Research on Separation Phase of Ground Launching of UAV

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Abstract. Grand launching of UAV is a potential technology which will greatly improve effectiveness and application range of UAV. Rocket booster grand launching is a technology which has a high degree of difficulty and multiple influence factors. Chimera mesh method and relevant CFD method are applied to ensure the successful performance of 6DOF motion body simulations of booster rocket separation phase so that aerodynamic characteristics of UAV and booster rocket in the separation phase can be revealed. The error and precision of the simulations are then analyzed and conclusions concerning UAV aeroforce and moment variation are drawn. Finally, the feasibility and safety of separation design in this thesis are testified.

1. Introduction

In practical applications of unmanned aerial vehicles (UAV), the launch phase is usually considered by technicians to be the most critical phase, and many countries have also made a lot of research on the take-off methods of UAVs. The use of solid rocket boosters to launch UAVs has the following advantages: less space required; no obvious constraints for environmental conditions; lower initial investment; no pressurization time required; after the launcher is installed, the UAV can still store for a long time. Rocket-powered launch platforms are widely used for launches of UAVs. The UAV flies away from the launcher under the thrust of one or more (usually two) solid rocket boosters. When flying to a predetermined altitude and speed, the UAV drops the solid rocket booster, and the main engine on the UAV completes the flight mission.

The research on the aerodynamic characteristics of the ground launch and separation process of the UAV is an important basis for the dynamic simulation, separation stability analysis and separation device and scheme design of the ground launch and separation process of the UAV. This paper focuses on the effects of the torque characteristics of the UAV, the particle trajectory and attitude angle of the solid rocket booster during the separation process, and investigates the separation characteristics under different separation schemes, so as to provide a certain basis for the design of UAV.

The UAV and solid rocket booster studied in this paper belong to a parallel configuration. As for the parallel configuration, according to the number of parallel solid rocket boosters, it is divided into single and double configuration. Due to the large volume of the single solid rocket booster, it can only be hung on the abdomen of the UAV, while the double solid rocket booster can be divided into two mounting types: post-wing and under-wing. The UAV researched in this paper uses the lower single-wing layout, and bundling method of the rocket booster is the double post-wing form.
Simulation analysis of texts adopts CFD calculation based on chimera mesh. Since the 1990s, chimera mesh have been widely used because they can flexibly handle complex shapes and solve adaptive problems of structural grid, so as to be widely used in the calculation of various complex flow fields, and the technology of dynamic chimera mesh has also been developed to describe the relative motion between objects [1-7].

2. Separation simulation of the UAV ground Launch

2.1. Governing equation

Conservation equation

The flow equation contains the following parts:

1) Mass conservation equation:
\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j) = 0
\]  \hspace{1cm} (1)

Where, \( \rho \) is the density and \( u_j \) is the mass average speed in the \( j \) direction.

2) Momentum conservation equation:
\[
\frac{\partial}{\partial t} (\rho u_j) + \frac{\partial}{\partial x_j} (\rho u_j u_j) = 0
\]  \hspace{1cm} (2)

Where, \( \rho \) is the density and \( u_j \) is the mass average speed in the \( j \) direction.

3) Energy equation:

The calculation in this paper uses inviscid flow, so the energy equation is as follows:
\[
\frac{\partial E_i}{\partial t} + \frac{\partial}{\partial x_j} \left[ (E_i + p) u_j \right] = 0
\]  \hspace{1cm} (3)

Where, \( E_i \) is the total energy in each control body, \( p \) is the pressure, and \( u_j \) is the average mass velocity in the \( j \) direction.
2.2. Finite volume and spatial dispersion
The governing equations and closed models are in vector form:

\[
\frac{\partial Q}{\partial t} + \nabla \cdot \vec{F}_c - (\nabla \cdot \vec{F}_D) = S \tag{4}
\]

Where,

\[
Q = [E_{\text{En}}, \rho_1, \ldots, \rho_n, \rho_u, \rho_v, \rho_w, E, E]^T
\]

\[
\vec{F}_c = F_c \hat{i} + G_c \hat{j} + H_c \hat{k}
\]

\[
\vec{F}_D = F_D \hat{i} + G_D \hat{j} + H_D \hat{k} \tag{5}
\]

