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Research on Divert and Attitude Control System Technology of Ballistic Missile Midcourse Maneuver Penetration Warhead

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Abstract: With the continuous development of American midcourse interception technology, it is particularly important to promote the midcourse penetration capability construction of ballistic missiles. The use of maneuver penetration technology in the midcourse of ballistic missiles can effectively deal with the midcourse interception of foreign missiles. In order to promote the development of midcourse maneuver penetration technology, this paper takes the Divert and Attitude Control System (DACS) of maneuver penetration warhead as the starting point, refers to the development of DACS of Kinetic Kill Vehicle in the United States, and summarizes the research status of gas valve, the key structure of DACS. On this basis, combined with the structural characteristics of maneuver penetration warhead, the key technologies related to the construction of DACS of penetration warhead are summarized, which lays a foundation for the development of DACS of penetration warhead in the future.

Keywords: Autonomous maneuver penetration; Midcourse intercept; Kinetic kill vehicle; DACS; Gas valve.

1. Introduction

Since 1980s, the United States has vigorously developed its missile interception technology and built a missile defense system. After development for more than 40 years, the United States has been in the forefront of the world in this technical field. In June 2020, the United States Department of Defense released a report entitled "Layer Homeland Missile Defense-Strategy for Protecting the United States", which further expounded the development plan of the current United States missile defense system. On November 17, 2020, the United States successfully conducted the sea-based midcourse interception experiment for intercontinental ballistic missiles for the first time by using standard-3 Block II A. The success of this experiment also indicates that the United States has the ability to carry out midcourse interception of intercontinental ballistic missiles. On the historical issue of penetration and interception, the rapid development of missile interception technology also means that the penetration capability construction of ballistic missiles needs to be continuously strengthened.

Among the current penetration modes, autonomous maneuver penetration of missiles is the most direct mode. Meanwhile, based on the theoretical analysis, autonomous maneuver penetration is also the most effective penetration mode. According to public information, Topol-M missiles have full maneuvering capability. In the midcourse trajectory, Topol-M achieves its maneuver penetration purpose by loading multiple maneuvering warheads [1]. Therefore, in the construction of ballistic missile penetration capability, the construction of midcourse autonomous maneuver penetration capability of warhead should be strengthened [2, 3].

Currently, the research on maneuver penetration mainly focuses on the solution of each axial acceleration of penetration missile [3], namely penetration guidance, which does not involve the specific nozzle layout and related working mechanism of divert and attitude control system. Therefore, relevant studies should be carried out for divert and attitude control system of penetration missile, and then the warhead penetration control law should be designed on this basis.

At present, there is relatively little research on divert and attitude control system of penetration missile. From the working mode and requirements, the divert and attitude control system of penetration missile is similar to the divert and attitude control system of Kinetic Kill Vehicle (KKV) to a certain extent, and both of them provide thrust for the divert and attitude control of warhead. With the development of missile defense technology in the United States, the divert and attitude control system of KKV has been mature, so we can learn from the related technologies of interceptor divert and attitude control system, and then promote the development of penetration missile divert and attitude control system.

Taking KKV as the background, this paper sorts out the development of its divert and attitude control system, and further summarizes the key structure of divert and attitude control system--the design and development of gas valve. Meanwhile, the related research results of our research group are introduced. Finally, combined with the structural characteristics of penetration warhead, the related key technologies for the construction of divert and attitude control system of maneuver penetration warhead are summarized.

2. Research status of divert and attitude control system of KKV

Since the United States put forward the "Strategic Defense Initiative" (SDI) plan in the early 1980s, the difficulties in its technical research mainly focus on the design and experiment of KKV [4]. From the perspective of divert and attitude control system, the research and development of KKV in the United States can be divided into three generations. The first generation uses binary liquid propellant; thes generation uses solid propellant and PWM technology to control KKV; the third generation also uses solid propellant, but overcomes the continuous thrust adjustment technology based on solid propellant. This section takes the American KKV as the background and the divert and attitude control system as the main line, and combs and summarizes the key nodes of its development process.

2.1. EHV（Experimental Hover Vehicle）

EHV is the first equipment [5] to participate in the Kinetic Kill Vehicle Hovered Interceptor Test (KHIT) at the National Hover Test Facility (NHTF), with a weight of 90.7 kg, and its divert and attitude control system adopts binary liquid propellant. The experiment was completed in April 1989. As the first omni-directional hover experiment of KKV prototype in the United States, the flight time of EHV was 24s. Through the preset hover flight path, EHV completed the corresponding maneuver through the divert and attitude control system and landed safely. As a milestone in the development of KKV in the United States, this experiment paves the way for the subsequent performance improvement and improvement of KKV. In August and September 1989, EHV hovered twice, respectively. These two experiments realized the closed-loop guidance and control of EHV based on infrared seeker images, and could lock and track simulated enemy targets through divert and attitude control system.

2.2. LEAP I

With the gradual complication of the trajectory related to incoming missiles, higher requirements are put forward for the interception capability of American interceptors, and the interception success rate of interceptors must be improved without greatly increasing the cost. One of the main factors of interceptor cost is the size and weight of interceptor. If smaller and lighter interceptor is adopted, the corresponding supporting equipment required will be greatly reduced and its maneuver ability will be improved. Divert and attitude control system is the main equipment of interceptor, and the core of reducing the mass and volume of interceptor lies in its lightweight and integration of divert and attitude control system. Therefore, the Strategic Defense Initiative Organization (SDIO) put forward the "Lightweight Exo-atmospheric Projectile" project, namely LEAP (Lightweight Exo-atmospheric Projectile), which aims to develop light KKVs that meet the above requirements.

The first LEAP experimental equipment, LEAP I, as shown in Fig. 1, was jointly developed by Rockwell and Rocketdyne [6]. The interceptor has made a breakthrough in the miniaturization of divert and attitude control system and electronic equipment. Compared with EHV, its weight is reduced to 18.1 kg, and it also uses binary liquid propellant with high pressure nitrogen as the power source for attitude control. The engine consists of four orbital control nozzles located around the center of mass with a thrust of 485N, and eight attitude control nozzles located at the tail of the interceptor with a thrust of about 4.4 N. In July, 1990, LEAP I carried out a hover experiment in NHTF [5]. The name of the experiment was Advanced Hovered Interceptor Test (AHIT). The hover time was 18s, and the target was tracked by visible light seeker [4].

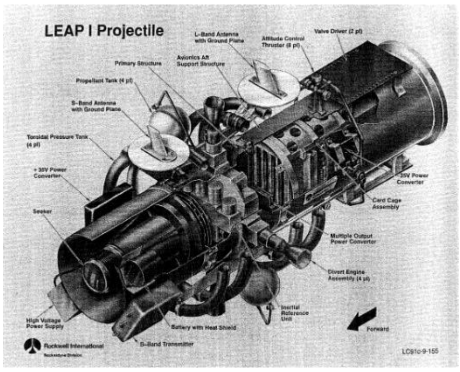

Fig. 1 LEAP I projectile[6]

2.3. LEAP II (U.S. Army LEAP)

LEAP II, also known as "U.S. Army LEAP", is developed by Hughes Aircraft Company, as shown in Fig. 2. Compared with LEAP I, the mass of the system was lower than 6.8 kg. The diameter of the system was 15cm and the length was 38cm. The layout of the interceptor is similar to LEAP I. There are four 160N orbital control nozzles at the centroid of the interceptor, which provide the lateral maneuver ability of the interceptor, and the response time is less than 5ms [7]. There are eight attitude control nozzles in the rear bulkhead of the interceptor, with a thrust of 4.5 N, which are used to adjust the attitude of the interceptor [8], and the response time is less than 1ms. LEAP II also uses binary liquid propellant, and the interceptor also includes high-resolution medium-wave infrared seeker, matching target acquisition and tracking computer, high-density small avionics, thin film optical telemetry transceiver and inertial measurement unit. In mid-March 1991, LEAP II enters NHTF for subsystem test, On the morning of April 23, 1991, LEAP II officially carried out hover experiment, During the whole test period lasting 10s, LEAP II executes a set of representative engines working sequence in interception mission, which is written into the system controller by pre-programming. During the experiment, the seeker tracking system keeps locking the long-distance target, and three orbit-controlled engines ignite about 100 times, and eight attitude-controlled engines ignite about 1400 times.

