Research on shock-vortex interaction of fairings based on dynamic unstructured overset grid

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Abstract. The fairing is used to protect the aircraft from aerodynamic heat and force at high-speed, while there exists strong shock-vortex interaction during fairing separation. The unsteady shock-vortex interaction is numerically studied based on dynamic unstructured overset grid in this paper, where the N-S equations and 6-DOF equations are couple solved. Due to the blocking effect of fairings and shocks, there is a strong vortex inside the fairings. With the separation of fairings, the vortex is strongly compressed by the shock of fairing. When the shock is very close to fairing, the vortex is forced into the Mach cone of aircraft and enlarges the Mach cone. There exists a strong shock-vortex interaction of shock-vortex compressing, transforming of vortex boundary and vortex-shock compressing during fairing separation.

1. Introduction
The fairing of the high-speed aircraft plays the role of maintaining the aerodynamic shape and protecting the internal equipment of the aircraft, while there exists strong a shock-vortex interaction during fairing separation. There would be bow shocks of both the fairings and aircraft during the fairing separation at high-speed. Due to the blocking effect of fairings and shocks, there is a strong vortex inside the fairings, and the vortex and shocks would interact with each other, it is necessary to understand the mechanism of shock-vortex interaction.

With the rapid development of computational fluid dynamics in recent years, numerical simulation methods are capable to simulate complex flow characteristics. Yuan studied the separation of high dynamic pressure fairing in low-altitude based on numerical method, and found “fill-stagnation-drain” flow characteristics in gas between fairing and aircraft [1, 2]. Cavallo researched the fairing separation process of a reentry aircraft based on dynamic mesh, and studied the movement trajectory before and after the fairing rotation separation and decoupling, and analyzed the synchronization and safety of split-type fairing separation [3]. Wang developed some numerical methods including moving boundary, mesh deformation and local mesh reconstruction, and studied the separation of fairing with high dynamic pressure at low altitude, and investigated the effects of the number of hoods, mass characteristics, and aerodynamic characteristics on the separation trajectory of fairing, preliminarily established the criteria of safe separation of fairing [4]. Liu Jun combined spring approximation and local mesh reconstruction together and developed an unstructured dynamic mesh method, and researched the separation process of rocket fairing in dense atmosphere at hypersonic speed [2]. Liu Zhen studied the fairing separation based on structured chimera grid, and illustrated the pressure oscillation of the infrared window area...
caused by the shock wave interference during the separation fairing separation [5]. Zhao researched the separation process of integral-type fairing based on structured overset grid, the influence of the asymmetric small rocket on the trajectory of fairing is presented, and indicated the effects of component interference and unsteady flow on fairing separation [6]. It can be seen the common numerical simulation methods of multi-body relative motion can be divided into dynamic grid method, overset grid method, dynamic adaptive cartesian grid method, in which overset grid method is most popular because of its high efficiency and high accuracy.

The unsteady shock-vortex interaction is numerically studied based on dynamic unstructured overset grid in this paper, where the N-S equations and 6-DOF equations are couple solved, the results show that there exists a strong shock-vortex interaction of shock-vortex compressing, transforming of vortex boundary and vortex-shock compressing during fairing separation.

2. Numerical Method

The simulations here are conducted by the China Aerodynamics Research & Development Center (CARDC) NNW-FlowStar software [7-8], an unstructured finite volume cell-center CFD solver and has participated in the 5th and 6th CFD drag prediction workshop [9]. Second-order accuracy in space is achieved by linear reconstruction in cells. The vertex-based Gauss method is used for gradient computations, to simultaneously fulfill accuracy and robustness. Roe scheme [10] is used for inviscid flux computations, and the Venkatakrishnan limiter [11] is used to restrict oscillation.

2.1. Governing Equations

The unsteady Navier-Stokes equations are discretized by a cell centered finite-volume method. The integral form of unsteady Navier-Stokes equations for a bounded domain \( V \) with a boundary \( \partial \Omega \) can be expressed as:

\[
\frac{\partial}{\partial t} \int_V \rho \mathbf{v} \, dV + \int_{\partial \Omega} \left( \mathbf{H}(Q) \cdot \mathbf{n} - \mathbf{Q} \mathbf{v} \cdot \mathbf{n} \right) dS = \int_{\Omega} \mathbf{F} \cdot d\mathbf{S}
\]

Where, \( Q = \left[ \rho, \rho u, \rho v, \rho w, \rho E \right]^T \), \( \mathbf{v} \) is the wall velocity and \( \mathbf{H}(Q) \) is the inviscid flux vector, \( \mathbf{H}_i(Q) \) is the viscous flux vector. Here, \( \rho, (u,v,w) \) and \( E \) denote the density, velocity of three directions, and specific total energy of the fluid. \( \mathbf{n} \) is the outward pointing normal unit vector of the boundary. The inviscid flux is replaced by a numerical Riemann flux function Roe schemes [10], and the viscous flux is discretized with central difference scheme [12].

