Design of a 40mm Caliber Ballistic Correction Steering Gear System

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Abstract. The ballistic correction projectile uses several limited open-loop corrections to reduce the error of the projectile flight or the deviation of the projectile from the target due to the target movement, thereby reducing the projectile dispersion error and improving the hit rate. This paper draws on the existing advanced steering gear design, and improves the rudder blade airfoil and its plane shape according to the flight speed of the ballistic correction projectile (Mach 2). Through the analysis of degrees of freedom, a pair of limit devices have been added to the housing to make the servo system work more stable and efficient. At the end of the paper, the conclusion that the 5V voltage is better than the 3.3V power supply is obtained through the control experiment. The safety and reliability of the servo system are further verified by the anti-torque simulation of the cam mechanism and the anti-overload simulation of the servo motor.

1. Introduction
In modern warfare, the three elements of distance, speed and precision of weapons and equipment play a vital role, and precision is given priority. Increasing the accuracy of weapons and equipment can reduce the amount of ammunition, speed up the pace of war, reduce the exposure of combat platforms and personnel, reduce material consumption and war logistics requirements, and minimize the collateral damage to civilians and non-military facilities during the war. The most effective way to improve the accuracy of the strike is to use precision guided weapons.

Since the Vietnam War, guided munitions have played an increasingly important role in previous wars. In the Vietnam War of 1961, the precision-guided munitions thrown by the US military only accounted for 0.2% of the total bombs. In the 1991 Gulf War, the multinational forces used a total of precision-guided munitions, accounting for 8.4% of the total bombings. In the US, the proportion of precision-guided weapons used by the US military was 35%. In the battlefield in Afghanistan in 2001, the proportion rose to 56%. In the 2003 Iraq war, the US-British coalition forces placed precision guided munitions and munitions. The use ratio is as high as 68% [1]. The ballistic correction projectile is a projectile that uses the ballistic correction system to easily control the projectiles in the flight and the ballistics of the warhead. The ballistic correction system in the bomb body is composed of a ballistic deviation detecting device, a ballistic correction command processor, and a simple control actuator. The steering gear is composed of a casing, a PCB circuit board, a servo motor, a gear and a
Due to its structural stability, speed, and strong torque, the current international mainstream uses the steering gear as the actuator of the ballistic correction project [3]. In addition, the selection of the appropriate power supply voltage and control commands can make the system more responsive and more stable. In summary, how to achieve efficient and orderly cooperation between steering gear, rudder and control commands [4] has become the key to the research of current guided guns.

2. Design of flight control unit for ballistic correction projectile

As shown in Fig.1, the flight control part of the ballistic correction projectile is composed of a servo motor, a cam, a rudder blade, a micro single chip microcomputer, a power source and a casing, wherein the microchip and the power source are installed inside the servo motor casing. When the system works, the power supply first supplies power to the single-chip microcomputer and the servo motor. The control chip outputs a PWM waveform of a specific duty ratio according to the entered code. The PWM electric signal drives the servo motor to rotate, and then the cam mechanism rotates through the connecting rod, and the two rudder blades are connected. The rod is radially linearly moved by the external force of the cam groove, and the stability of its movement is ensured by the two limit jaws on the flight control housing. Since the ballistic correction projectile has a diameter of 40 mm, the maximum diameter of the casing is 40mm, and the minimum dimensions of other components are not more than 40mm. The flight control section is divided into upper and lower parts, the upper part is the working area of the cam mechanism and the rudder mechanism, and the lower part is used to carry the servo motor and the micro-single chip. Because of the anti-overload requirement, the bottom baffle must be closed. And it fits on the bottom of the motor.

2.1. Rudder mechanism and cam mechanism

The rudder design includes aerodynamic layout design and shape design [5]. The aerodynamic layout, also called the aerodynamic configuration, refers to the form in which the aerodynamic surface (including the wing, tail, control surface, etc.) is arranged in the circumferential and axial directions of the body and the shape of the body (including the head, the middle, and the tail). Various changes. The rudder blade is a kind of operation surface, which can change the aerodynamic characteristics of the full projectile and improve the maneuverability of the projectile, thereby realizing ballistic correction. In addition, the snake piece has a certain influence on the stability of the whole projectile. Therefore, it is necessary to make a reasonable aerodynamic layout of the rudder piece. Aerodynamic layouts are
generally divided into two broad categories along the axial and circumferential directions of the body [6].

