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The aerodynamic interference characteristics of TSTO vehicle stage separation

Yuelong He, Haichuan Yu*, Lan Chen, Dun Li

(China Academy of Aerospace Aerodynamics, Beijing, 100074, China)

Abstract: Aerodynamic interference problems and stage separation problems are taken as the key technology for two stage to orbit (TSTO) vehicle. The research of aerodynamic interference characteristics and stage separation problems can make great contribution to development of TSTO reusable launch vehicle (RLV). Three-dimensional unstructured Cartesian grid is used to numerically investigate the TSTO vehicle aerodynamic interference problems. The aerodynamic interference characteristics are described in terms of separation distance, interference of multi-body. Analyses of simulation results show that the interference will make great effect on drag characteristic and lift characteristic of vehicle at $d/L<0.13$, while the interference will make great effect on pitching-moment characteristic at $d/L<0.24$. Aerodynamic interference will lead to a negative pitching-moment on Stage I in initial position, at the same time Stage II gained a positive pitching-moment. A separation program which relies on aerodynamic force for TSTO vehicle stage separation has been developed, the safety factors of TSTO vehicle stage separation were analyzed by numerical simulations to ensure the safety for TSTO vehicle stage separation. Analyses of simulation results show that TSTO vehicle stage separation which relies on aerodynamic force can be achieved at a small negative attack angle, while the TSTO vehicle stage separation which relies on aerodynamic force will not be safe at a positive attack angle. Separation program which relies on aerodynamic force for TSTO vehicle stage separation can greatly simplify the separation institutions, which can realize the large-scale TSTO vehicles stage separation safely.

Key Words: TSTO, aerodynamic interference characteristics, stage separation, separation program, separation distance.

1. Introduction

The space plane has the ability to traveling with high speed in the atmosphere, access to space and reentry to the earth, which lead researchers all over the world pay much attention to the development of the future generation of reusable space shuttle based on the space plane. Most of the studies were focused on two groups of concept called SSTO(Single Stage To Orbit) and TSTO(Two Stage To Orbit), SKYLON, HOTOL, CNES, Sanger, STAR-H are their famous and important examples[1,2,3,4]. Considered the current technology situation, the TSTO concept is more feasible, and that SSTO concept is faced with great technical challenges.

The TSTO systems show specific advantages, which lead a lot of studies be performed on different systems of TSTO, such as the general design, propulsion system, configuration design, separation system, launching method, etc. The current paper focused on the multi-body separation process which is not mentioned in SSTO, but acts as one of the key problems in TSTO concept.

The parallel stage separation program in

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TSTO concept is different from the traditional multi-body separation process, because of the comparable size, complex lifting configuration, large dynamic pressure, etc. The aerodynamic interference affects on the carrier is little when the carrier release a small store, to the contrary the influences during the TSTO parallel stage separation can't be ignored. The space planes are usually designed as complex lifting configuration to meet the load and high L/D demand, which lead to complex mutual interference. NASA has developed a set of next generation RLV stage separation wind tunnel tests based on the LGBB model[5]. In fact early in the 1960s to 1970s, the aerodynamic problems during stage separation with two similar size bodies have been taken into account[6]. Other researchers also paid much attention to such problems[7,8,9].

In current paper we would introduce the TSTO configuration that developed in China. The basic aerodynamic interference research, and the separation process simulation results are introduced either.

2. Vehicle Description

Consider the situation that there is not exist a actual TSTO vehicle in the world, several Chinese aerodynamic academies carried out a program to develop a feasible TSTO system[9]. These aerodynamic academies include China Academy of Aerospace Aerodynamics(CAAA), China Aerodynamics Research and Development Center(CARDC), Aerodynamics Research Institute(AVIC-ARI) and Dalian University of Technology(DUT).

The primary model is illustrated in Fig. 1. Both of the two stages of the vehicle are designed as reusable. The first stage(carrier stage) powered by TBCC, and has the ability to vertical takeoff vertical landing(VTVL), which asked the first stage could flight with wide speed range. For this purpose, the outer-wing of the carrier stage(the blue part of the model in Fig. 1) is deformable, the dihedral angle of the outer-wing could various to adapt the flight speed. The second stage(orbital stage) is a X-37-like configuration. The model is simplified for pre-study. The simplified form model did not include the inlet, nozzle, attachment and release system.

