Study on afterbody-effects of multi-stage separation at high-speed

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Abstract. The stage separation of high-speed vehicle is complicated at high dynamic pressure, usually accompanied by strong shock and vortex interaction. There exists a strong interaction between first stage and second stage, which called “afterbody-effects”. The aerodynamic mechanism of “afterbody-effects” is studied in this paper based on numerical simulation. The aerodynamic characteristics of a simplified three-dimensional projectile model at different distances between stages at 0° angle of attack is researched with structural mesh. The results show that the vortexes of stages have a significant impact on the aerodynamic characteristics of different stages, As the distance between stages increases, the drag coefficient of the first stage increases, and the drag coefficient of the second stage increases first and then decreases.

1. Introduction

With the development of active protection technology, in order to improve the penetration capability of aircraft, the requirements for stealth and speed performance of aircraft are becoming higher and higher, and the research of hypersonic aircraft is accelerated. Generally, a two-stage or multi-stage series connection is used to increase the flight speed of the aircraft. For two-stage and multi-stage aircraft, when they are separated between stages, due to the mutual influence of aerodynamic forces between the two stages, including outflow and engine jets as well as the mutual interference of the connecting parts. It involves phenomena such as shock wave interference, separation flow and vortex, which makes the aerodynamic characteristics of the separation process more complicated, and there is a danger of collision between stages.

At present, wind tunnel tests and numerical simulations are mainly used for the two-stage separation problem, and corresponding conclusions have been obtained. Wang Zhijian, Zhou Weijiang, Zhao Xuejun, Wang Yunpeng and others have studied the problem of separation between stages of tandem layout aircraft [1-5]. Luo Jinling, Modelyadi M.A, Jiao Ruyan and others have studied the problem of separation between stages of non-series layout [6-8].

There are two types of interstage separation: cold separation and hot separation. Cold separation is separation before the ignition of the upper-level engine, The separation force of the cold separation is mainly from the reverse nozzle or reverse thrust rocket of the self-propelled stage; The aerodynamic force acting on the booster stage and separation after the ignition of the upper-level engine is called hot separation[2]. This paper mainly uses numerical simulation to study the influence of the aerodynamic characteristics of between the first and second stages in the case of cold separation.
2. Numerical Method

The computations here were conducted by using the China Aerodynamics Research & Development Center (CARDC) MFlow-code, which is an unstructured finite volume cell-center CFD solver and has participated in the 5th and 6th CFD drag prediction workshop. Second-order accuracy in space is achieved by linear reconstruction in cells. The vertex-based Gauss method is adopted for gradient computations, to simultaneously fulfill accuracy and robustness [9]. Roe scheme is used for inviscid flux computations.

2.1. Geometry and Computational Grids

2.1.1. Geometry Model. The simulation model adopts a simplified three-dimensional projectile model: The first stage is a cylinder with a diameter of 400mm and a length of 960mm; the second stage is a tapered head model with a total cylinder length of 200mm, the total length is 1195mm, as Figure 1. In order to study the influence of the distance between stages on the aerodynamic characteristics of the first and second stages, this paper mainly analyzes the aerodynamic characteristics of the two stages when the speed is 7Ma, the angle of attack is 0° at the height of 11km, and the ratio of the gap L to the diameter D is different. The value of L/D shows in Table 1.

![Figure 1. Geometric model.](image)

| Distance L/mm | 4   | 10  | 40  | 80  | 120 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 1000 |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Gap diameter ratio (L/D) | 0.01 | 0.025 | 0.1 | 0.2 | 0.3 | 0.5 | 0.75 | 1   | 1.25 | 1.5 | 1.75 | 2   | 2.5  |

2.1.2. Grids Model. In this paper, the method of hexahedral grid uses for grid division. During study the aerodynamic forces of the first and second stages in different gaps between the two stages, in order to ensure the credibility of the calculation results, the amount of grid is different at different L/D values, the mesh amount increases with its value, to ensure that the largest mesh size in the gap is similar.

![Figure 2. Grid model.](image)
2.2. Governing Equations

The fluid motion control equation is a compressible N-S equation, and the form in the rectangular coordinate system is as follows:

$$\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial G}{\partial z} = 0$$

(1)

The non-viscous flux uses the HLLE++ flux differential splitting method, the limiter uses Venkat, and the viscous item uses the center format. Since the calculated incoming flow condition is supersonic flow, the outer boundary remains at the incoming flow value. The downstream boundary is the downstream of the rear body, which is the supersonic exit. The physical quantity of the boundary point is directly obtained by extrapolating from the inner point.

3. Numerical Results

The figure 3 shows the change of the drag coefficient of the second stage, the bottom of the second stage and the first stage with L/D when the angle of attack is 0°. Represents the second stage exists alone, when L/D is 0. The figure shows that: The drag coefficient of the second stage decreases first and then increases with the increase of L/D, reaching the minimum value near 1; When L/D is 2.5, the drag coefficient of the second stage is close to the drag coefficient when the second stage is free flight; The drag coefficient of the second stage bottom first decreases and then increases with the increase of L/D; When L/D is between 0.3 and 1.5, its value is negative, the value is the smallest when L/D is 1; The drag coefficient of the first stage increases with the increase of L/D. It can be seen that when L/D is less than 2.5, the influence of the first stage to the second stage exists, and when L/D is 1, the “after-body effects” is the largest.

