Research on Design Method of High Speed and High Dynamic Pressure Separation Structure

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Abstract. The inter-stage separation scheme has always been the focus and difficulty of low-altitude high-speed aircraft design. The separation reliability of low altitude high-speed aircraft is required to be higher. Experts and scholars have carried out design research on different forms of separation schemes. In this paper, two typical kind of inter-stage separation schemes are introduced. For aircraft A, a point cold separation scheme is adopted, which is connected by four explosive bolts, and two piston push rods provide separation impulse. For aircraft B, exhaust ports are opened on both sides of the rear of the transition section. The tail section is equipped with four "X" full-motion rudders for flight control. In addition, two horizontal stabilizers were added to improve stability. Based on the comparison and analysis of different inter-stage separation schemes for The separation reliability of low altitude high-speed aircraft is required to be higher. Experts and scholars have carried out design research on different forms of separation schemes. two different types of aircraft A and aircraft B, a new high reliability inter-stage separation scheme is proposed, the feasibility of the scheme is verified by simulation analysis, and the design of the stage separation structure under high dynamic pressure and high speed with compact layout is realized.

1. Introduction
The separation reliability of low altitude high-speed aircraft is required to be higher. Experts and scholars have carried out design research on different forms of separation schemes. In this paper, a new separation scheme is proposed based on the analysis of several separation schemes for aircraft, and the simulation analysis is carried out.

2. Analysis of separation scheme

2.1. Separation scheme of aircraft A
The aircraft A is 3.66m long and weighs 1270kg. The aircraft is connected to the carrier through an adapter. When the separation condition is reached, the aircraft is disconnected from the adapter.

A point cold separation scheme is adopted, which is connected by 4 explosive bolts, and 2 piston push rods provide separation impulse. The detailed separation structure is shown in figure 1. Two explosion bolts pass through the adapter compartment frame and are screwed into the rear bulkhead of the aircraft. They are installed horizontally to the lower ends of the two keels to connect the aircraft to the corresponding adapter bulkhead This structure effectively connects the keel of the test aircraft with the collet keel of the adapter.
2.2. Flight test and separation scheme of aircraft B

The aircraft B verification machine consists of a booster stage, an intermediate transition section and a cruise stage. As shown in the figure 2, the verification machine has a total length of 7.6m, a total weight of 1780.4kg, and a maximum width of 0.6m. Exhaust ports are opened on both sides of the rear of the transition section. The tail section is equipped with four "X" full-motion rudders for flight control. In addition, two horizontal stabilizers were added to improve stability.

Before the booster was separated, the cruise stage slowly rotated 180° around the main axis, and the precursor compression surface changed from downward to upward. Subsequent booster separation and ignition of the super-combustion ram engine. After the engine is stable, the aircraft rotates 180° again to resume normal cruise. By flipping the aircraft B flight attitude into a negative angle of attack, this scheme improves the intake port lip Mach number, ensuring the start performance of the intake port at low flight Mach number conditions; while reducing the intake port. The upper surface structure design of the aircraft does not reduce the lift coefficient after the overturn, the aircraft can still maintain the flight altitude and cruise trajectory, and the control difficulty has not increased significantly.

2.3. Connect the unlocking device

Commonly used connection unlocking devices are: explosion bolts, low-impact separation devices and cutting cables[1]. Explosive bolt impact is relatively large, but the structure is simple and the reliability is high. Compared with the explosion bolt, the impact of the low impact separation device is relatively
small, but the structure is complicated, the installation operation is cumbersome, and the connection thickness is strict. The use of cutting ropes has requirements on the cabin structure and materials, and the ambient temperature.

2.3.1. Selection of connection and unlocking device. Limited by the aircraft, lower-level structure and layout. According to the loading conditions of the tail end of the aircraft, the tail end of the aircraft mainly bears the axial pressure and the bending moments in the Y and Z directions. Therefore, the explosion bolt or the low-impact separation device should be installed along the Y and Z directions. May be remotely located. The initial design is four explosive bolts or low-impact separation devices, the layout is shown below, and the calculation of the diameter of the connecting bolts of the explosive bolts or low-impact separation devices is carried out. The connection structure between the aircraft and the lower stage is shown in figure 3.

![Figure 3. The connection structure between the aircraft and the lower stage](image)

Use formula (1) to calculate the working tension:

\[ P = \frac{2M}{nD} + \frac{T}{n} \]  

(1)

Where \( M \) is the bending moment load on the abutment surface; \( D \) is the relative distance of the connection; \( T \) is the axial tensile load; \( n \) is the number of connections. Calculated under the worst working conditions, the working tension of connection point 4 is the largest, \( P_{\text{max}} = 29748.3 \) N. Under this working condition, the total pull force of the connection is \( P_0 = 1.8 \times P_{\text{max}} = 1.8 \times 29748.3 = 53546.94 \) N. Design load \( P_0 = 107093.88 \) N.

The total tensile force at the connection should be less than the tensile limit of the explosive bolt or low-impact separation device. Depending on the load capacity requirements, a low-impact separation device or an explosion bolt can be selected.