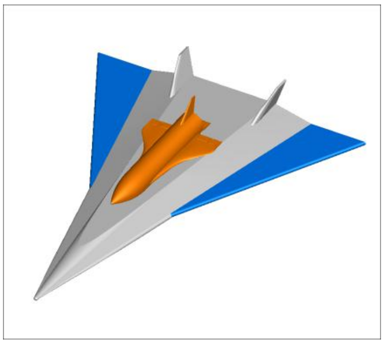

Fig. 1 The primary configuration of the model

The weight and size scale of the TSTO vehicle model are listed in Tab. 1. Ref[9] has introduced the estimation method of these data in detail. When they combined together, the gravity center of the two stages in x direction are the same, which could decrease the control difficulty.

Tab. 1 The weight and size of the model

Stage	Mass(T)	Length(m)	Span(m)
I	300	85	60
II	200	35	17

The staging condition of current TSTO model was set as Ma=3.0. The work in current paper are based on this staging condition.

3. Numerical Method

To simulate the complex stage separation process, the solver that combined the dynamic grid, unsteady flow numerical method and coupled with the 6DOFs trajectory equations has been developed.

The separation process is dispersed into several time steps during simulation, there are flow field simulating and grid reconstructing in each time step. The procedure is:

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1. Create body-fitted Cartesian grid for flow field simulating;
2. Solve the governing equations, and attain the force and moment of each components;
3. Solve the trajectory equations for the velocities, positions and other variables of each compoinents in the next time step;
4. Generate the computing grid for the next time step;
5. Repeate all the steps above until the end.

3.1 Dynamic Grid

The grid reconstructing technology is implemented for applications with large displacement, and for the cases contains small displacement movements only, we use the dynamic grid method based on the spring analogy[11] and combine the moving wall boundary conditions to the governing equations to solve the flow field.

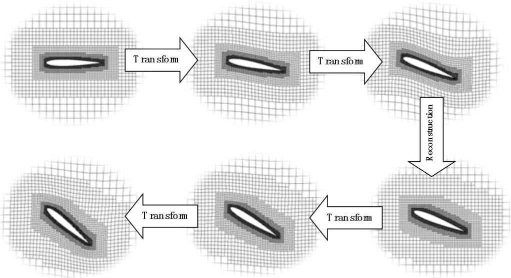

Fig. 2 Schematic of dynamic grid

3.2 Governing Equations

The ALE(Arbitray Lagrangian Eulerian) method that combined the Eulerian method and Lagrangian method is employed for the unsteady aerodynamic simulation. The integral form of the ALE governing equations could written as:

$$\frac{\partial}{\partial t}\iiint\limits_{\Omega(t)} \mathbf{W} dv + \iiint\limits_{\partial\Omega(t)} \nabla\vec{\mathbf{F}} d\Omega = \iiint\limits_{\partial\Omega(t)} \nabla\vec{\mathbf{F}}_v d\Omega$$

The conservation variables $\mathbf{W}$, inviscid-flux vector $\vec{\mathbf{F}}$, and the viscous flux vector $\vec{\mathbf{F}}_v$ are given by:

$$\mathbf{W} = \begin{bmatrix} \rho \\ \rho\vec{\mathbf{V}}_x \\ \rho\vec{\mathbf{V}}_y \\ \rho\vec{\mathbf{V}}_z \\ \rho E \end{bmatrix}^T \quad F = \begin{bmatrix} \rho V_r \\ \rho V_r u + p n_x \\ \rho V_r v + p n_y \\ \rho V_r w + p n_z \\ \rho V_r E + p\mathbf{V} \end{bmatrix} \quad F_v = \begin{bmatrix} 0 \\ \tau_{xi} \\ \tau_{xj} \\ \tau_{xk} \\ \tau_{ij}\vec{\mathbf{V}}_j + q \end{bmatrix}$$

