Design of retractile fins actuator based on hollow piezoelectric motor

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Abstract. In the initial stage of the exterior ballistic, the centroid of the simple guided rocket will change with the fuel consumption of rocket engine, so the flight stability in the initial stage and the manoeuvrability in the whole trajectory correction process must to be comprehensively considered. For this challenge, in this paper, a specific actuator and aerodynamic configuration based on the integration of retractile fins structure and rotor of hollow piezoelectric motor is proposed. And the research on the structure of the actuator and the scheme of the retractile mechanism are carried out. The wind-induced rolling moment of the actuator under different flight conditions (angle of attack, Mach number) is simulated and analyzed by numerical computation method, and the load characteristics of the piezoelectric motor of the actuator is analyzed and tested. The results show that when the flight speed is 0.8 Ma, 1.0 Ma, the angle of attack is 0~6°, the maximum induced rolling moment of the actuator is 0.30 N.m, and the load speed of the piezoelectric motor is 25r/min when the excitation voltage is 450V and the excitation frequency is 40.2kHz, which can meet the requirements of the projectile flying environment.

1. Introduction

With high precision and cost-effectiveness ratio, the simple guided rocket is a new type of equipment to meet the needs of precision strike in modern war, which is compatible with the original launch platform, and has the advantages of both conventional ammunition and precision guided ammunition [1]. At present, the general configuration of the fixed canard is mostly used in the guided rockets [2]. During the whole trajectory correction process, the normal aerodynamic force is adjusted by the deflection of the fins or the rotation of the head driven by the actuator, to realize the two-dimensional trajectory correction at a low cost. In the active phase of the external trajectory of the guided rocket, the engine continues to burn and propels the rocket to accelerate, and the centroid of the rocket gradually moves toward the head of the rocket until the engine stops working, also known as the end point of the active phase (expressed in K point). The configuration design of the canard needs a certain amount of stability reserve to ensure the flight stability of the rocket before the K point, obviously causing loss of the flight maneuverability after the K point and ultimately affecting the correction effect of the two-dimensional trajectory [3].

In order to solve this problem that the correction kit needs to take into account flight stability in the initial stage and the manoeuvrability in the whole trajectory process, in this paper, a hollow piezoelectric motor actuator integrated with the retractile canard fins is proposed and designed. Then, the wind induced rolling moment [4] of the actuator during the rocket flight is computed by ANSYS...
FLUENT software under different flight Mach numbers and angles of attack. Finally according to the simulation data, the load characteristics of the actuator is tested.

2. System design of the actuator

2.1. Motor structure and working principle
Developed in 1980s, piezoelectric motor is a new type of piezoelectric actuator, utilizing the converse piezoelectric effect of piezoelectric materials to drive the rotor through the friction between the stator and the rotor and transfer the driving force [5]. Compared with the traditional electromagnetic motor, it has the advantages of fast response, large torque, low speed, no electromagnetic interference, self-locking, and simple structure [6]. Therefore it has been widely used in aerospace, weapon equipment, precision instruments and other fields. Based on the research of our research group, this paper presents a kind of hollow piezoelectric motor actuator which is integrated with the canard fins. Shown in figure 1, the hollow piezoelectric motor is composed of hollow stator, rotor, piezoelectric ceramic plate, bearing, locking nut and belleville spring. The preloading between the stator and rotor is adjusted by the locking nut and belleville spring. When the high frequency AC voltage is applied to the piezoelectric ceramics plate attached to the stator, the converse piezoelectric effect is inspired to excite the dentate hollow stator to produce high frequency micro mechanical vibration, and the vibration is converted into the rotating motion of the rotor through resonance amplification and friction coupling to drive the load.