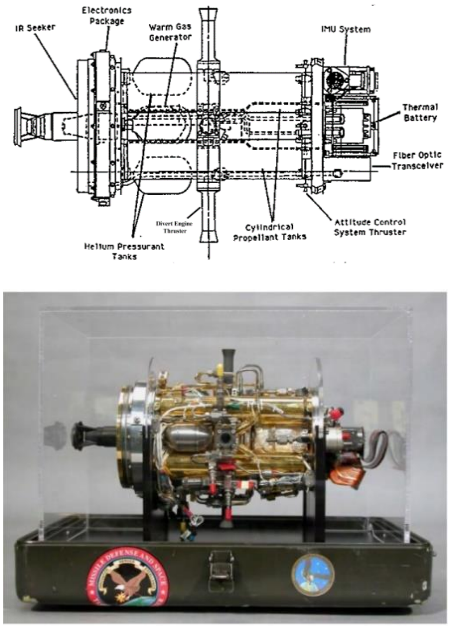

Fig. 2 U.S. Army LEAP[9]

2.4. LEAP III (Air Force LEAP)

LEAP III, also known as "Air Force LEAP", is jointly developed by Boeing, Rockwell and Rocketdyne, and its structure is shown in Fig. 3. LEAP III was developed and suspended in the same year as LEAP II, and the length of LEAP III was 55.6 cm. The diameter is 45.7 cm and the system weight is 10.8 kg, which is slightly heavier than LEAP II, but still has a great improvement compared with LEAP I. The divert and attitude control system of the interceptor is the same as LEAP I [5], which adopts binary liquid propellant, four divert control nozzles with thrust of 485N, and eight attitude control nozzles with thrust of about 4.4 N. During the levitation test on August 22, 1991, LEAP III hovered at an altitude of 6m, and simulated the maneuver state during the actual space engagement through a series of lateral maneuvers. The whole hover experiment lasted for 17s.

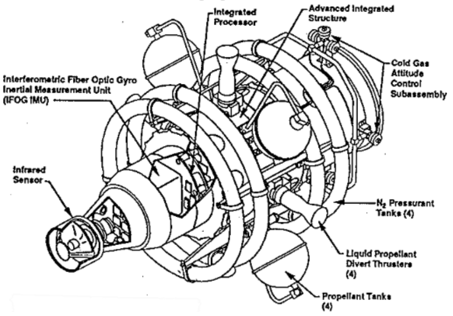

Fig. 3 Air Force LEAP[5]

2.5. Advanced LEAP

Considering the filling, storage and maintenance of liquid propellant, the United States considered using solid propellant instead of liquid propellant for divert and attitude control system of interceptor, which further reduced the cost and improved the reliability of the system. In March 1993, the Advanced Lightweight Exo-atmospheric Projectile was launched. Aerojet is mainly responsible for the launch of divert and attitude control of this project, which cooperates with Societe Europeenne de Propulsion (SEP) to carry out corresponding research and development.

The research and development of Aerojet is based on the solid LEAP developed by Thiokol in 1991. The interceptor developed by Thiokol is used as a space-based interceptor of the United States Air Force, as shown in Fig. 4. The total weight of the solid LEAP is about 5kg. Its divert and attitude control system structure includes 1 gas generator, 4 222N divert control systems and 6 29N attitude control systems, and the propellant is HTPB/AP/AI composite propellant [10]. However, due to the limitation of space-based launch, the interceptor has strict quality standards, which leads to concessions in cost, mass production capacity and system stability in order to meet the quality requirements [11].

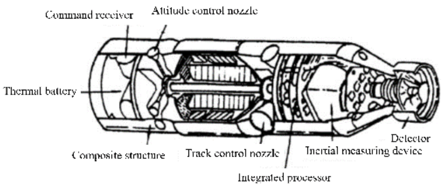

Fig. 4 Thiokol LEAP[10]

Aerojet Company combines Pulse Width Modulation (PMW) technology. After two upgrades and improvements on the basis of Thiokol LEAP, the solid divert and attitude control system is finally determined as the structure shown in Fig. 5 [11]. In order to reduce the system quality, Aerojet uses carbon-carbon (CC) composite materials and carbon-silicon carbide (C/SiC) materials instead of traditional superalloy materials. The divert control thrust of the divert and attitude control system is 315N, the response time is less than 6ms, the pitch thrust of attitude control is 31.5 N, the yaw/roll thrust is 15.5 N, the response time is 2ms, and the working time of the engine is 20s.

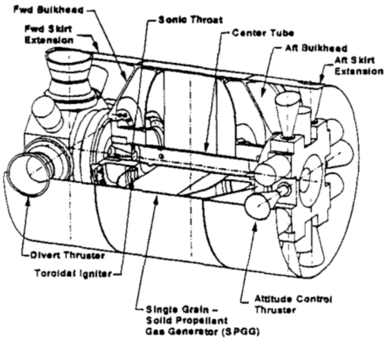

Fig. 5 Solid DACS[11]

Since the "Advanced Lightweight Exo-atmospheric Projectile" project, solid propellants have been widely used in interceptors, the most representative of which is the Standard-Missile-3 (SM-3) interceptor.

2.6. Standard-3 Block I A Interceptor

The development of the standard-3 missile interceptor comes from the United States Navy Aegis LEAP Intercept (ALI) [12]. The interceptor was developed by ATK Company (which acquired Thiokol Company in 2001), and its divert and attitude control system is also called MK 142 solid divert and attitude control system.

MK 142 solid divert and attitude control system is a pulse type solid divert and attitude control system, as shown in Fig. 6 and 7. The divert and attitude control system includes a gas generator, 4 divert control systems and 6 attitude control systems. The thrust of each divert control system is 222N, the thrust of each attitude control system is 29N, and the total mass of the interceptor is 5kg. SDACS adopts three-stage charge, among which the first stage pulse charge is TPH-3510, the second stage pulse charge is TP-H-3511, and the cruise stage charge is TP-H-3512 [13]. Standard-3 solid divert and attitude control system mainly solves the interior ballistic design of solid divert and attitude control system, the performance of control valves and the integration of subsystems and kinetic energy warhead.

The Standard-3 Block I A missile successfully completed three interception tests in January, June and November 2002.

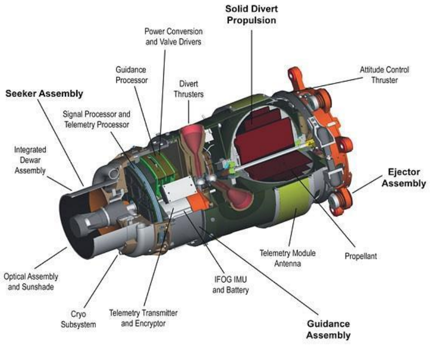

Fig. 6 SM-3 Kinetic Warhead[14]

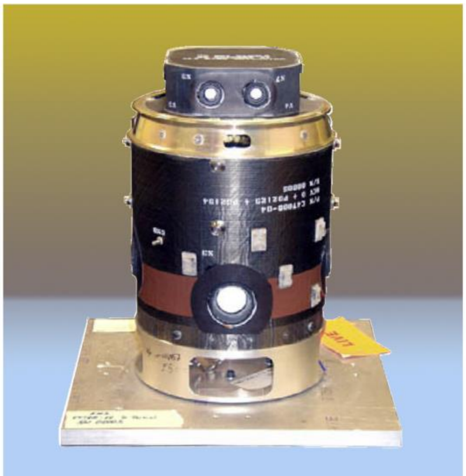

Fig. 7 SM-3 first flight SDACS[12]

2.7. Standard-3 Block I B/II A Interceptor

When the Standard-3 Missile was upgraded to Block I B, the fourth-stage solid divert and attitude control system was replaced, and the Throttling Divert and Attitude Control System (TDACS) designed by Aerojet Company was adopted, as shown in Fig. 8 [14]. This type of solid divert and attitude control system also continued to be used on Block II A. A total of 10 throat thrusters are used in the throttle solid divert and attitude control system, of which 4 are used for divert control and 6 are used for attitude control, which can realize accurate thrust control, and the thrust adjustment range is 0 ~ 6672N. At the same time, the engine can realize adjustment between high thrust and endurance thrust [15]. Compared with the original pulse solid divert and attitude control system, the new throttle solid divert and attitude control system has higher flexibility and further improves the utilization efficiency of propellant.

