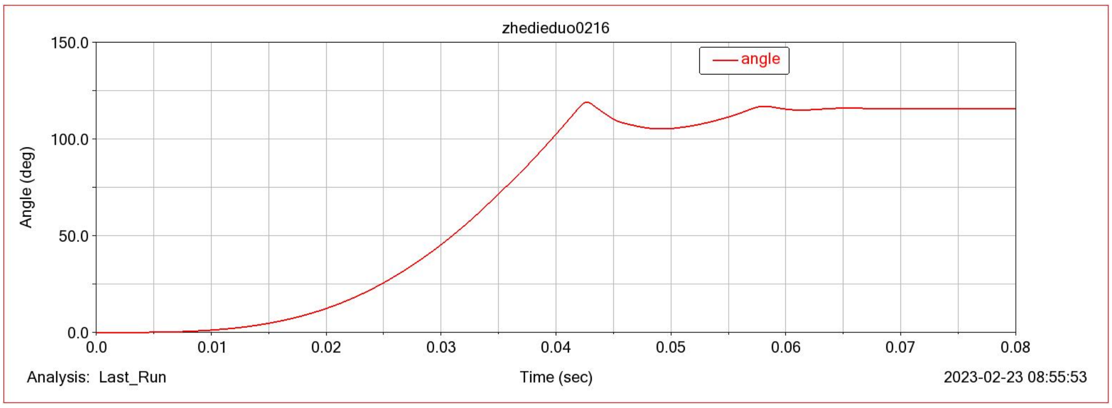

Fig. 3 Angle over time curve in the case of equivalent ejection mass not changing with thrust.

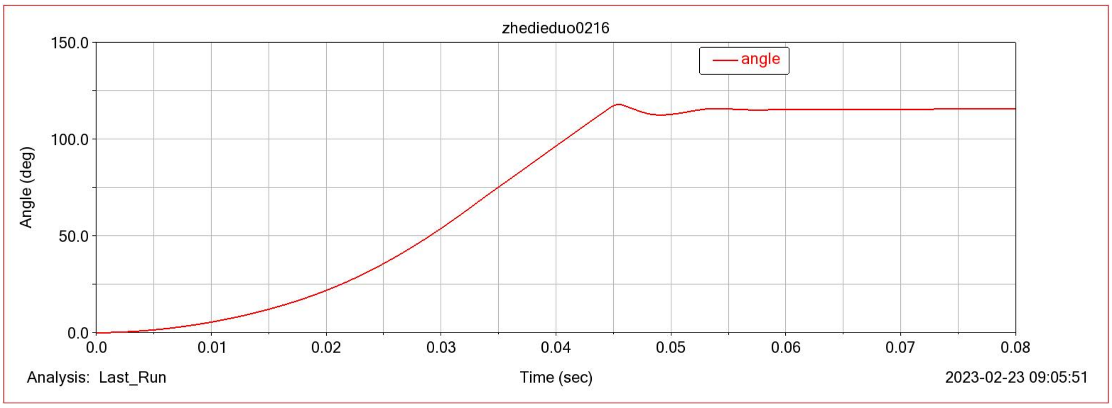

Fig. 4 Angle over time curve in the case of equivalent ejection mass changing with thrust.

3. Summary

According to the above, compare the simulation result considering the effect of thrust on the equivalent ejection mass as input or not, it can be seen that the outer rudder unfolding time becomes longer after considering the effect of the equivalent ejection mass. This is due to the fact that the gunpowder thrust at the initial stage of the unfolding is relatively small, the piston rod hasn't yet begun to move and the screw engages with the screw sleeve. There is a large resistance that hinders the movement of the piston rod and the unfolding of the rudder. This result is in line with people's knowledge of the actual unfolding process, but only in qualitative terms to make the calculation of the process more accurately, but also need to quantitatively analyze the accuracy of this method and with the actual process of the error range. This requires not only actual experimental validation, but also a series of tests on gunpowder and pyrotechnic actuators to determine the values of the parameters in the differential internal ballistics equations.

In conclusion, this article comprehensively researches the calculation method of variable thrust equivalent ejection mass for the internal ballistic equation of the pyrotechnic folding rudder, and the simulation calculation model obtained can be directly applied to the engineering development to guide the design and test. These researches help to promote the development of the pyrotechnic folding rudder.

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