![Hollow piezoelectric motor](image)

**Figure 1.** Hollow piezoelectric motor.

2.2. Retractile mechanism of canard fins
Combined with the hollow piezoelectric motor, a kind of control device for the retractile fins is designed. The fins and the rotor of the hollow piezoelectric motor are integrated. Before the K point, the fins remains in the projectile body under the constraint of the inertial safety device, as shown in figure 2(a). When the engine competes acceleration, the safety device is triggered by the recoil force and centrifugal force produced by projectile spinning, releasing the canard fins, as shown in figure 2(b). Without additional power device driving, the whole actuator system is compact and simple, effectively reducing the weight of the system. Meanwhile, this mechanism can delay the fins’ aerodynamic effect on the projectile and eliminate the adverse impact of the fins on the trajectory in the acceleration process of the projectile’s active phase by releasing the fins at the right time. Thereafter the canard fins extending from the projectile body and the whole projectile produce normal control force, which relies on hollow piezoelectric motor to drive the rotor fins to achieve trajectory correction, ultimately achieving a fine balance of stability and manoeuvrability in the whole trajectory correction process.
3. Aerodynamic load analysis of the actuator

3.1. Simulation model and grid generation

In this paper, the two-dimensional trajectory correction rocket as shown in figure 3 is taken as the research object, with a total length of 1140mm and a maximum diameter of 100mm, which belongs to a kind of tail stabilized projectile. In the process of projectile flying, in order to reduce the direction dispersion due to eccentricity error caused by engine thrust, projectile’s manufacturing and assembling, the rotation speed of the rocket body is required to be between 6r/s and 10r/s. In order to generate the correction force in a specific direction, the fins controlled by the actuator are required to keep stationary relative to the inertial space [7,8]. Therefore, the certain load capacity and speed of the actuator are required.

![Diagram of projectile model](image)

Figure 3. Diagram of projectile model.

Sliding mesh method [9] is a kind of unsteady numerical computation method, which has been widely used in the field of aerodynamic simulation of rotating machinery, such as wind turbine and projectile flight in recent years. The model is meshed by ANSYS ICEM software. The flow field, a cylinder with diameter of 16m and height of 32m is composed of two parts: the small cylinder is the rotational domain, which rotates periodically as shown in figure 4(a). The rotating speed around the central axis of the projectile is 600r/min. The external large cylinder area is the static outflow field, the internal boundary of the rotating domain is the surface of the projectile, and the external boundary of the static domain is the surface of large cylinder. The inner boundary of static domain and outer boundary of rotational domain are set as interface as shown in figure 4(b).

In the projectile trajectory, the relative motion exists between the surface and the air. Because of the viscous effect of the air, a very thin boundary layer [10] is formed near the surface of the rocket. The air flow in the boundary layer is very complex, but it has an important influence on the aerodynamic characteristics of the projectile, which can not be ignored. Therefore, in the numerical computation, the multi-layer boundary layer grid is generated on the surface of the projectile to simulate the layer accurately as shown in figure 4(c). The boundary layer grid is set as the triangular grid, the first layer is $10^{-4}$m high, the grid extension ratio is 1.2, the rest calculation domain is divided into tetrahedral unstructured grid, and the areas with violent flow changes such as the head and fins are densified, as shown in figure 4(d), the rest of the grid can be relatively loose [11,12], which can not only ensure the accuracy of numerical computation, but also reduce the calculation amount. Finally, the grid number of the whole computation area is about 5.04 million.
Figure 4. Diagram of mesh generation.
3.2. Computation model settings
The shear stress transport (SST) k-ω turbulence model based on turbulence energy equation and diffusion rate equation can adapt to various physical phenomena of pressure gradient change, such as rotating machinery. Meanwhile, considering the transport of turbulent shear stress, the model can accurately simulate the phenomenon of boundary layer by the application of wall function. Therefore, in this paper, the SST k-ω model is adopted to calculate the low-speed rotation of the guided rocket. In the Options column of the SST k-ω model, check Compression effects. In the setting of the boundary conditions, the implicit density-based solver is adopted to solve the compressible flow. The time option is transient, and the density is ideal-gas. Due to the maximum flight speed of the projectile is so high, which is a transonic flow, that we should activate the energy equation. The inlet flow uses the pressure far-field boundary conditions, and the value is set by the Mach number and angle of attack. The remaining conditions adopt default values. Set the rotation domain in the Cell domain condition, check mesh motion, and then set the rotation speed and rotation axis of the rotational domain. The projectile rotates at the same speed with the rotation domain; the surface of the projectile is set as the non-sliding wall, and the interface between the rotation domain and the static domain is set in the Mesh interface.