The Standard-3 Block II A missile was tested twice in 2016, namely the verification of propulsion system and the verification of divert control and attitude control capability of KKV in space. On February 3, 2017, the third test was carried out, and a medium-range ballistic missile target was successfully intercepted by using ship-launched Standard-3 Block II A missile in the waters near Hawaii. On November 17, 2020, the sea-based midcourse anti-missile interception experiment for intercontinental missiles was successfully carried out for the first time. Fig. 9 shows the Block II A interception demonstration animation released by Raytheon Company of the United States.

Fig. 8 TDACS

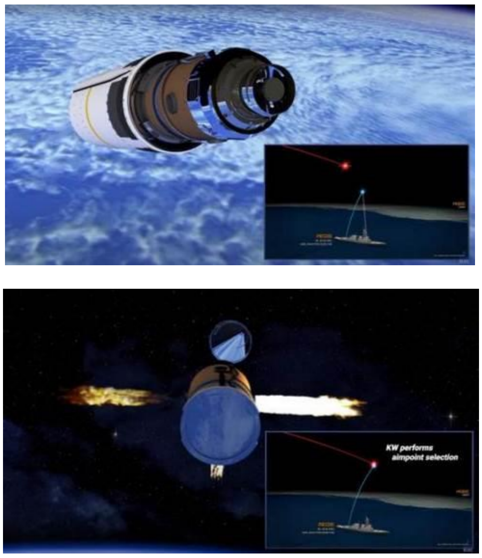

Fig. 9 SM-3 Block II A interception process

2.8. Development Summary of Divert and attitude control system of American KKV

Since 1980s, the divert and attitude control system of American KKV has been continuously developed and iterated. As shown in Fig. 10, from the initial binary liquid divert and attitude control system to the solid divert and attitude control system, and then to the throttle solid divert and attitude control system used today, its development process can be summarized into the following three points.

(1) Solid propellant gradually replaces liquid propellant. At first, EHV and LEAP I/II/III of American KKV all use binary liquid propellants. However, with the improvement of operational requirements, higher requirements are put forward for the cost, maintenance, storage and safety of KKV, especially for American space-based and sea-based KKV. Solid propellants are safer than traditional liquid propellants. Therefore, since the Advanced LEAP project, the divert and attitude control systems of American KKV have all used solid propellants.

(2) KKV is developing towards lightweight and integration. At first, the weight of EHV reached 90.7 kg, but the excessive weight will inevitably affect the design and research and development of the lower stage engine. Therefore, the LEAP project was launched in the United States, and the divert and attitude control system, as the main component of the interceptor, needs to be improved in light weight and integration first. Since LEAP I, the mass of KKV has been reduced to less than 20 kg, LEAP II and LEAP III have reduced the mass of KKV to less than 10kg, and LEAP II has reduced the mass to the lowest 6.8 kg. With the beginning of Advanced LEAP project, solid propellant was used in divert and attitude control system of KKV, and then the mass of KKV began to stabilize at 5kg.

(3) The follow-up control capability of divert and attitude control system has been continuously improved. With the use of solid propellant, the control ability of divert and attitude control system has become a major problem. At first, the control mode was pulse width modulation (PWM) control, and the equivalent thrust control was realized by adjusting the duty cycle. Subsequently, Aerojet Company developed the throttle solid divert and attitude control system, which can realize continuous thrust adjustment, and the follow-up control capability of the solid divert and attitude control

system was qualitatively improved.

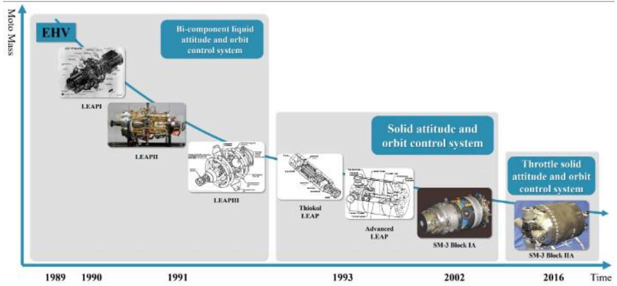

Fig. 10 Development of U.S. Kinetic Kill Vehicle

3. Research status of valve structure of solid divert and attitude control system

When the divert and attitude control system of KKV transits from binary liquid propellant to solid propellant, the primary problem to be solved is thrust control, and the core lies in the design of gas valve. Based on the summary and analysis of public data, the valve structures of solid divert and attitude control systems are mainly divided into three categories: pneumatic valve structure, rotary valve structure and pintle valve structure.

3.1. Research Status Abroad

3.1.1. Pneumatic valve structure

The pneumatic valve structure causes the pressure change on both sides of the valve through the opening and closing of small airflow, forming a pressure difference, realizing the reciprocating movement of the valve, thus realizing the thrust switching of the nozzle. The opening and closing of small airflow can be realized by driving a rotating valve or a solenoid valve by a motor. Thiokol LEAP and Advanced LEAP use this type of valve construction [11].

Aerojet Company designed two schemes when developing Advanced LEAP. The first scheme is modeled after Thiokol LEAP, and its layout and valve structure are similar to Thiokol LEAP, as shown in Fig. 11 and 12. The valve structure is characterized in that the orbital transfer nozzle is controlled by a double-headed poppet valve, while the attitude nozzle is directly controlled by an electromagnetic drive valve, as shown in Fig. 12. In the working process, the double-headed poppet valve is driven by the gas generated by the combustion chamber. Gas enters and exits the control chambers C1 and C2 through two solenoid valves, and the resulting pressure difference controls the opening and closing of the intermediate double-headed poppet valve. The advantages of this system lie in simple structural design and fast response speed. Aerojet Company has achieved 3ms switching response in cold air experiment, and the compact structure can facilitate the design of large expansion ratio of rail-controlled nozzle.

Although the design of double-head cone valve can meet the requirements of divert and attitude control system of interceptor, the structural design also has some shortcomings. Due to the hardware limitation of the valve, the pitch channel and yaw channel must be offset longitudinally during the installation process, which will bring chattering problem to the system, and it will also be difficult to zero the thrust of the system.

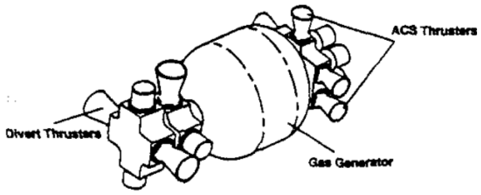

Fig. 11 Aerojet first DACS concept

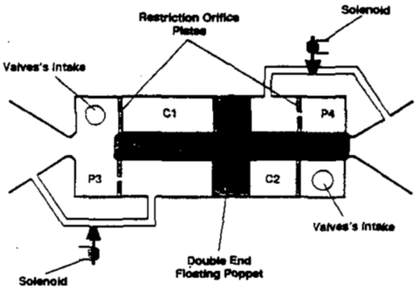

Fig. 12 Dual poppet optional schematic

Considering this problem, Aerojet Company designed another one-way pneumatic valve, as shown in Fig. 13 and Fig. 14. The structure of the system is characterized in that each rail-controlled nozzle is controlled by a single-head poppet valve and a pilot-operated solenoid valve. In the working process, the pressure under the single-head cone valve is controlled by opening and closing the pilot solenoid valve, so as to realize the change of the pressure difference between the upper and lower parts of the valve, and then control the switch of the valve. The valve solves the problem that the pitch channel and the yaw channel are not coplanar in structural design, each nozzle can be controlled independently, which further increases the flexibility of the engine. However, the disadvantage of this valve is that the compactness is reduced, and the throat area between the combustion chamber and the valve assembly needs to be added to maintain constant propellant mass flow and stable system response.