Dispersion theorem is adopted to discretize the governing equation:

\[
\frac{d}{dt} \int Q dV + \int (\vec{F}_c - Q \vec{v}_g - \vec{F}_D) dA = S dV \tag{6}
\]

For a grid, the above equation becomes:

\[
\frac{\partial (QV)}{\partial t} + \sum_{f=1}^{N_{\text{faces}}} (\vec{F}_c - Q \vec{v}_g - \vec{F}_D)^{n+1} \cdot \hat{n}_f^{n+1} \Delta A_f = S^{n+1} \Delta V^{n+1} \tag{7}
\]

\[
\vec{F}_{cm} = \vec{F}_c - Q \vec{v}_g
\]

Rearranged items are:

\[
\frac{\Delta Q}{\Delta t} \Delta V^{n+1} + \sum_{f=1}^{N_{\text{faces}}} \left( \frac{\partial \vec{F}_{cm}}{\partial Q} \right)_f^{n} \Delta A_f - \left( \Delta V \frac{\partial S^n}{\partial Q} \right) \Delta Q = S \Delta V^{n+1} \tag{8}
\]

\[- \sum_{f=1}^{N_{\text{faces}}} F_f^n \hat{n}_f^{n+1} \Delta A_f + Q^n \partial V^n \]

2.3. Spatial numerical method
The high-order precision format is prone to non-physical numerical oscillations where the gradient is large. By adding a limiter, the gradient of the physical quantity is limited to ensure that the distribution of the physical quantity in the control volume unit is monotonic, so that new extreme values are avoided, thus achieving the purpose of suppressing the numerical oscillation near the discontinuity.

Minmod and monotone Van Leer limiter, \(q\) represents any primitive variable, and \(\xi\) represents the distance from the center of the unit to the center of the unit surface. The local gradient of the variable is:

\[
\frac{dq}{d\xi} \bigg|_{\xi = \frac{1}{2}} = \frac{q_{i+1} - q_i}{\xi_{i+1} - \xi_i} \tag{9}
\]
\[
\begin{align*}
\frac{dq}{d\xi} _{i+\frac{1}{2}} = \frac{dq}{d\xi} _{i+\frac{3}{2}} \\
r_{i+\frac{1}{2}} = \frac{dq}{d\xi} _{i+\frac{1}{2}}
\end{align*}
\]

\[q_{i+\frac{1}{2}}^R = q_i - \Psi \left( r_{i+\frac{1}{2}} \left( \frac{q_{i+1} - q_i}{\xi_{i+1} + \xi_i} \right) \xi_i \right) \]

\[q_{i+\frac{1}{2}}^L = q_i - \Psi \left( r_{i+\frac{1}{2}} \left( \frac{q_i - q_{i-1}}{\xi_i + \xi_{i-1}} \right) \xi_{i-1} \right)
\]

Where, \( \Psi \) is the slope limiter.

2.4. Solution of flow field
Generally, the time stepping method is used to solve problems for discrete equations. For the steady flow problem in computational fluid dynamics, the basis for judging whether the calculation results converge is usually to observe whether the change of the residual error is lower than a given value. The time stepping method is a good solution for unsteady flow developed from steady flow or unsteady flow.

There are one explicit and two implicit formats for the time stepping method for calculation. For general accuracy problems in computational fluid dynamics, the dissipation of the implicit format is significantly greater than the dissipation of the explicit format.

1) Block diagonal implicit format
The implicit format is the block diagonal iteration method and Jacobi point iteration method. This method is actually a subset of the Jacobi point iterative program, and its discrete equation is:

\[
\left[ \frac{\Delta V}{\Delta t} + \sum_j \left( \frac{\partial F_{em}}{\partial Q_j} \right)^m - \frac{\partial F_D}{\partial Q} \right] \cdot \hat{n} \Delta A_j - \Delta V_{aq+1} \frac{\partial S}{\partial Q} \right] \Delta Q = RHS(Q)
\]

Where, \( RHS(Q) = S \Delta V_{aq+1} - \sum_j F_j \cdot \hat{n} \Delta A_j + Q^n \partial V_j \). all off-diagonal terms in this discrete equation are omitted.

2) Multi-step Runge-Kutta format

\[Q^0 = Q^n\]

\[Q^m = Q^0 + \alpha^m \frac{\Delta t}{\Delta V} \text{rhs} \left( Q^0 \right), m = 1 \sim M \]

\[Q^{aq+1} = Q^n\]

The accuracy of the multi-step Runge-Kutta format is determined by the value of \( m \), which represents the accuracy of several orders.

