Numerical Simulation of Mars Exploration Rover Heat Shield Separation

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Abstract

A DDES method, which is a hybrid RANS-LES method, is proposed for numerical simulation of Mars Exploration Rover heat shield separation. The heat shield and back shell drag characteristic and aerodynamic interference effect between them are analyzed at different axial separation distances. The computational results are compared to the experimental results. And then security analysis of heat shield separation is discussed. The results indicate that the aerodynamic interference effect of heat shield and back shell is the most serious inducing a suction force while the axial distance is less than two heat shield diameters. And there will be a recontact risk after heat shield separating while the axial distance is less than five heat shield diameters. To ensure successful heat shield separation, the axial distance must be larger than five heat shield diameters.

Keywords: Numerical Simulation, Heat Shield Separation, Afterbody, Mars Exploration Rover, Hybrid RANS-LES Method, Drag Characteristic

1.Introduction

In order to safely touch down on Mars' surface, Entry Descent and Landing (EDL) methods are employed in the lander missions to Mars^{[1]-[2]}. The implementation process include cruise stage separation, hypersonic entry, parachute deploy, heat shield separation, radar data collection starts, back shell separation, powered descent and sky crane flyaway etc. Thereinto, heat shield separation is the key stage which may incur risk easily.

After heat shield separation, what remains is the back shell with the lander attached to it and this combined body is referred to as afterbody. When air flow past the heat shield that is a blunt body, a wake zone will develop in the backside. And there will be a zone near blunt body base where the air flow direction is inverse to the incoming flow direction, which is called return-flow zone. While heat shield is jettisoned by separation spring, the whole afterbody will be located at the wake of heat shield and there will be an aerodynamically induced suction force pushes the heat shield back into afterbody. Therefore, to ensure successful heat shield separation, two step problems must be solved. First, the separation spring has to impart sufficient impulse to overcome this suction. Second, there has to be a sufficient ballistic coefficient difference between the heat shield and afterbody such that the heat shield descents faster. However, there are considerable uncertainty in Mars' atmospheric conditions, namely atmospheric density and winds. It is very important to do the research of heat shield separation.

There are much research work about Mars exploration in America^{[3]-[6]}, including the investigation of heat shield separation. Lang carried out wing tunnel test of Viking heat shield separation previously^[7], and the test results were systematic analyzed by Behzad^{[8]-[9]}. In China, there are also some research about Mars exploration, which are mostly review

article^{[10]-[11]} or analysis of EDL technology^{[12]-[14]}, and none of research paper about heat shield separation has been seen.

The focus of this paper is numerical simulation of heat shield separation. Aerodynamic properties of heat shield and afterbody are discussed separately. And only the drag force characteristic is researched.

2.Heat Shield Separation Model

Mars Exploration Rover^[15] is chose as calculation model, shown in Figure 1. Drag force of heat shield and afterbody at different separation distances are compared and analyzed. The separation distances include axial separation distance (Δx) and lateral separation distance (Δz), shown in Figure 2. For preliminary study, only the axial separation distance is investigated.



3.Calculation Method

RANS-LES hybrid method is adopted for numerical calculation^[16], which integrates Reynolds Average Navier-Stokes (RANS) and Large Eddy Simulation (LES). The basic idea of RANS-LES hybrid method is simulating high-frequency small-scale motion in near wall area by using RANS method and low-frequency large-scale motion in separated flow area by using LES method. The classical Detached Eddy Simulation (DES)^{[17]-[18]} is improved and Delayed Detached Eddy Simulation (DDES)^[19] is gained. The method is constructed from RANS turbulence model equation. The detail of DDES method and control equation can be seen from reference [16] and reference [20].

In order to validate the reliability of above calculation method, Shenzhou capsule configuration is used for case check, wind tunnel test of which has been carried out in FD-12 wind tunnel at China Academy of Aerospace Aerodynamics. Test condition: Mach number equal to 0.9, Reynolds number per unit length equal to 1.8×10^7 . Comparison of computational result and experimental result are presented in Table 1. The error is within 2%, indicating the veracity of calculation method.

Table 1.	Comparison	of computational	l result and e	xperimental	result
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Results	Axial force coefficient
Experimental result	1.20
Computational result	1.22

4.Numerical Simulation Results

The heat shield separation height is 5 kilometers of Mars Orbital Laser Altimeter (MOLA)^[21]. Table 2 presents Mars atmosphere parameters.