3.3. Numerical computation results
The research object of this paper is the tail stabilized projectile. The maximum flight speed is about 1.0Ma, and most of the time in the trajectory process is about 0.8Ma. Therefore, in the numerical computation, the simulation values of speed are 0.8Ma and 1.0Ma. The main purpose of this chapter is to calculate the wind-induced rolling moment of the actuator in the flight conditions at the two Mach numbers, and to provide the basis for the design of the actuator, to examine whether the actuator meets performance requirements.

Select Mach number of 0.8Ma, 1.0Ma and angle of attack of 0°, 2°, 4° and 6° to calculate. The simulation results are shown in figure 5. Under the same Mach number, the induced rolling moment is positively related to the angle of attack and increases with the angle of attack, and the induced roll moment at 1.0Ma is significantly greater than 0.8Ma. According to the figure, we can learn that the maximum induced rolling moment of the actuator is about 0.30N.m.

![Figure 5. Curve of induced rolling moment with angle of attack at different Mach numbers.](image)

4. Load performance analysis and test of the actuator

4.1. Test system
A load performance test platform is designed and built for the assembled actuator. The test platform is mainly composed of signal generator, power amplifier, hysteresis dynamometer, regulated power supply and slip ring, as shown in figure 6. The signal generator and power amplifier are used to provide the electric signals to drive the piezoelectric motor, the slip ring is used to connect the rotating
parts, and the regulated power supply is used to provide the voltage for the dynamometer. The hysteresis dynamometer is composed of the stator with tooth pole, hollow hysteresis cup rotor, excitation coils and other parts. When the current passes through the internal coils, the magnetic line will be generated to form the magnetic circuit and generate torque, and the output torque can be regulated by changing the excitation current to acquire the load torque required by the test. According to the data measured by our research group, the maximum no-load speed of the piezoelectric motor is 208r/min, and the torque is 0.35N.m, and the maximum aerodynamic load torque is 0.30N.m calculated by the numerical computation results above, so the 1N.m dynamometer can meet the test requirements.

![Figure 6. Load performance test platform of hollow piezoelectric motor actuator.](image)

4.2. Load performance test results
The test results are shown in figure 7. With the increase of load torque, the rotation speed of the actuator decreases gradually. When the maximum induced rolling torque is 0.30N.m, the excitation voltage is 450V and the excitation frequency is 40.2kHz, the test results show that the rotation speed of the actuator is 25r/min, the actuator can meet the requirements of the projectile flying environment.

![Figure 7. Load characteristic curve of the actuator.](image)

5. Conclusion
In this paper, a kind of actuator based on the hollow piezoelectric motor rotor and retractable canard fins is designed and tested, which can solve the problem of low-cost projectile's comprehensively considering the flight stability in the initial stage and the manoeuvrability in the whole trajectory
The aerodynamic characteristics of the rocket assembled with the actuator have been computed by CFD software FLUENT. The simulation results shows that the maximum wind-induced rolling moment of the actuator is 0.30N.m in the trajectory process of low rotation and high speed. Finally, according to the simulation result, the load performance of the actuator is tested to obtain the load characteristic curve of the actuator. The test results show that when the load torque is 0.30N.m, the peak value of excitation voltage is 450V, and the frequency is 40.2kHz, the rotating speed of the actuator can reach 25r/min, which can meet the actual demand.

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