2.2. Governing Equations

A dual time-stepping is used to advance the time-accuracy solution in time. The Lower Upper-Symmetric Gauss-Seidel (LU-SGS) is used to solve Eqs. (1), and the sub-iteration of each physical time step is also calculated by using LU-SGS. The forward and backward sweep forms are given in Eqs. (2) - (3), where \( \phi = 0.5 \), and \( \tau, V^* \), \( V_{in} \), \( \lambda_{max} \), \( n, N \) denote the pseudo time, the volume of grid cell, the surface velocity of grid cell, spectral radius, iteration step, surface number of grid cell, respectively.

\[
\delta Q^r = -\frac{1}{2} \sum_{i=1}^{N} \left( \mathbf{H}(Q^r) + \delta Q^r \right) - \lambda_{max} \lambda^r \delta Q^r \mathbf{S}_i
\]

\[
\delta Q^r = \frac{1}{2} \sum_{i=1}^{N} \left( \mathbf{H}(Q^r) + \delta Q^r \right) - \lambda_{max} \lambda^r \delta Q^r \mathbf{S}_i
\]

\[
RHS(Q^*) = \frac{1}{2} \left( \mathbf{Q}^* \mathbf{V}^* + \phi (\mathbf{Q}^* \mathbf{V}^* - \mathbf{Q}^{r-1} \mathbf{V}^{r-1}) \right) + \frac{1}{2} \mathbf{H}_i \cdot \mathbf{n} \mathbf{S}_i - \sum_{i=1}^{N} \mathbf{H}_i(Q^*) \cdot \mathbf{n} \mathbf{S}_i
\]
2.3. Geometry and Computational Grids

The aircraft of THAAD (Terminal High Altitude Area Defense) system is a typical high-speed aircraft. A simplified model of THAAD aircraft is employed in this paper to study the separation characteristics of two-split-type fairing. We focus on the flow characteristics of fairing, so the model is further simplified, and the booster is discarded from THAAD aircraft model (Fig.1).

![Figure 1. The geometry of two-split-type fairing.](image1)

Fig. 2 shows the local grids of the fairing, the computational grids are unstructured hybrid grids, including triangular prism, pyramid, and tetrahedral grid. It can be seen from the symmetry plane that the grids near the fairing are specially refined to simulate the flow characteristics. Dynamic unstructured overset grids are employed to simulate the dynamic separation of fairings. The overset grid method separates the complicated flowfield into several simple sections, the grids of each section is generated independently and the flowfield of each section is computed independently [13-15], the data of flowfield is transferred between the interfaces of overset grids by interpolation, and the overset grid method is most popular in the numerical simulation of dynamic multi-body relative motion [16, 17]. The total number of grid cells is 31 million.

![Figure 2. The geometry of two-split-type fairing.](image2)

3. Results and Discussion

A standard model of multi-body separation is used to verify the numerical methods. The unsteady shock-vortex interaction during the separation of two-split-type fairing is discussed in this section.

3.1. Methods verification

A wing/pylon/finned-store standard (WPFS) model of NASA is used to verify the numerical method [18]. WPFS model is standard model used to verify the ability to simulate the multi-body separation, and there are a lot of wind tunnel and numerical results [19, 20]. The flow conditions for the WPFS is: Ma=0.95, attack angle α=1°.

Fig. 3(a) shows the overset grids of wing and store, the mesh of wing is a background grid, and the total number of grid cells is 5.53 million. Fig. 3(b) shows the attitude of the external store separated.
from the wing, it can be seen that the CFD results coincide well with wind tunnel results, the results indicate the numerical method is able to simulate the process of multi-body separation.

![Image](image1.png)

(a) Overset grid of WPFS model  (b) Attitude of the external store

**Figure 3.** WPFS model numerical verification.

3.2. **Typical flow characteristics during the fairing separation**

3.2.1. **Generation of vortex**

![Image](image2.png)

(a) Pressure distribution  (b) Streamline distribution

**Figure 4.** Flow characteristics when separation angle =0°

The unsteady shock-vortex interaction during the separation of two-split-type fairing is numerically studied based on dynamic overset grids. Fig.4 shows the flow characteristics when separation angle =0°, at which the fairings have not separated, and it is a typical and normal Mach cone.

Fig.5 shows the pressure distribution and streamline distribution when the separation angle is 10°, at which the fairings have separated to a small angle. There are bow shocks of both the fairings and aircraft due to high-speed airflow, and the shock waves converge near the head of aircraft. The shock wave of
the fairing continues to move towards the bottom of the fairing after being reflected by the wall of the aircraft, but the airflow is blocked at the tail of the fairing and then flows back along the wall of the fairing, and the backflow airflow moves with the shock wave of fairing after meeting the shock wave. Therefore, a strong vortex is formed inside the fairing under the interaction of shock wave/ fairing /aircraft, and the boundary of vortex is the shock wave of the fairing.