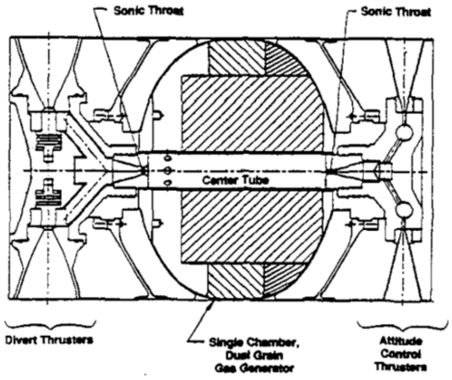

Fig. 13 Aerojets DACS concept

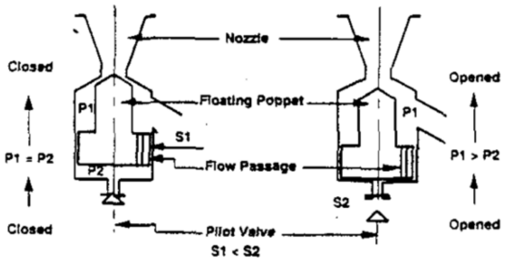

Fig. 14 Signal poppet optional schematic

3.1.2. Rotary valve structure

Rotary valve mainly refers to using servo motor to drive the valve to rotate, and directly realize the switching of gas between various nozzles. Davide Morrow of Garrett Company put forward a spherical rotating valve scheme, the early valve structure is shown in Fig.15 and Fig.16 [16], including guide vanes, spherical seals, motors, transmission rods, etc. When one nozzle needs to be opened, the guide vanes are rotated to drain the gas to the nozzle in this direction, and the spherical seals will move in the opposite direction of the nozzle under the action of pressure, and finally the nozzle in this direction will be completely closed. When commutation is needed, the guide vane is rotated by the motor to cross the centerline position, and then the vane will complete commutation under the action of gas pressure, and the spherical seal will move to the nozzle on the other side under the action of gas pressure. When the guide vane is in the center line position, the gas will be ejected at the same time in both nozzles, thus realizing zero thrust.

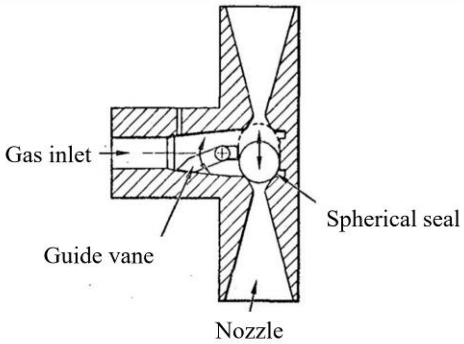

Fig. 15 Schematic of valve design

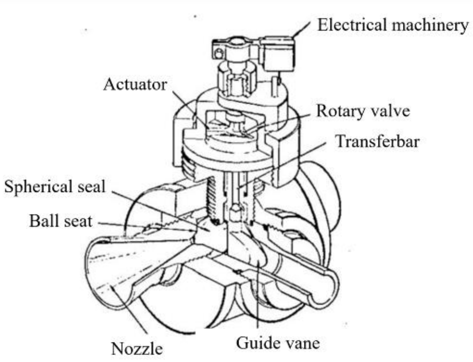

Fig. 16 Schematic of thruster assembly

Subsequently, Davide Morrow's team improved the valve structure and re-proposed a double-ball switching scheme, as shown in Fig. 17 [17], the section of which is the axial surface of the valve assembly. The basic principle of this scheme is the same as that of single ball switching scheme, which realizes the commutation of gas by spherical seals. However, the system adopts two spherical seals, which can have faster response speed when the commutation movement distance is longer, and at the same time, this scheme can close two nozzles at the same time.

Fig. 18 and Fig. 19 are two sections showing the front and back planes of the shaft in the valve assembly respectively. As shown in Fig. 18, the guide vane is in the intermediate position, and the gas enters the intermediate area of the two spherical seals through the holes 48 and 50, and the spherical seals will close both nozzles at the same time under the action of pressure. Behind the passage 48 of the shunt blade is a passage 51 connecting a pair of passages 52 that extend through the shaft support member and communicate with the space between the two spherical seals. When the shunt blades are in the intermediate position, the passage 52 is not connected to the opening 51. When one of the propeller nozzles needs to be opened, the shunt blades are rotated. The connection between the Passage 48 and the Passage 50 is interrupted, and the gas no longer enters the middle area of the two spherical seals. At this time, the spherical seal on one side will move to the sealing ball on the other side under the action of gas pressure. Due to the rotation of the guide vane, the Passage 51 communicates with the Passage 52, and the gas in the middle area of the two sealing balls will be discharged to the ambient atmosphere through the Passage 52 and the Passage 51.

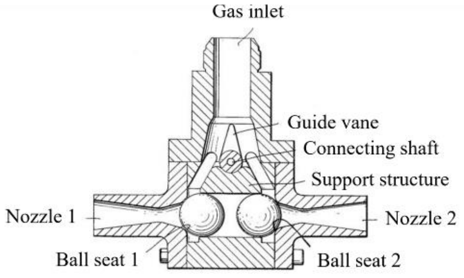

Fig. 17 Schematic of double ball valve

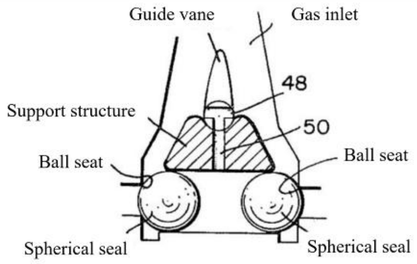

Fig. 18 Schematic of the valve with the section in front of the axial plane

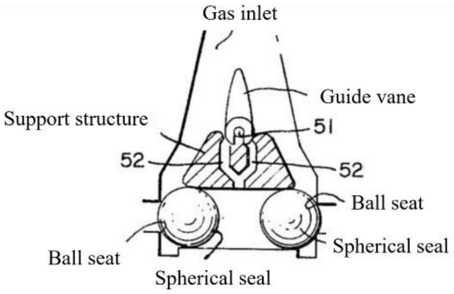

Fig. 19 Schematic of the valve with the section of the plane behind the axis plane

3.1.3. Pintle valve structure

Pintle valve is the most widely used valve structure in the United States at present. From the Standard-3 Block I B, its throttle solid divert and attitude control system began to adopt this kind of valve structure. Pintle valve changes the nozzle throat area by moving the needle valve back and forth, thus changing the thrust. As shown in Fig. 20. When the needle valve is withdrawn from the throat, the throat area increases and the combustion chamber pressure, propellant burning rate and thrust output decrease. When the needle valve is inserted, the throat area decreases and the combustion chamber pressure, propellant burning rate and thrust output increase.

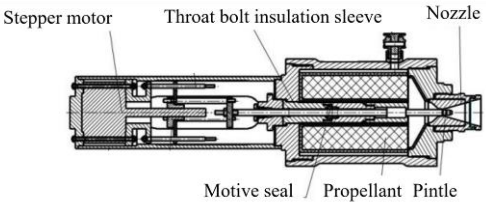

Fig. 20 Schematic of a pintle valve

Aerojet Company of the United States is the first company to study this kind of valve structure, and it is also the first company to successfully develop controllable solid divert and attitude control system [18].

The company pioneered the development of controllable solid propulsion technology from 1960s to 1970s. However, due to the limitation of system integration and related technologies, it could not be applied to industrial products. Until 1990s, great breakthroughs were made in high temperature materials, electromechanical actuators and control electronic technology. Aerojet Company further promoted the development of controllable solid propulsion technology, mainly including single pintle propulsion and multi-nozzle integrated system [19], as shown in Fig. 21 and 22.