Ма	Height[km]	$\rho_{\infty}[kg/m^3]$	$T_{\infty}[K]$
0.3	5	0.00762	222

Table 2. Mars atmosphere parameters

Heat Shield Drag Force characteristics

Figure 3 shows variation of heat shield drag force coefficient with axial separation distance Δx (normalized by heat shield diameters D). As axial separation distance increasing, the drag force coefficient of heat shield augments rapidly and reaches maximal value at $\Delta x=1D$. Then it minishes rapidly for axial distance $1D<\Delta x<3D$ and reaches minimal value at $\Delta x=3D$. For axial distance $4D<\Delta x<10D$, drag force coefficient of heat shield grows slowly and almost remain constant at $\Delta x=10D$, meaning heat shield is no longer affected by afterbody while $\Delta x>10D$.

The computational drag force coefficient of heat shield is compared with the experimental result in reference [8] as a function of axial separation distance up to ten diameters away, shown in Figure 4. The computational results match well with the experimental results.



Back Shell Drag Force characteristics

Figure 5 shows variation of afterbody drag force coefficient with axial separation distance Δx . The drag force coefficient of afterbody is nearly zero at $\Delta x=0$, and the reason for this behavior is because the heat shield shadows afterbody and blocks the flow of incoming air. As axial separation distance increasing, the drag force coefficient of afterbody decreases rapidly and reaches minimal value at $\Delta x=1D$, and then increases for axial distance $1D<\Delta x<10D$. Especially while $\Delta x<2D$, the drag force coefficient of afterbody is negative, which means the afterbody is being sucked forward because of formation of low pressure air flow in the volume between heat shield and afterbody.

The computational drag force coefficient of afterbody is also compared with the experimental result in reference [8] as a function of axial separation distance up to ten diameters away, shown in Figure 6. The comparison results are qualitative similar and quantitative different. The computational drag force coefficient reaches minimal value at $\Delta x=1D$ while the experimental drag force coefficient reaches minimal value at $\Delta x=2D$.



Figure 5. Variation of back shell drag force coefficient with axial separation distance



Figure 6. Comparison of back shell computational result and experimental result

Comparative Analysis

The drag coefficient curves for heat shield and afterbody are presented in Figure 7 as a function of axial separation distance.

The interference aerodynamics occurs when heat shield and afterbody are in close proximately to each other which influence their respective aerodynamics. This interaction effect decreases as their separation distance increases. When the axial separation distance is ten heat shield diameters away from afterbody, there is little aerodynamic interference.

For $\Delta x < 5D$, the drag force coefficient of heat shield is bigger than afterbody, so that afterbody will descend faster than heat shield and there will be a risk of recontact. For $0 < \Delta x < 2D$, the drag coefficient of afterbody becomes negative because of formation of low pressure air flow in the volume between heat shield and afterbody (see Fig.8). Conversely to the "suction" phenomenon on afterbody, the heat shield experiences increased drag in this region. The separation springs need to produce a sufficient impulse to overcome this "suction" force, otherwise the heat shield will simply slam back into afterbody. For $\Delta x > 5D$, the drag force coefficient of heat shield is smaller than afterbody, so that heat shield will descend faster than afterbody and not recontact.

In an ideal scenario, as the heat shield separates, the spring system produces sufficient impulse to overcome the suction force and pushes the heat shield away from afterbody until $\Delta x=5D$. And then the ballistic coefficient of the heat shield will be just slightly higher than afterbody in order for separation to continue increasing with time while $\Delta x>5D$, and so that the heat shield will descend faster than afterbody and not recontact.



Figure 7. Comparison of heat shield and back shell drag force coefficient



Figure 8. Flow field contour of axial separation distance $\Delta x=1D$

5.Conclusions

A RANS-LES method was constructed to numerical simulate heat shield separation of Mars Exploration Rover. This paper discusses how to assess the heat shield separation risk numerically and minimize the recontact risk. The outcome indicates that the computational results match well with the experimental results, which means the veracity of calculation method.

The drag force coefficient of heat shield is bigger than afterbody for $\Delta x < 5D$, and there will be a recontact risk in this region. For $0 < \Delta x < 2D$, the interaction effect between heat shield and afterbody is most serious and the drag coefficient of afterbody becomes negative. For $\Delta x > 5D$, the drag force coefficient of heat shield is smaller than afterbody, therefore the heat shield will descend faster than afterbody and not recontact.

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