![Image](image1.png)

**Figure 5.** Flow characteristics when separation angle =10°

3.2.2. Shock-vortex compressing

![Image](image2.png)

**Figure 6.** Flow characteristics when separation angle =25°

Fig.6 shows the pressure distribution and streamline distribution when the separation angle is 25°, at which the fairings have separated to a large angle. It can be seen from flow field that, the shock waves of upper and lower half-fairings form an asymmetric flow field, because the upper and lower half-shields are of asymmetrical configuration, and it is still a shock-vortex-dominated flow field. With the gradual
increase of the opening angle, the shock waves of fairings are getting closer to the wall of the fairings, and the vortex inside the fairings is gradually compressed by the shock waves. Although the space of vortex is compressed, the boundary of the vortex is still the shock waves of fairings. Due to the large separation angle of the fairings, strong separation flows are formed on the leeward side of the fairings.

3.2.3. Vortex-shock compressing

Fig. 7 shows the streamline distribution when the separation angle is 38° and 45°. When the separation angle is 38°, the flow field has two major changes. First is the change of the position and boundary of the vortex. The vortex is no longer attached to the fairing, instead, it is converted to the head of the aircraft, and the boundary of the vortex is converted from the shock wave of fairing to the Mach cone of aircraft. Another change is that the Mach cone of the aircraft is significantly larger than that in Figure 4/5/6. The mechanism of the flow field transformation is the strong interference between shock waves and vortex. With the increasing of separation angle of fairing, the shock wave of the fairing is getting closer to the fairing, and the vortex is strongly compressed by the shock wave. But the vortex cannot move backward due to the block of fairing, so the vortex is "squeeze" into the Mach cone of aircraft. As a result, the Mach cone of the aircraft is strongly compressed by the vortex, so the Mach cone becomes larger compared with Figure 4/5/6. When the separation angle is 45°, the fairing has separated from the aircraft, and the block effect of the fairing is weakened, and the main vortex is squeezed outside of the fairing by the shock wave, and the Mach cone of the aircraft returns to normal.

There exists a strong shock-vortex interaction of shock-vortex compressing, transforming of vortex boundary and vortex-shock compressing during fairing separation.

4. Conclusion

The flow characteristics of high-speed two-split-type fairing separation is numerically researched based on unstructured overset grid. Results show that numerical method can obtain a clear flow structure and movement trajectory of the fairings. There exists a strong interaction of vortex and shock waves, and the boundary of vortex is compressed by shock waves. The upper and lower half fairings separate asymmetrically at the high angle of attack or sideslip.

Acknowledgments

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References

[1] Yuan Y Li D Ma Y L et al 2019 MISSILES AND SPACE VEHICLES 5 17.
[2] Liu J Wang W Guo Z et al 2016 Journal of Ballistics 18(3) 34.
[3] Cavallo P Dash S 2000 Denver: 18th Applied Aerodynamics Conference.
[4] Wang W 2008 Changsha National University of Defense Technology.
[5] Liu Z Xu M 2011 Engineering Mechanics 28(7) 252.
[6] Zhao X H 2009 Changsha National University of Defense Technology.
[7] Cui P C Deng Y Q Tang J et al 2016 Acta Aeronautica et Astronautica Sinica 37(10) 2992.
[8] Cui P C Tang J Li B et al 2018 Acta Aeronautica et Astronautica Sinica 39(3) 121569.
[9] Levy D Laflin K Tinoco E 2013 51st AIAA Aerospace Sciences Meeting DLR.
[10] Roe P L 1997 Journal of Computational Physics 135(2) 250.
[11] Venkatakrishnan V 1993 31st Aerospace Sciences Meeting & Exhibit Reno USA.
[12] Zhang Y B Zhou N C Chen J T 2015 Acta Aerodynamica Sinica 33(3) 279.
[13] Jerme D L Duchaine F Gicquel L et al 2018 Journal of Computational Physics 363 371.
[14] Brazell M J Sitaraman J Mavriplis D J 2016 Journal of Computational Physics 322 33.
[15] Völker S Brunswig J Rung T 2017 Computers & Fluids 148 39.
[16] Wang W Yan C Yuan W et al 2016 Acta Aeronautica et Astronautica Sinica 37(10) 2980.
[17] Huang Y Yan C Wang W et al 2017 Journal of Beijing University of Aeronautics and Astronautics 43(2) 285.
[18] HEIM E R 1991 AEDC-TSR-91-P4 New York AEDC.
[19] Kim D H Park Y M Lee I et al 2005 AIAA Journal 43(1) 53.
[20] Tang Z G Li B Zheng M et al 2009 Acta Aeronautica Sinica 27(5) 592.