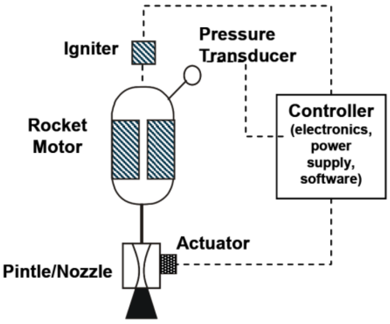

Fig. 21 Schematic of a single pintle rocket motor

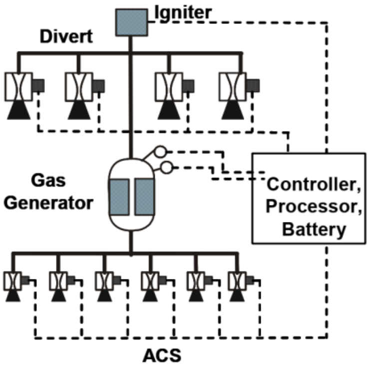

Fig. 22 Schematic of multiple thruster system

Single pintle valve is a simple solid thrust control form. The schematic diagram of Aerojet's single pintle valve is shown in Fig. 23, and the performance of this engine is shown in Table 1. During the test phase, Aerojet used this engine to increase the range of HAWK missile by 30%.

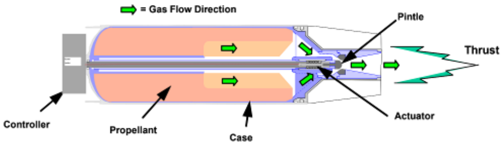

Fig. 23 A single pintle nozzle in a rocket motor

In the aspect of multi-nozzle integrated system, Aerojet Company started the related research and development work in 1991, and completed the related experiment of SM-3 missile in 1998 [18], which indicates that the controllable solid divert and attitude control system has achieved high maturity. Each nozzle of the system can continuously adjust the thrust through needle valve, and the needle valve can increase the total throat area of the system, thus significantly reducing the combustion chamber pressure, thereby reducing the burning rate of propellant and prolonging the mission time. As can be seen from Fig. 24, the pressure in the combustion chamber can be reduced to below 0.6 MPa during the experiment, and the working time of the system can reach 115s.

Tab 1. Performance for single pintle nozzle

Parameter name	Numerical value
Thrust/N	44~1300000
Adjustment ratio	40:1
Pressure/MPa	0.3~29
Response time/ms	≤10
Start-stop times	≤20

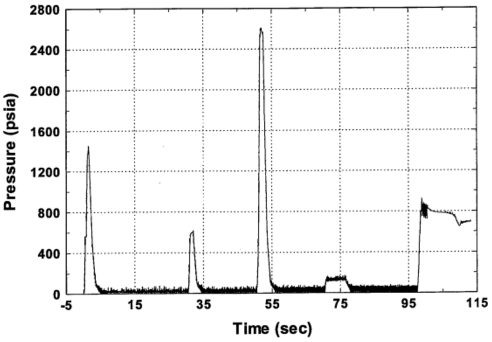

Fig. 24 SM-3 is solid DACS test[18]

With the research of controllable solid propulsion technology by Aerojet Company, the multi-nozzle integrated system developed by Aerojet Company has been applied in many aspects, including the variable thrust system of jet escape seat, the jet reaction system of agile tactical missile, the attitude control system of launch vehicle and the divert and attitude control system of interceptor. Fig.25 is an experimental diagram of a multi-nozzle integrated system developed by Aerojet Company.

Fig. 25 Experiment of multiple thruster system

ATK Company also has great development in pintle valve structure. Because the surface of the traditional needle valve will bear the high load when the combustion products pass through, the transmission mechanism of the needle valve needs to provide a large force, which affects the thrust response time. At the same time, the size and mass of the transmission mechanism are also increased. In 2010, ATK Company proposed a pintle valve structure with load balancing capability, as shown in Fig. 26 [20]. The structure comprises a nozzle, a valve assembly and a thrust control assembly. An exhaust passage is added to the needle valve in the structure. The exhaust passage consists of a central passage and four radial passages. The radial exhaust passage is connected with the central passage and evenly distributed around the needle valve. The exhaust chamber is located at the other end of the needle valve and connected with the exhaust passage. In the actual working process, the gas reaches the exhaust chamber through the exhaust passage to balance the load exerted by the combustion products on the surface of the needle valve.

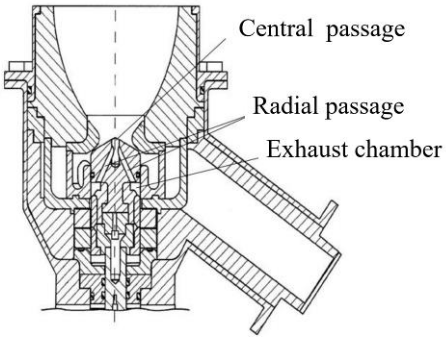

Fig. 26 Schematic of improved pintle valve

3.2. Domestic research status

3.2.1. Pneumatic valve structure

Yao Xiaoxian's research team of Beijing Institute of Technology designed a pneumatic valve attitude control system for attitude control of KKV. The schematic diagram is shown in Fig. 27 [21]. The gas generated by the solid gas generator enters the working air cavity inside the attitude control system through the air inlet, and a small part of the gas enters the control air cavity through the throttle as the control air flow from the working air cavity. Under the action of the control signal, the electromagnet manipulates the baffle to close the nozzle on one side and release the nozzle on the other side, so that the pressure of the control air chamber on both sides of the piston is unbalanced. Assuming that the baffle moves from left to right, the nozzle 1 is closed, so that the pressure of the control air chamber 1 gradually increases and the pressure of the control air chamber 2 gradually decreases. When the thrust generated by the pressure difference between the control air chambers on both sides is enough to overcome the resistance of the piston, the piston drives the rocker arm head to move to the left, and the rocker arm rotates around the swing axis to close the nozzle 1 and open the nozzle 2, thus generating the attitude control thrust to the left. When the control signal changes phase, the direction of attitude control thrust is switched.

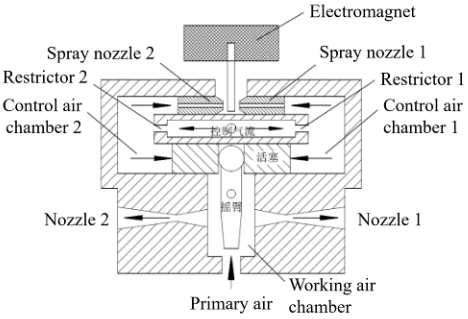

Fig. 27 Schematic of nozzle and valve working principle

Under the action of aerodynamic piston, the structure drives the rocker arm to open or close the nozzle, which can realize the rapid response of thrust. In the experimental process, the delay time of the initial structure is 8ms, and the delay time of the optimized structure is shortened to 6ms. At present, the engine has been successfully applied to a certain ballistic correction projectile as an attitude control element. The attitude control system used in hot gas experiment is shown in Fig. 28.

Fig. 28 ACS before hot-fire test

3.2.2. Rotary valve structure

Domestic research on rotary valve is relatively few, but for solid divert and attitude control system, rotary valve structure has great advantages for system integration and fast response. Xi'an Institute of Aerospace Power Technology has successfully developed a solid divert and attitude control system based on rotary valves [22]. The system structure and valve structure are shown in Fig. 29 and Fig. 30.

The overall layout of the engine is 4 +6 structure, with 4 rail-controlled nozzles and 6 attitude-controlled nozzles. The rail-controlled nozzles are 2 +2 structure, that is, each servo motor controls two nozzles with an included angle of 90°, and the attitude-controlled nozzles are 3 +3 structure, namely each servo motor controls three nozzles with an included angle of 90°. Taking attitude control nozzle as an example, as shown in Fig. 30, the valve structure adopts the design concept of combining stator and rotor. The valve cavity is the stator structure of the valve, and the valve core is the rotor structure. Three gas outlets are arranged at an adjacent interval of 90° on the valve cavity, and a sector-shaped area of 180° is cut on the valve core as a gas channel. When the valve core rotates, three nozzle switching controls can be realized. In order to achieve the purpose of fast response, hollow cup design is adopted for the spool rotor, which reduces the structural mass and moment of inertia of the rotor.