The variables ρ, $\vec{\mathbf{V}}$, E and p are the density, velocity total energy per unit mass, and pressure of thr fluid. τ is the viscous stress tensor, q is the heat flux vector. Unlike the origianl N-S equations, the ALE form governing equations contains the variable named relative velocity $\vec{\mathbf{V}}_\mathrm{r}$, which stands for

$$\vec{\mathbf{V}}_\mathrm{r} = \vec{\mathbf{V}} - \vec{\mathbf{V}}_g$$

Here $\vec{\mathbf{V}}_g$ stands for the grid velocity, and

$$V_\mathrm{r} = \vec{\mathbf{V}}_\mathrm{r} \cdot \vec{\mathbf{r}}$$

Here, $\vec{\mathbf{r}} = x\vec{\mathbf{i}} + y\vec{\mathbf{j}} + z\vec{\mathbf{k}}$ is the position vector.

We employ the cell-centered finite volume method to solve the governing equations. The convective flux is discred by Roe scheme or AUSM family, the variables at both sides of the cell faces are reconstructed by MUSCL method. The time derivative term is solved by Rung-Kutta method for explicit form, and LU-SGS method for implicit form. The farfield boundary condition is based on the 1D Riemann invariant, and the wall boundary condition should satisfy the no-slip condition.

The ALE form equations are different from the original governing equations for the grid velocities are introduced into the ALE equations. Thus the numerical method should take the grid velocities into account. Furthermore, some additional aspect should be considered, such as the GCL(Geometry Conservation Law). The integral form mass conservation equation is:

$$\frac{d}{dt}\iiint \rho dv + \iint \rho\left(\vec{\mathbf{V}} - \vec{\mathbf{V}}_g\right)\cdot\vec{\mathbf{n}} dS = 0$$

The idea of the references[12,13] is that, in the uniform flow field the GCL equation should be satisfied:

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$$\frac{d}{dt}\iiint dv + \iint \vec{\mathbf{V}}_g \cdot \vec{\mathbf{n}} dS = 0$$

That means the grid movement should not affect the variables in the uniform flow field.

3.3 The Trajectory Equations

The aircraft during morphing process was treated as rigid body that suffering the driving force, gravity, aerodynamic forces. The transfer and rotation of the rigid body are independent, thus the movement of the rigid body could separated into two parts:

$$\begin{cases} F = d(mV)/dt \\ M = \dfrac{d}{dt}\left(\sum \vec{\mathbf{r}}_i \times m_i \vec{\mathbf{V}}_i\right) = \dfrac{d(\mathbf{I}\cdot\vec{\boldsymbol{\omega}})}{dt} \end{cases}$$

The simulating of the governing equations and the trajectory equations are at different coordinate system, thus to couple the two equations, the transfer between the two coordinate system should be considered first.

4. Analysis and Discussion

The nominal staging condition of current TSTO concept is set as flight Mach number at 3, and with altitude equals 20km. All of the discussion would base on this condition.

There are two parts in this section, one is about the static interference characteristics of the TSTO vehicles, and the second is the dynamic process during the parallel stage separation.

4.1 Interference Characteristics

The current section focus on the aerodynamic characteristics differences that between the vehicles in the free stream and combined status, which called the static interference characteristics in the paper.

The two vehicles were placed at different relative position for the combined characteristics analyzing, in which status that the stage I keep static, and the stage II moved in normal direction. The distance between the two stages has been indicated the different cases, which is presented as d. Variable d/L has been applied for normalization, where L is the reference length that equals to the length of the stage II. The minimal d in these cases in current paper equals 0.3 metre.

Fig. 3 shows the pressure contour at four typical positions. When d/L=0.01 the upstream flow was blocked at the head of the stage II, which lead a high-pressure zone. At the location that d/L=0.13 and d/L=0.24, there are shock trains between the two vehicles. Especially in the d/L=0.13 location, the lift coefficient of the two bodies that list in Fig. 4 show that the lift on the stage I has the minimum value near this location, to the contrary there is a maximum point of the stage II's lift near the corresponding location. And when the d/L larger than 0.5, the distance between the two parts is large enough that the head shock of the stage II has past the stage I, the aerodynamic disturb became weak.