Divided along the circumference of the body, the common aerodynamic layout includes "one" type, "+" type and "X" type. Divided along the radial direction of the body, the common aerodynamic layout includes normal and duck. Since the rudder blades designed in this paper are a pair, a "one" type circumferential aerodynamic layout is adopted. In order to better adjust the position of the center of mass of the projectile, reduce the mass of the whole projectile, and increase the lift-to-drag ratio of the whole projectile, the duck-rudder axial aerodynamic layout is adopted.

The selection of the geometrical features of the rudder blade is mainly determined by the speed of the simple guided rocket in the controlled flight segment [7]. The steering gear system in this paper is mainly used for simple guided projectiles with flying speeds in the supersonic speed (around 2Mach). For the rudder piece in this paper, the rudder blade airfoil adopts a circular arc symmetrical type with a length of 12mm and a pair of arc radius of 20mm. The plane shape is rectangular, and the rectangle is 12mm long, that is, the airfoil length. The rectangle is 8mm wide.

The cam acts as a key mechanism for converting the rotational motion of the motor into a linear reciprocating motion of a pair of rudder blades, and its contour curve needs to be specially designed. As shown in Fig.2, the minimum distance from the center of the groove is a, the maximum distance is b, and the maximum length of the rudder mechanism is x. The radius of the intelligent correction shell is 20mm, and according to the geometric relationship, the ternary equation system (1) is obtained.

\[ a + x = 20, \quad b + x = 28 \]  

![Figure 2. trench size analysis](image)

Take \( a = 5mm \), then \( b = 13mm, \quad x = 15mm \). The data can be collated to obtain the precise shape of the rudder mechanism and cam mechanism.

2.2. Limit device
Degree of freedom [8] not equals one, indicating that the degree of freedom is too much, the whole structure is unstable during operation [9]. Therefore, it is necessary to add a pair of limit jaws on the inside of the ballistic correction housing to make the mechanism degree of freedom \( F=1 \). Thus, the rudder blade has a unique travel path in the telescopic reciprocating motion.

3. Experiment and simulation

3.1. Power supply voltage control experiment
This experiment is a control experiment, using software \( \mu \)Vision Keil5, ATTINY85 micro-single-chip and MG90S micro-servo motor. By changing the voltage supplied to the microcontroller, the response speed of the MG90S is tested to calculate the time required to rotate 90°. The experimental results are shown in Table 1.


### Table 1. Control experiment data

| Voltage | Software | Single chip model | Servo motor model | Rotation angle | Time |
|---------|----------|-------------------|-------------------|----------------|------|
| 3.3V    | Keil5    | ATTINY85          | MG90S             | 0-90°          | 0.6s |
| 5V      | Keil5    | ATTINY85          | MG90S             | 0-90°          | 0.45s|

### 3.2. Steering gear anti-overload simulation

When the artillery fires, it will instantly generate a huge thrust, so that the projectile can leave the cannon with enough kinetic energy to fly to the target. Considering that the servo motor is installed inside the shell of the projectile, in order to ensure that it is not damaged by the huge force at the moment of firing, it is necessary to carry out anti-overload simulation and simulation analysis [10], and judge whether the structure meets the anti-overload requirement through data.

In this paper, ANSYS workbench 15.0 software is used as the platform, and the data of the US Army Bofors 40mm L/70 tracer projectile is taken as an example to check the strength of the internal servo motor module of the steering gear. Bofors 40mm tracer full weight 2.51kg, projectile weight 0.96kg, gun initial velocity 1005m / s, barrel length 2.25m, twist line length 1.93m, kinetic energy about 484812J.

According to formula (2), the time required for the acceleration of the ballistic correction projectile is obtained, and then brought into the momentum theorem formula (3), the instantaneous force of the fire can be obtained.

\[
\text{Cannon Length/Projectile Velocity}=\text{Acceleration Time} \tag{2}
\]

\[
F_t=mv'-mv \tag{3}
\]

In the formula, \(F_t\) means the moment of firing, it means the acceleration time of the ballistic correction missile, and \(mv\) and \(mv'\) respectively represent the momentum before and after the acceleration of the ballistic correction projectile. According to common sense, \(mv=0\). Substituting the relevant parameters into equation (2), the acceleration time of the projectile is 0.0019s, and then substituting it into equation (3), the instantaneous force \(F_t\) is 507789.47N.