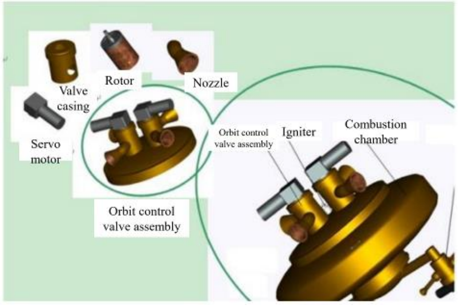

Fig. 29 System structure diagram

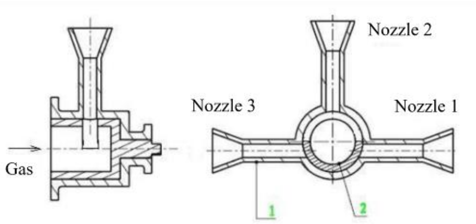

Fig. 30 Valve structure diagram

3.2.3. Pintle valve structure

A great deal of research has been done on the structure of pintle valve in China, including principle analysis, structure design, control system design and so on. Northwestern Polytechnical University and 41 institutes of the Fourth Research Institute of China Aerospace Science and Technology Corporation have established an experimental test system for pintle engine, and carried out a series of experiments and numerical simulation research.

In engineering experiment, Wang Yilin developed a non-coaxial pintle variable thrust engine test system and carried out the principle test of pintle variable thrust engine [23], as shown in Fig. 31. The design of the test system solves the key problems such as pintle structure, dynamic seal, driving device and thrust measurement. Through the experiments of different motion processes of pintle, the pressure characteristics of pintle engine are studied. Wei Xianggeng made further experimental analysis on the pressure response of non-coaxial pintle variable thrust engine [24], and it is determined that the slow response of pressure is caused by the slow dynamic response of propellant. The experimental study of pressure bimodal response is carried out by using mature propellant with low pressure intensity index. The research results provide a basis for the analysis of response characteristics of variable thrust engine with non-coaxial pintle.

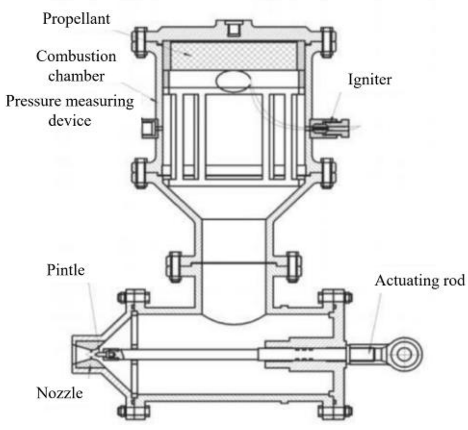

Fig. 31 Schematic of experimental thruster

Wu Yuan et al. developed a set of electric servo-driven pintle variable thrust solid rocket motor test system [25]. As shown in Fig. 32, the interior ballistic adjustment characteristic test of pintle variable thrust solid rocket motor was carried out. The experimental results show that the axial motion of the anti-ablation pintle can adjust the interior ballistic characteristics of the engine in real time, and realize the four-stage pressure adjustment.

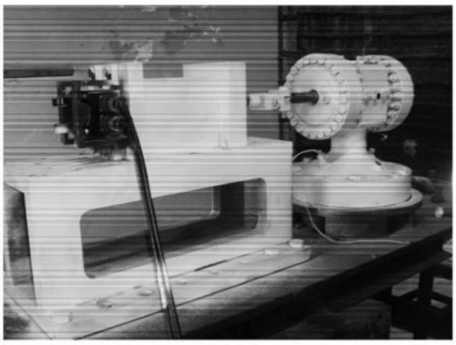

Fig. 32 Test system of pintle controlled solid motor driven by electric servo

In terms of numerical calculation, Li Juan established a numerical model of steady-state flow field of pintle engine, and verified the numerical model with principle test results [26]. A large number of numerical calculations have been carried out to reveal the flow characteristics of pintle engine, and the influence laws of pintle configuration, nozzle configuration, pintle position and their matching relations on flow field, thrust and efficiency have been obtained. Optimal pintle and nozzle profiles have been obtained from the perspective of thrust regulation performance and specific impulse efficiency. Suggestions are put forward for the design of nozzle and control system of pintle engine.

Hua Lihui used numerical simulation to optimize the process of laryngeal plug profile [27], and analyzed the changes of various parameters in the flow field according to different actuating speeds and free volumes of laryngeal plug; The experimental study of non-coaxial pintle engine was carried out.

The thrust control principle and method of pintle variable thrust solid motor are systematically studied [28], and the comprehensive performance of various thrust control methods is simulated and tested. A complete mathematical model of thrust control system is established, and the steady-state and dynamic characteristics of the system are obtained, which provides a theoretical basis for the design of thrust control system.

Aiming at the unsteady influencing factors of pintle solid rocket motor and thrust control of pintle solid rocket motor under high combustion temperature propellant, Beijing Institute of Technology [29-31] studied the influence of different factors on unsteady regulation characteristics of pintle variable thrust solid rocket motor. Using the grid dynamic layer model of Fluent software, the internal flow field of the throat plug in the process of uniform velocity adjustment is simulated, and the effects of the throat plug velocity, the main nozzle structure parameters and the propellant pressure index on the unsteady characteristics are analyzed. At the same time, in order to study the thrust control of low pintle solid rocket motor with high combustion temperature propellant, a coaxial variable thrust solid rocket motor test system is designed, and the structure diagram is shown in Fig. 33. The system is driven by hybrid linear stepper motor as pintle, combined dynamic seal mode is adopted, and ignition test is carried out with propellant with high combustion temperature and high-pressure strength index, and the pressure of combustion chamber is adjusted from 2 to 12.1 Mpa.

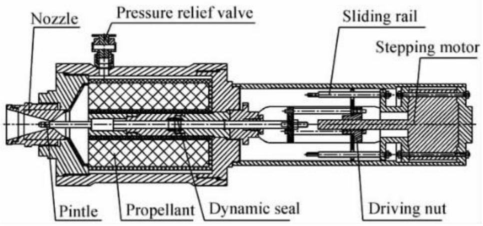

Fig. 33 Structure of pintle controlled solid motor

4. Related research progress of our research group

High temperature gas valve is the key to the research of divert and attitude control system for penetration warhead. It is the key index in the development of valve to realize long-term stable control of engine thrust and fast response control of thrust. In the research of high temperature gas valve, our research group designed a rotary fast response high temperature gas valve, as shown in Fig. 34.

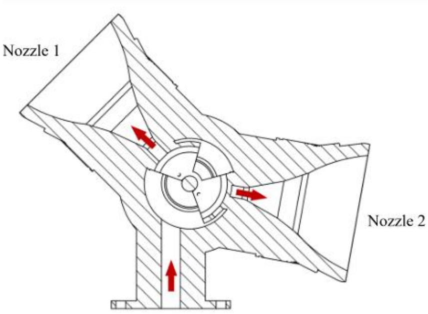

Fig. 34 Schematic diagram of rotary gas valve

The valve core of the valve is a spherical rotor, which is driven to rotate by an actuator. After the gas enters the valve cavity from the lower inlet, under the action of the spherical valve core, the fast response switching of thrust in different directions can be realized. In the development process, our research group mainly solved the following two problems.

4.1. Long-term high-temperature dynamic sealing and heat insulation technology.

Through the gradient combination of multiple materials, the research group realized that the working time of the valve is 45s, the temperature of the cold end of the actuator does not exceed 40 ℃, and the rotating shaft rotates stably. The temperature measurement results are shown in Fig. 35.