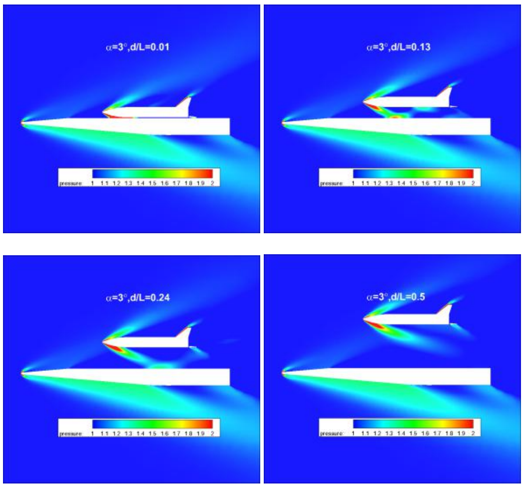

Fig. 3 The pressure contour at different locations

Fig. 4 illustrated the lift coefficients of the two stages at different locations. The green dotted line in the figure is the coefficient of the vehicle in free stream. The Cl of stage I in combined status is smaller than that in free stream, because of the high pressure zone between the two stages in the combined status, especially at small d/L range. The high pressure zone locates in the leeward of stage I, which led to the decease of the lift. On the other hand, the lift of stage II increased cause of the high pressure on the windward.

Similar to the lift, the drag of the two bodies are decided by force position that induced by the high pressure zone. If the high pressure zone located on the windward, the drag would increase.

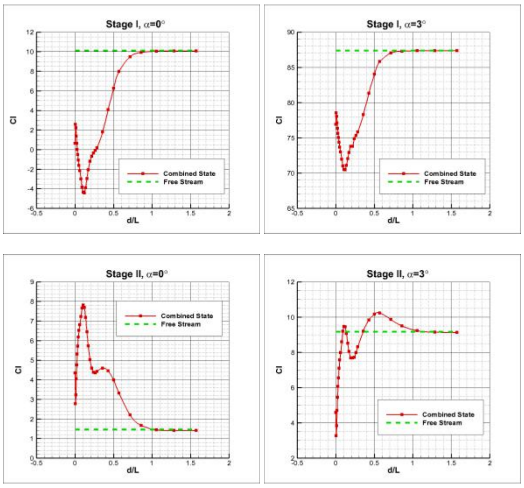

Fig. 4 Lift coefficients at different locations

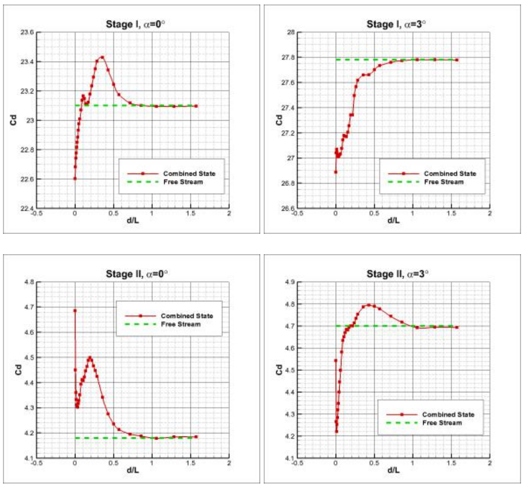

Fig. 5 Drag coefficients at different location

The pitching moment plays an important role during the parallel stage separation, which could affect the pitching angle. The location of the high pressure zone and the development of the shock train are the two key factors that would affect the pitching moment. The high pressure zone near the stagnation aera that ahead of the stage II is before the mass centre of the vehicles, thus the pitching moment of stage I is negative and that of stage II is positive when d/L is small. After the shock train appered, the high pressure flow move downstream, and the aerodynamic centre moves downstream either. In this period, the moment changed rapidly along with d/L increased.