First, the built servo motor model is imported into the software and meshed. Since the servo motor housing material is low carbon steel, the input has a modulus of elasticity of 2.06×10\(^11\), a Poisson's ratio of 0.3, and a density of 7.84g/cm\(^3\). According to the dimension drawing of the MG90S servo motor in Section 1.3 of this paper, it is calculated that the bottom force area is 0.000800444 square. A uniform load of 1810688453.8582 N/m\(^2\) was applied to the bottom of the servo motor. The degree of deformation of the motor is gradually distributed along the Z-axis, and the deformation of the bottom surface is up to 0.00112 mm, which is less than one percent of the thickness of the motor casing, which is basically negligible. Therefore, it is concluded that the servo motor meets the requirements of overload resistance.

### 3.3. Cam Torsion Simulation

When the motor rotates at a constant power, the lower the speed, the greater the torque. The SG90 servo motor can generate a torque of 1.6kg/cm, and the cam groove stroke is 5mm. According to the conversion, when the cam rotates, it is pressed against the rudder link to generate a pressure of 31.36N.

Introduce the built cam model into ANSYS Workbench 15.0. The cam material is low carbon steel with an elastic modulus of 2.06×10\(^11\), a Poisson's ratio of 0.3, and a density of 7.84g/cm\(^3\). A 31.36N uniform pressure is applied inside the cam groove. The results show that the maximum shape of the inner side of the cam groove becomes 0.194×10-10m, and the actual stress is 93.4899Pa, which is basically negligible. Therefore, it is concluded that the cam structure satisfies the requirements of torsional strength.
4. Conclusion

1. According to the control experiment, when other conditions are the same, using a higher 5V voltage supply can effectively speed up the rotation speed of the servo motor and shorten the response time. The ballistic correction project described in this paper spins or does not rotate during the flight. Shortening the response time of the steering gear system can greatly improve the combat performance of the ballistic correction projectile.

In this paper, the ballistic correction missile has a flight speed of about 2 Mach and belongs to supersonic flight. During the flight, the rudder blade generates shock and expansion waves when cutting the air, resulting in greater flight resistance. According to the supersonic linearization theory, the rectangular airfoil design is adopted to effectively reduce the flight resistance.

In this paper, through the calculation of the degree of freedom of the cam and the rudder mechanism, it is known that the steering system is unstable. It is creatively proposed to install a pair of limit jaws on the inner casing of the ballistic correction bomb, so that the degree of freedom of the system is 1, thereby ensuring that the flight control portion of the entire ballistic correction project can operate effectively.

Through the torsional simulation of the cam mechanism and the anti-overload simulation analysis of the servo motor, it can be seen that the structural strength of the low carbon steel fully meets the emission requirements of the ballistic correction projectile. The steering gear system composed of the components can be used in the 40mm projectile launching process. Work efficiency and stability.

References

[1] Xu Guotai. Research on the technology of simple guided rocket retractable electromagnetic steering gear [D]. Nanjing University of Science and Technology, 2013.

[2] Huang Jianxun. Design of ballistic correction projectile electromagnetic steering system [D]. Nanjing University of Science and Technology, 2009.

[3] Zeng Fanju. Design of control system for ballistic correction projectile electric steering gear [D]. Shenyang Institute of Technology, 2010.

[4] Zeng Weili, Yao Xiaoxian, Lin Fan. Drive design test and simulation of electromagnetic steering gear [J]. Aerospace Control, 2008(02): 68-70+78.

[5] Li Hongyan, He Yang, Cai Peng, Jiang Chunyan, Xu Xin. Design of control system for electric steering gear for UAV [J]. Micro motor, 2018, 46(10): 85-88.

[6] Ran Lingfeng. Research on a distributed electric steering gear for UAV [J]. Henan Science and Technology, 2019(08): 56-58.

[7] Yuan Jiabin, Liu Wei. Research on New Polarized Electromagnetic Drive Servo of Micro Air Vehicle [J]. Journal of Nanjing University of Aeronautics and Astronautics, 2004(01): 48-51.

[8] Mitsumi Electric Co. Ltd.; "Vibration Actuator And Portable Device" in Patent Application Approval Process (USPTO 20190207496) [J]. Energy Weekly News, 2019.

[9] General Electric Technology GmbH; Patent Issued for Actuator Spring Lifetime Supervision Module For A Valve And Actuator Monitoring System (USPTO 10, 233, 786) [J]. Computers, Networks & Communications, 2019.

[10] Li Hao, Jia Fangxiu, Zhou Qiang, Zhang Tianyu. Modeling and simulation of double-rotor permanent magnet synchronous electric steering gear [J]. Journal of Ordnance Equipment Engineering, 2019, 40(06): 143-148.