3) Jacobi iterative implicit format
For the Jacobi point iterative method, the nearest adjacent units "N" to "i" are only considered. Reprocessing discrete equation is:
\[
\frac{\Delta V^{n+1}}{\Delta t} + \sum_i \left( \frac{\partial F_{\text{cm}}}{\partial Q} - \frac{\partial F_D}{\partial Q} \right) \cdot \hat{n} \Delta A_i - \Delta V^{n+1} \frac{\partial S}{\partial Q} \bigg|^{n}_{n+1} \right ] \Delta Q^{n+1} = \text{RHS} (Q)
\]

For the problem of computational fluid dynamics studied in this paper, the Jacobi iterative implicit format can accelerate the convergence very well, so we choose the Jacobi iterative implicit format to calculate the flow fields in this paper.

2.5. Chimera mesh

Chimera mesh technology first divides the computing domain into several subdomains, and then combines the flow field information between different subdomains. The use of Chimera mesh will greatly reduce the difficulty of gridding because the subfields do not need to share boundaries when performing flow field calculations, so that each subregion can generate a high-quality body fitted grid. The boundary conditions in the overlapping area are achieved by using interpolation methods to provide the necessary information between the sub-domains, in order to obtain the calculated value of the full flow field. This method has high reliability and application value [8-19].

In this paper, the Chimera mesh is used for calculation, and the number of layers of the UAV body fitted grid is 10 to 20 to meet the requirements. Because the separation problem studied in this paper is the rocket booster in a double post-wing form whose solid rocket booster is located on the wing, it is important to ensure the grid quality on the wing of the UAV during gridding. The figure below shows the surface grid distribution and spatial grid distribution of the UAV.

Figure 2. Chimera mesh
In this paper, the subsonic separations of the post-wing form at 2° attack angle are calculated. The subsonic velocity taken is 0.6 Ma. The separation characteristics of the solid rocket booster of the UAV are calculated: the solid rocket booster is separated by active release, and the entire system is separated by the point force and aerodynamic force provided by the separation mechanism.

Figure 3. Distribution of UAV in Double Post-wing form and Solid Rocket Booster (SRB)

3. Separation calculation of the double post-wing form

3.1. Results of steady calculation

The aerodynamic characteristics of the UAV in the combination of the and the SRB at the subsonic state and the aerodynamic characteristics of the UAV after normal flight (without the influence of the SRB) are obtained through steady calculation. According to the theoretical analysis, if the SRB is successfully separated from the UAV, the aerodynamic characteristics of the UAV will gradually converge to the aerodynamic characteristics of the steady flight state after the UAV is separated from the SRB.

(a) Flow field distribution around the UAV at Ma = 0.6
Figure 4. Steady Calculation Results of the Subsonic Separation of the Post-wing form (Ma = 0.6)

3.2. Calculation conditions of subsonic separation

This state is an emergency separation state. At this time, the UAV and the SRB have not reached the
predetermined separation height and speed, but due to the emergency situation, the UAV and the SRB must be separated. The altitude is 5 kilometers, and the state of the atmospheric environment is shown in Table 1. At this time, the dynamic pressure is about 6 times that of the supersonic separation state shown in Table 5.2. The aerodynamic force and torque are in a relatively high order in this separation state, which is a dangerous state for the UAV. There is a danger of collision between the drone and the solid rocket booster during the separation process. It is necessary to simulate the separation in this state to ensure that the UAV will not collide with the SRB during the separation process.

Table 1. Data in Subsonic Calculation State

| Name                        | Unit   | Value   |
|-----------------------------|--------|---------|
| Freestream velocity        | m/s    | 192     |
| Angle of attack             | deg    | 0       |
| Static pressure             | Pa     | 54020   |
| Dynamic pressure            | Pa     | 13613   |
| Static temperature          | K      | 255     |
| Gravitational acceleration  | m/s²   | 9.8074  |
| Air density                 | Kg/m³  | 0.74    |

3.3. Analysis and comparison of subsonic separation results

Figure 5. Displacement Curve of the Center of Gravity of SRB along the X-axis (Ma=0.6)

Figure 6. Displacement Curve of the Center of Gravity of SRB along the Y-axis (Ma=0.6)
In short, the safety of the separation is to ensure that the SRB does not collide with the UAV during the entire separation process. If the calculation conditions allow, it can be calculated until the distance between the SRB and the UAV reaches more than twice the characteristic length of the SRB. In this way, the UAV and the rocket booster will be difficult to occur without power and the influence of severe crosswind. However, in view of the complexity of the problem in this paper, the amount of calculation is large, so this state is calculated to 1.2S after the separation, and the displacement, velocity and acceleration of the moving body are comprehensively judged to obtain the safety of separation.