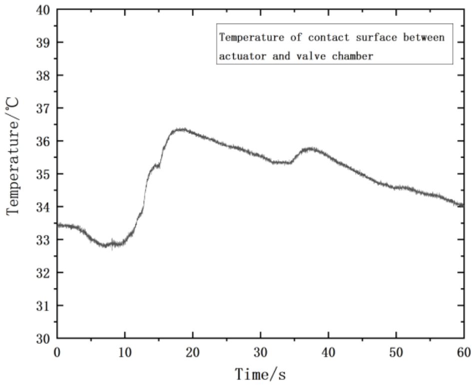

Fig. 35 Temperature of contact surface between actuator and valve chamber

4.2. High temperature resistant and fast response valve technology.

Our research group can realize stable thrust switching under the working conditions of chamber pressure 7Mpa, gas temperature 2000K and working time 45s by using spherical valve. The thrust measurement results are shown in Fig. 36. The black curve is the thrust output curve of No.1 nozzle, and the yellow curve is the thrust output curve of No.2 nozzle. As can be seen from the figure, the rotary valve can realize stable and fast thrust switching and stable thrust output. As shown in the figure, from top to bottom, the thrust output of nozzle 1, the switching intermediate state and the thrust output of nozzle 2 are respectively.

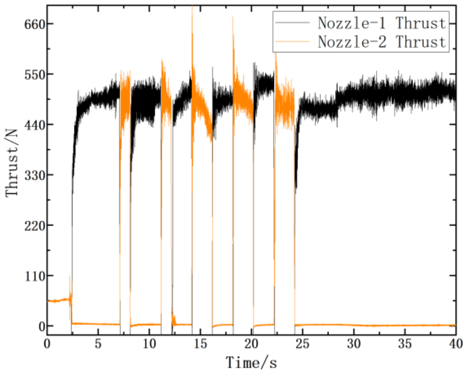

Fig. 36 Thrust switching data

(a) Nozzle-1 output thrust

(b) Intermediate state

(c) Nozzle-2 output thrust

5. Key technologies of divert and attitude control system for midcourse maneuver penetration warhead

5.1. Particularity of autonomous maneuver penetration warhead

Combined with the development status at home and abroad, the divert and attitude control system of autonomous maneuver penetration warhead should learn from the development route of American KKV divert and attitude control system and use solid propellant as its propellant. However, the autonomous maneuver penetration warhead can not fully learn from the KKV, and it has its own particularity.

In the aspect of divert and attitude control system, although there are similarities between autonomous maneuver penetration warhead and KKV, there are still great differences. The first task of KKV is to hit the target by collision, Achieve the purpose of interception, Therefore, its design idea is to install seeker, control system and other related devices on the basis of divert and attitude control system. However, the primary task of autonomous maneuver penetration warhead is to destroy the target by reentry strike, and its interior is equipped with a specific warhead, as shown in Fig. 34. The Fig. shows MK21 warhead cabin carried by American militia-3, and W87 nuclear warhead is carried inside MK21. Its internal structure is shown in Fig. 35. MK21 warhead is also called Advanced Ballistic Reentry Vehicle [32]. Unlike KKV, the internal space of MK21 warhead is very limited. The front end is mainly used for loading nuclear warhead, and only the back end has some space for installing divert and attitude control system and related guidance devices. Therefore, it is difficult to realize the traditional "4+6" divert and attitude control system structure on the warhead.

Fig. 37 MK21 warhead module

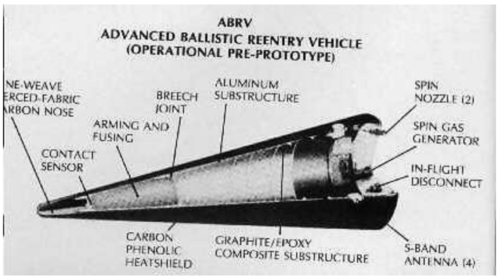

Fig. 38 Section view of MK21 warhead

5.2. Key Technologies of Divert and attitude control system for Autonomous maneuver penetration Warhead

According to the development status of divert and attitude control system and valve structure of KKV at home and abroad, combined with the actual structure of autonomous maneuver warhead. In this paper, the following six key technologies are summarized for building divert and attitude control system of autonomous maneuver penetration warhead.

(1) Structural design of integrated system in confined space

Due to the structural limitation of the maneuver penetration warhead, it is difficult to use the divert and attitude control system structure of the traditional KKV "4+6". Therefore, it is necessary to design an integrated divert and attitude control system structure matching with the penetration warhead in its confined space. The structure needs to meet the following two constraints:

The structure of divert and attitude control system can meet the requirements of warhead maneuver penetration. Because the warhead is loaded at the front end, it is impossible to install the orbital thruster at the centroid position, but the maneuver trajectory transfer capability of the warhead must be met.

The structure of divert and attitude control system must meet the limitation of warhead space size. Because the available space of warhead is mainly concentrated in the rear end, the new system structure should adopt an integrated way and be concentrated in the rear space of warhead. The divert and attitude control system of warhead should share a set of propulsion system, and then realize the integration of the system, so as to achieve the purpose of compressing the structural size of thruster.

(2) Lightweight and fast response valve technology of divert and attitude control system

The key index of divert and attitude control system lies in the response time of thrust. At present, the response time of gas valves in America is generally less than 10ms. During the development of divert and attitude control system for penetration missile, the response time of thrust can be reduced by optimizing the valve structure.

Pneumatic valve realizes the opening and closing of valve air cavity through solenoid valve, which drives piston to move and realize thrust switching. Therefore, it is necessary to optimize the design of valve air cavity, improve the change speed of air cavity pressure, shorten the time needed for air cavity stability, and then shorten the thrust response time on the premise of ensuring system stability.

Rotating valve can be realized directly by motor, and its response time can be realized by reducing the moment of inertia of the valve. At the same time, on the premise of ensuring dynamic sealing, the response frequency of the valve can be improved by reducing the friction torque.

The pintle valve structure realizes stepless thrust adjustment through the forward and backward movement of the needle valve, The response time of pin valve system is related to many factors, including propellant characteristics, free volume of combustion chamber, moving speed of pin bolt, etc. In the design of pin bolt structure, the high load on the head of pintle during thrust adjustment should be considered, so the head load can be balanced by pin bolt structure design to reduce moving resistance and shorten response time.

(3) Solid propellant technology

The performance of propellant itself is an important factor that determines the pressure response speed of the engine for the pintle valve structure. Therefore, in order to realize the rapid response of the engine pressure and the nearly rectangular thrust curve. According to the characteristics of pintle valve system, the propellant with high pressure strength index and high dynamic response performance should be developed.

For pneumatic valves or rotary valves, their working characteristics are that the thrust direction is switched by rapid switching of valves. In order to ensure the stability of the system, it is necessary to ensure the stability of the internal pressure of the engine during the valve switching process, so that the pressure in the combustion chamber can keep constant or change in a small range. Therefore, it is necessary to use propellants with low pressure index or negative pressure index.

(4) Technology of lightweight high temperature resistant valve material

During the working process of the divert and attitude control system, the valve structure is always in high temperature gas environment, which requires high mechanical properties and ablation resistance of materials under high temperature conditions. Foreign countries combine superalloy with light materials (such as C/C materials) to improve its ablation and erosion resistance while maintaining the advantages of high strength, impact toughness and low density of C/C.

Research on new lightweight high-temperature resistant materials has also been carried out in China. For example, in the development of high-performance C/Sic (carbon ceramic) materials, relevant key technologies have been broken through in China. C/Sic materials are basically strong at 2000K high temperature, and have great application prospects in valves of divert and attitude control systems.

(5) Precise and stable thrust control technology

The precise control of thrust is mainly aimed at the pintle valve structure, The thrust control process of the system is a complex nonlinear process, Strong nonlinearity and a large number of uncertain factors make its dynamic response process complex and changeable, At the same time, it also includes the coupling of many engine parameters and the reverse spike of negative thrust adjustment. Therefore, it is necessary to develop a specific control system for pintle valve to realize accurate thrust control. At the same time, under the closed-loop control system, the best position of pin bolt can be determined according to the pressure of combustion chamber to realize the optimal adjustment of the system.

(6) Integrated control technology of warhead autonomous maneuver penetration and divert and attitude control system

In view of the midcourse autonomous maneuver penetration problem, the zero-control miss distance is close to the maximum when the speed increment direction is perpendicular to the line-of-sight direction [33]. Therefore, the attitude of autonomous maneuver warhead needs to be adjusted during penetration to ensure that the speed increment during orbital maneuvering is perpendicular to the line-of-sight direction.