Figure 3. Portions drag coefficient L / D curve.

Figure 4-6 shows the velocity cloud diagram and streamline distribution diagram of the symmetry plane when L/D is 0.1, 1, and 2. The figure shows that: When the airflow through the gap, it separates at the bottom edge of the second stage, a part of the airflow moves across the gap in a straight line to form a gap shear layer, and part of the airflow expands into the gap. Due to the effect of the top of the first stage and the bottom of the second stage, the airflow through the gap forms vortices in the gap. When L/D is 0.1: there are four vortices symmetrical with respect to the axis of symmetry in the gap, and the vortices decrease closer to the Centerline; An obvious shock wave appears at the bottom of the first stage. When L/D is 1: The number of vortices in the gap is two; Shock waves appear at the bottom and head of the first stage, but the bottom shock waves are obviously weaker; A x-negative-direction high-speed flow appears near the center of the gap. When L/D is 2: The number of vortices in the gap is two, but the center of the vortex is obviously close to the top of the first stage, and the streamline
density at the bottom of the second stage is less than the top of the first stage, the first stage head shock is obvious; A x-negative-direction high-speed flow appears near the center of the gap. With the increase of L/D, the shock wave at the bottom of the first stage weakens, and the head shock wave increases; When L/D is less than 2.5, the flow in the gap is dominated by vortices, and as the gap increases, the shock wave interference increases; With the increase of L/D, the x-negative-direction high-speed flow area in the gap center increases; In the three cases, the x-direction-velocity of the airflow near the top of the first stage and the bottom of the second stage is similar; When L/D is 1 and 2, the expansion of the air into the gap is similar, and it is significantly stronger than when L/D is 0.1.

Figure 4. The velocity cloud diagram and streamline diagram of the symmetry plane in L/D=0.1.

Figure 5. The velocity cloud diagram and streamline diagram of the symmetry plane in L/D=1.

Figure 6. The velocity cloud diagram and streamline diagram of the symmetry plane in L/D=2.
The drag of the projectile at supersonic speed is mainly composed of friction drag and pressure drag (including shock wave drag). When the L/D changes, the change of the drag for first and second stage is mainly caused by the change of the pressure drag, it is mainly caused by the pressure change of the bottom of the second stage and the top of the first stage. Its value is mainly determined by the velocity of the airflow in the x-direction and the airflow density acting on the surface. Fig. 4-6 shows that: In the three cases, the velocity of the airflow in the x-direction near the top of the first stage and the bottom of the second stage is similar, so the difference is mainly caused by the airflow density acting on the surface. When the gap is small, due to the expansion of the gas flow into the gap in the shear layer weaker, less airflow through the gap, resulting in a lower airflow density in the gap; When L/D is 1 and 2: the airflow expands in the shear layer similarly. The airflow into the gap is similar, and the airflow in the gap is mainly in the form of a vortex. When the L/D is 2, the center of the vortex is closer to the top of the first stage, resulting in low airflow density at the bottom of the second stage.

![Figure 7](image1.png)

**Figure 7.** Pressure and density cloud diagram at the bottom of the second stage in L/D= 0.1.

![Figure 8](image2.png)

**Figure 8.** Pressure and density cloud diagram at the bottom of the second stage in L/D= 1.

![Figure 9](image3.png)

**Figure 9.** Pressure and density cloud diagram at the bottom of the second stage in L/D= 2.
Figure 7-9 shows the pressure and density cloud diagram at the bottom of the second stage when L/d is 0.1, 1, and 2. The figure shows that: When L/D is 1, the bottom pressure is obviously greater than 0.1 and 2, in the case of L/D is 0.1 is slightly greater than L/D is 2, it corresponds to the drag coefficient; When L/D is 1, the bottom density is significantly greater than 0.1 and 2, and in the case of L/D is 0.1 is slightly greater than 2, which corresponds to the pressure cloud diagram.

4. Conclusion
This paper uses numerical simulation to study the influence of the aerodynamic characteristics of the first and second stage by different distances between stages at 0° angle of attack, and draws the following conclusions: When the L/D is less than 2.5, the drag coefficient of the second-stage is smaller than it alone, and with the increase of L/D, its drag coefficient decreases first and then increases, when L/D is near 1, its drag coefficient is the smallest; Due to the influence of the "after-body effects", when the gap is within a certain range, negative resistance will appear at the bottom of the second stage, forming thrust; When the gap is small, the flow in the gap is mainly vortex, and as the gap increases, the shock wave flowing in the gap interferes Increase; When L/D is less than 2.5, the drag coefficient of first stage increases with the increase of L/D.

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