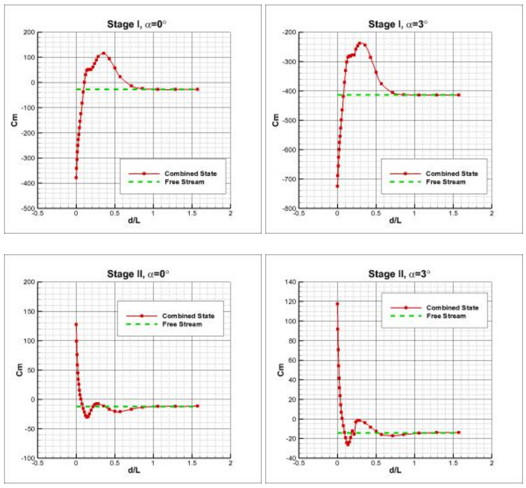

Fig. 6 Pitching moment coefficients at different location

4.2 Stage Separation Simulation

The aerodynamics moment would drive the angle between the two vehicles expaned when d/L is small, which is helpful for the separation. But the sepration process is nonlinear, and the movement is coupled with aerodynamics seriously. To chosse several cases to study the TSTO separation process that with such scales and combined together would beneficial for the similar project in the future.

For the TSTO stage separation, the vehicles' movement and pose changement should be pay much attention. There are mainly two numerical method for the separation program estimation, one is the Monte-Carlo method that based on static arodynamic database, the other is the CFD/RBD numerical simulation. Here we use the CFD/RBD method for stage separation program mesurement.

The separation conditions are illustrated in

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Tab. 2. We only considered the different angles of attack(AoAs) in current paper, other factors would be brought in after more particular program came out.

Tab. 2 The separation cases

No.	1	2	3
AoA(deg)	2	0	-2

Fig. 7-Fig. 9 show the separation process of these cases. The cases selected all with small aoas, but the separation process of these three cases are quite different.

The two vehicles in case 1 could not separate safely, after a period of close-flight, the two bodies meet each other. When the aoa is positive, the normal force of the two bodies could not applied them to separate rapidly, indeed the pitching moment made them head inside, which decreased the safely separation possibility.

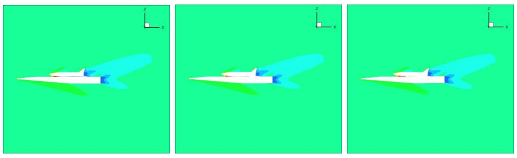

Fig. 7 Separation process of Case 1

Fig. 8 shows the separation maps of case 2. Stage II head up rapidly in the early stage, and the pitching angle oscillated when they have certain distance, which made the two stages to be faced with the risk of rush.

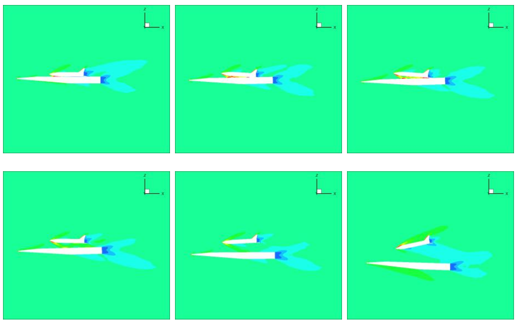

Fig. 8 Separation process of Case 2

In case 3 the distance between the two vehicles increase quickly after the separation. And the relative angles of them change slowly, which led the separation imagines looks like co-phase swinging, along with the normal distance increased all the time.

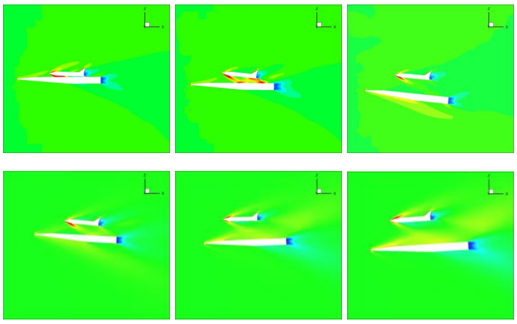

Fig. 9 Separation process of Case 3

The cases that simulated in current paper are too simple, many factors have not mentioned, such as the control and separation device, configuration details, ballistic trajectory parameters, etc. The separation program that simulated in current paper showed the possibility that TSTO vehicles could separate with pure aerodynamic force.

5. Conclusion

The research in current paper show a new TSTO program. The CFD method was applied for aerodynamic interference characteristics study. The lift, pitching moment showed obvious trend against the parameter d/L. Several separation cases with pure aerodynamic force were also simulated, result showed that the possibility that TSTO stage separation with aerodynamic only.

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