In the design process of warhead maneuver penetration control system, an integrated model of warhead penetration and divert and attitude control system should be established. In the traditional penetration guidance problem, the attitude control problem of warhead should be added, and the multi-nozzle cooperative control of divert and attitude control system should be considered at the same time. The specific idea is shown in Fig. 36.

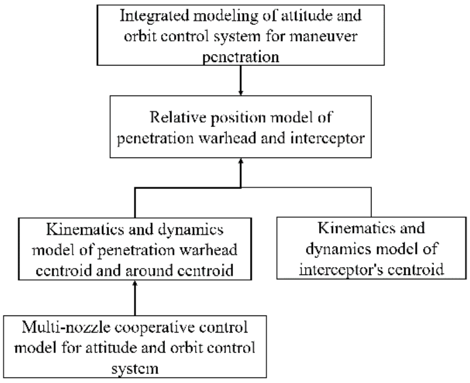

Fig. 39 Integrated control of maneuver penetration and DACS

6. Conclusion

American missile interception technology has been developed for more than 40 years. Many experimental results show that American interception technology has certain actual combat capability and can achieve midcourse interception of intercontinental ballistic missiles. Traditional penetration means are difficult to play an effective role, so it is necessary to build midcourse autonomous maneuver penetration capability of warheads.

The first problem to be solved in midcourse autonomous maneuver penetration of warhead is the power problem, namely autonomous maneuver penetration of divert and attitude control system. In this paper, the development of divert and attitude control system of KKV in America is combed. At the same time, the research status of gas valve, the key structure of divert and attitude control system, is further summarized. This paper introduces the related research results of our research group. Finally, combined with the structural characteristics of autonomous maneuver penetration warhead, six key technologies for the development of autonomous maneuver penetration divert and attitude control system are summarized, which have a certain engineering application foundation in related technical fields in China, but it still needs in-depth research and a large number of experimental verification when applied to maneuver penetration warhead. Autonomous maneuver penetration technology of warheads is an effective means to deal with foreign missile interception, which needs to start from both hardware development and software development at the same time to continuously promote the construction and development of autonomous maneuver penetration capability of warheads in China.

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References

[1] Qin Z J, Zhang Z M. Topol-M intercontinental ballistic missile of Russia [J]. Missiles and Space Vehicles, 2001 (01): 55-62.

[2] Li L. Research on maneuver penetration of ballistic missile warhead [D]. Harbin Institute of Technology, 2011.

[3] Wang Y Q, Ning G D, Wang X F, et al. Maneuver penetration strategy of near space vehicle based on differential game [J]. Acta Aeronautica ET Astronautica Sinica, 2020, 41 (S2): 69-78.

[4] Wen D Y. Development status of orbit transfer and attitude control system for kinetic energy weapons in the United States [J]. Modern Defense Technology, 1995 (04): 32-37.

[5] Wen D. The Development Status of US Kinetic Weapon Divert and Attitude Control System[J]. Modern Defense Technology, 1995(04):32-37.

[6] Webber T E. GROUND TESTING KINETIC ENERGY PROJECTILES FOR THE LIGHTWEIGHT EXOZTMOSPHERIC PROJECTILE (LEAP) PROGRAM[J]. 2011.

[7] Weiss A. Status of the first LEAP space flight test[J]. International Journal of Social Economics, 2013,37(October):951-969.

[8] Smith F, Camp D J, Leister K K. Lightweight Exo-Atmospheric Projectile Space Test--LEAP 2 Flight[J]. aiaa journal, 1992.

[9] Baker P, Funari A. Army Lightweight Exo-Atmospheric Projectile (LEAP)[J]. Aiaa Journal, 1992.

[10] Ceng P, Zhong L W, Xiao L J, et al. Development status and trend of divert and attitude control power system of kinetic energy weapons abroad: 37th Technical Exchange Conference of China Aerospace Third Professional Information Network and 1st Joint Conference of Aerospace Power, Xi'an, Shaanxi, China, 2016 [C].

[11] Zhang D X and Wang Z B. Solid propellant divert control and attitude control system of KKV [J]. Winged Missiles Journal, 2001 (02): 37-41.

[12] Coon J, Yasuhara W. Solid propulsion approaches for terminal steering[J]. AIAA and SDIO, 2nd Annual Interceptor Technology Conference, 1993.

[13] Prins W, Spencer A, Roberts J. SM-3 SDACS Flight Test Successes: 39th AIAA Joint Propulsion Conference, Huntsville, Alabama, 2003[C].

[14] Xu D D, Kou Y, Wang J Y, et al. Research on American Solid Divert and attitude control Thrust System Technology [J]. Winged Missiles Journal, 2015 (07): 64-70.

[15] Zhang Y, Ceng P, Zhong L W, et al. Research on Standard-3 Missile Solid Rocket Motor: 38th Technical Exchange Conference of China Aerospace Third Professional Information Network and 2nd Joint Conference on Aerospace Power, Dalian, Liaoning, China, 2017 [C].

[16] Hou X, Fu P, Wu Y. Energy management technology of solid rocket motor and its new progress [J]. Journal of Solid Rocket Technology, 2017, 40 (01): 1-6.

[17] Morrow D, Mcallister P, Evans R. High-performance graphite thruster valve system using a 4500 deg solid propellant gas generator: 9th Propulsion Conference, 1973[C].

[18] Morrow D, Scottsdale A. Valve:

[19] West L, Carlson R. Solid Divert Breakthroughs that Enable Mission Flexible TMD Interceptors[J]. Solid Divert Breakthroughs That Enable Mission Flexible Tmd Interceptors, 1998.

[20] Napior J, Garmy V. Controllable Solid Propulsion for Launch Vehicle and Spacecraft Application, 2006[C].

[21] Cover C L, Drendel A S. Rocket thruster comprising load-balanced pintle valve:

[22] Yang Z. Research on solid attitude control system of KKV [D]. Beijing Institute of Technology, 2015.

[23] Lu J, Li X H. Application Research of Negative Pressure Index Propellant in Solid Divert and attitude control system: The Third China Aerospace Propulsion Technology Forum, 2020 [C].

[24] Wang Y L. Experimental study on the principle of pintle variable thrust solid motor [D]. Northwestern Polytechnical University, 2007.

[25] Wei X G, He G Q, Li J, et al.Pressure response analysis of non-coaxial pintle variable thrust engine [J]. Journal of Solid Rocket Technology, 2009, 32 (04): 409-412.

[26] Wu Y, He G Q, Sun L G, et al. Interior ballistic regulation characteristics of pintle variable thrust solid rocket motor [J]. Journal of Solid Rocket Technology, 2009, 32 (05): 511-513.

[27] Li J, Wang Z L, Zheng K, et al. Numerical analysis of dynamic response characteristics of thrust adjustable solid rocket motor with pintle [J]. Journal of Solid Rocket Technology, 2009, 32 (01): 48-52.

[28] Hua L H, Tian W P, Gan X S, et al.Numerical simulation of nozzle flow field of thrust adjustable thrust engine with pintle [J]. Journal of Solid Rocket Technology, 2008 (04): 344-349.

[29] Cheng C. Thrust control method and performance simulation research of pintle solid variable thrust motor [D]. Northwestern Polytechnical University, 2017.

[30] Wang J X, Wei Z J, Wang N F. Study on unsteady influencing factors of variable thrust solid rocket motor [J]. Transactions of Beijing Institute of Technology, 2011, 31 (09): 1018-1022.

[31] Wang J X, Wei Z J, Wang N F. Test of pintle variable thrust solid rocket motor with high combustion temperature [J]. Journal of Propulsion Technology, 2012, 33 (01): 89-92.

[32] Wang J X, Wei Z J, Wang N F. Analysis of influencing factors of pressure response rate of pintle engine [J]. Science & Technology Review, 2012, 30 (02): 18-21.

[33] Huang P Q. Why did the United States Department of Defense replace MK12A with ABRV to equip MX missile [J]. Foreign Missile Technology, 1985 (03): 14-22.

[34] Wu Q X, Zhang W H. Research on Midcourse Maneuver penetration of Ballistic Missile [J]. Journal of Astronautics, 2006 (06): 1243-1247.