In the calculation process, the separation mechanism provides two separation forces to the front and rear of the SRB. Compared to the UAV, the SRB flies out backward at an oblique angle. The above three pictures about the SRB displacement in three directions illustrate this point, which meets the design requirements for the motion trajectory of the solid rocket after separation.

**Figure 7.** Displacement Curve of the Center of Gravity of SRB along the Z-axis (Ma=0.6)

**Figure 8.** Variation Curve of Yaw Angle of the SRB (Ma = 0.6)
Figure 9. Variation Curve of Pitch Angle of the SRB (Ma = 0.6)

The above three pictures are the angular displacement of the SRB in the overall coordinate system from 0 to 1.2s. From the above figure, you can see that the rocket booster appears to rise, and the head is closer to the wing tip in an eight-figure form. In this way, the SRB has a certain angle of attack and sideslip angle. The force acting on the rocket booster has a lift force and a lateral force directed to the wing tip, and has a tendency to diverge.

Figure 10. Variation Curve of Pitch Angular Velocity and Angular Acceleration of SRB (Ma = 0.6)

From the figure above, we can observe the changes in pitch angular velocity and angular acceleration of the SRB. Before 1.0s, the pitch angular velocity and angular acceleration basically show a linear growth trend.

Figure 11. Variation Curve of Yaw Angular Velocity and Angular Acceleration of the SRB (Ma = 0.6)
Figure 12. Variation Curve of Lifting Force of the SRB (Ma = 0.6)

Figure 13. Variation Curve of Lateral Force of the SRB (Ma = 0.6)

Figure 14. Variation Curve of Pitch Moment of the SRB (Ma = 0.6)
Figure 15. Variation Curve of Lateral Moment of the SRB (Ma = 0.6)

Figure 16. Variation Curve of Lifting Force of the UAV (Ma = 0.6)

Figure 17. Variation Curve of Pitch Moment of the UAV (Ma = 0.6)

From the force and moment characteristics of the SRB, the results of calculation and simulation are in line with the inferences in the design scheme. Figure 5.11 shows the curve of lift force of the SRB over time. It is not difficult to see that SRB has a small negative lift force at the initial moment of
separation. If no corresponding measures are taken and external force is applied to the SRB during the initial separation, it will collide with the wing of the UAV. Figure 5.12 is the curve of lateral force of the SRB over time. During the relatively long period in initial separation stage, its lateral force is relatively small. If no corresponding measures are taken, the rocket booster will keep a close distance from the UAV in the initial separation stage. At this time, if a crosswind blows, the rocket booster will easily collide with the UAV. Through the relevant calculations in the research of this paper, it can be found that if the SRB does not apply separation force or the separation force matches with the design poorly at the initial separation time, the rocket booster will collide with the UAV after the separation begins. The specific details are not included in the main research content of this paper, and will not be repeated here.

![Mach number Distribution of the Belly of the UAV and SRB at Different Separation Periods (Ma = 0.6)](image)

**Figure 18.** Mach number Distribution of the Belly of the UAV and SRB at Different Separation Periods (Ma = 0.6)
Figure 18 shows the movement of the UAV and the SRB from 0s to 1s and Mach number distribution of the UAV. At 1s, both the lifting force and the lateral force of the SRB are divergent. It is believed that in this state, the rocket booster and the UAV can be safely separated.

4. Conclusion
In this paper, the double post-wing form used in the ground launch of the UAV is taken as the research object. The structured grid generation technology and the overset mesh technology are used. In-depth and meticulous research is made for this type of separation configuration through computational fluid dynamics methods. In this paper, through theoretical analysis and a large number of numerical simulation calculations, the flow field and movement of this type of UAV separation configuration during the entire separation process are obtained, and the analysis is performed to obtain some data with reference value, which lays a certain foundation for further design and research in the future and has certain engineering application value.

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