2.3.2. Comparative analysis. Depending on the carrying capacity, both the low-impact separation device and the explosion bolt can meet the separation requirements. From the perspective of structural layout and operability, the installation of both needs to open the operation port at the lower stage, but when installing the low-impact separation device, the connecting bolt needs to be pulled through the connection surface with a tow bar[3]. Tighten the release nut and apply a tightening torque on the release nut. After completion, remove the tow bar and install the pressure plate to fix the separation nut. The lower stage is required to have a larger opening, which adversely affects the strength and rigidity of the lower stage. Explosive bolts are easy to install. They only need to be installed on the lower stage side and apply a tightening torque. The requirements for the size of the opening are relatively low. Comprehensive consideration, choose the explosion bolt as the separation device.

2.4. Guide positioning device

Separation system guide positioning device generally uses positioning guide pins to resist shear and guide positioning, and its length is related to connection thickness and separation simulation results. Two types of shear guide structure types, positioning guide pin and cone surface + cone sleeve, were compared and demonstrated.
2.4.1. Locating Pin Scheme. A short positioning pin is provided on the butt surface of the flight test warhead body for shear support and installation positioning, which can prevent the explosive bolt from being sheared and affect normal separation[4]. There are 4 positioning pins installed near the explosion bolt mounting holes on the tail frame of the aircraft, as shown in the figure 4.

![Figure 4. Schematic diagram of the rear end of the aircraft](image)

According to the load conditions, the tail frame Mx of the aircraft is converted into shear force, and after combining with Fx and Fy, the worst case shear force of positioning pin 2 is 3937N. Therefore, the diameter of a single positioning pin is:

\[
D = 2\sqrt{\frac{fQ}{\pi \tau b}} = 2\sqrt{\frac{2 \times 3927}{3.14 \times 640}} = 3.95\text{mm}
\] (2)

Considering installation and other factors when designing the structure, the positioning pin diameter and other parameters are designed as follows: the diameter of the pin segment of the positioning pin is Φ10mm, the length of the column segment is 20mm; the thread M8 × 1, the length is 15mm; Plane out at the column section for easy clamping and tightening.

2.4.2. Conical surface + cone sleeve scheme. Considering that the positioning pin has a certain effect on the separation, a tapered sleeve (titanium alloy) is installed at the lower end front frame explosion bolt connection hole. The corresponding aircraft tail frame is provided with a tapered hole, and the contact between the tapered sleeve and the tapered hole is used for shearing. The structure of the connection between the aircraft and the lower stage is shown in the figure 5 and figure 6.

![Figure 5. Part of the connecting boss](image) ![Figure 6. A part of the cone sleeve connected](image)

2.4.3. Summary. The aircraft is separated in the atmosphere, and there is strong aerodynamic interference during the separation process. The positioning pin may cause interference to the separation and even cause jams. Therefore, this solution uses a cone surface + cone sleeve solution.

2.5. Impact absorption device
The function of using the explosion bolt box as the shock absorbing device is mainly to store explosive separated nuts and screws, etc., to avoid causing harm to the equipment in the aircraft. The nut that cooperates with the explosion bolt in the aircraft is a homemade square nut. An explosion bolt box is designed on the outside of the square nut (connecting the corner box, as shown in figure 7). At the same time, a honeycomb structure is designed on the wall of the explosion bolt box to absorb the impact of the explosion bolt.
Figure 7. Corner box on the upper right side of the fuselage

When the explosion bolt is installed, place the square nut on the side directly opposite the square nut in the corner box, and apply a pre-tightening force to the explosion bolt with a tool from the lower stage side. The schematic diagram of the structure of the left side nut and corner box on the lower part of the aircraft fuselage is shown in figure 8, and the structure of the rest of the check is similar[5].

Figure 8. Internal structure of the left corner of the fuselage

2.6. Separation impulse device

The scheme uses mature separation impulse devices, namely reverse thrust rocket and thrust termination device to provide separation impulse.

2.6.1. Thrust termination device. The boost engine will activate the thrust termination device at the end of the flight, that is, open 4 ejection tubes. The comprehensive negative thrust curve of the boost engine is shown in figure 9. It can be seen from the figure that after the thrust termination device is turned on, the engine thrust is positive, and after a certain period of time, the engine thrust starts to become negative.

Figure 9. Negative thrust-time curve

2.6.2. Retro-Rocket. A total of two retro-rockets are located at the end of the booster stage. The line connecting the thrust action points of two reverse thrust engines and the intersection of the bullet axis is 1.145m away from the full bomb origin.

The average thrust of a single retro-rocket thrust is 10kN, and the included angle between the nozzle installation axis and the rotary axis of the booster engine is 25°. Retro-rocket performance is shown in table 1. Thrust of retro-rocket is shown in figure 10. Position of retro-rocket thrust point is shown in figure 11.
Table 1. Capability of retro-rocket.

| Parameter Name                      | Unit | Parameter Value |
|------------------------------------|------|-----------------|
| Average Thrust                     | kN   | 10              |
| Average Thrust Deviation           |      | ≤15%            |
| Average Working Time               | s    | ≥0.35           |
| Ignition Delay Time                | ms   | t80≤35ms        |
| Asynchrony                         | ms   | ≤35ms           |
| Back Thrust Engine Thrust Line Traverse | mm   | ±5             |
| Deflection of Thrust Line of Reverse Thrust Engine |      | 22              |

Figure 10. Thrust of retro-rocket

Figure 11. Position of retro-rocket thrust point

3. Conclusion

In this paper, a new separation scheme is proposed, which is composed of a connecting unlocking device, a guiding positioning device, a separating impulse device and a shock absorbing device. The feasibility of the scheme is verified by simulation analysis, and the design of the separation structure under high speed and high dynamic pressure is realized, which improves the reliability of the separation system.

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