Investigation of store separation characteristics by leading edge spoilers before supersonic cavity

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Abstract. The internal cavity is widely used on new generation aircraft. However, there are some new aerodynamic and acoustic issues accompanied with the internal cavity. Store separation is a challenge when separated from a high-speed cavity, the store usually generates nose-up pitch moment due to the separated flow and large static pressure gradient, which is a threat to store separation safety. Leading edge spoiler is an effective passive flow control method to improve the store separation characteristics, however the effects of varisized leading edge spoiler on store separation characteristics are still unknown. In this paper, a parameterized leading edge spoiler model is established to investigate the store separation characteristics by leading edge spoilers flow control before supersonic cavity, a small aspect ratio fly-wing aircraft and a simplified store model are employed to simulate the store separation characteristics. Numerical results show that the leading edge spoiler lifts the shear layer and significantly changes the pressure distribution inside the cavity, which makes the store a nose down pitch angle during separation. The height of leading edge spoiler greatly influences the store separation characteristics for it changes the shear layer and vortex structure. The angle of spoiler and the gas between spoiler and aircraft also have great effects on store separation, larger angle and smaller gas lead to less nose-up angle.

1. Introduction

The internal cavity is widely used in new generation aircraft, however, the cavities generate strong unsteady characteristics when exposed to airflow during store separation [1, 2]. It has been observed that a store usually generates upward force moment when separated from an internal aircraft bay, the store may return back and strike the aircraft due to the large upward angle, which is a serious threat to the safety of aircraft. The store separation characteristics have to be known to ensure safe separation from internal aircraft bay. Many researchers explored methods of cavity flow control and improving the cavity environment, according to the need for external energy the control methods can be divided into passive and active flow controls. Passive control strategies usually employ more simple structure than active control strategies. Lawson and Barakos summarized the passive flow control studies [3, 4], most passive flow control methods employ leading edge modifications such as leading edge plate spoiler, serration, block, transverse rods and active blowing. Saddington found that leading edge control methods are more effective at suppressing cavity tone amplitudes than trailing edge modifications [5]. A well-designed passive control device is an easier and more ideal choice compared with active method [6].
The control mechanism and effectiveness of leading edge spoiler before a cavity of a small aspect ratio fly-wing aircraft is studied in this paper, numerical simulations are performed to research the effects of leading edge spoiler on store separation.

2. Numerical Method

The computations here were conducted by using the China Aerodynamics Research & Development Center (CARDC) MFlow-code [7-8], which is 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 $\Omega$ with a boundary $\partial \Omega$ can be expressed as:

$$
\frac{\partial}{\partial t} \int_{\Omega} \rho \mathbf{v} \cdot d\mathbf{V} + \int_{\partial \Omega} \left( H(\rho \mathbf{v} \cdot \mathbf{n}) - \mathbf{Q} \cdot \mathbf{n} \right) dS = \int_{\Omega} \mathbf{H} \cdot \mathbf{n} dS
$$

Where, $\mathbf{Q} = [\rho, \mathbf{v}, (\rho u, \rho v, \rho w)]^T$, $\mathbf{v}_g$ is the wall velocity and $H(Q)$ is the inviscid flux vector, $H_i(Q)$ 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 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. The Venkatakrishnan limiter [11] is used to restrict oscillation.

2.2. Time-stepping

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 $\tau, V^\prime, v_{ad}, \lambda_{max}, n, N$ 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.

$$
\left( \frac{V_{ri}^{rej}}{\Delta \tau} \frac{1}{2} \mathbf{H}(\rho v_{ad}) + \frac{1}{2} \sum_{i=1}^{N} (\lambda_{max} - v_{ad}) S_i \right) Q_{ri}^{rej} = -RHS(Q_{ri}^{rej}) - \frac{1}{2} \sum_{i=1}^{N} \left( \mathbf{H}(Q_{ri}^{rej} + \lambda_{max} \delta Q_{ri}^{rej}) - \mathbf{H}(Q_{ri}^{rej}) \right) S_i
$$

$$
\delta Q_{ri}^{rej} = Q_{ri}^{rej} - \frac{1}{2} \left( \frac{V_{ri}^{rej}}{\Delta \tau} \frac{1}{2} \mathbf{H}(\rho v_{ad}) + \frac{1}{2} \sum_{i=1}^{N} (\lambda_{max} - v_{ad}) S_i \right) Q_{ri}^{rej} - \frac{1}{2} \sum_{i=1}^{N} \left( \mathbf{H}(Q_{ri}^{rej} + \lambda_{max} \delta Q_{ri}^{rej}) - \mathbf{H}(Q_{ri}^{rej}) \right) S_i
$$

$$
RHS(Q_{ri}^{rej}) = - (1 + \phi) Q_{ri}^{rej} V_{ri} + (1 + \phi) Q_{ri}^{rej} V_{ri}^\prime + \frac{(1 + \phi) Q_{ri}^{rej} V_{ri} - Q_{ri}^{rej} V_{ri}^\prime}{\Delta \tau} + \frac{(1 + \phi) Q_{ri}^{rej} V_{ri}^\prime - Q_{ri}^{rej} V_{ri}}{\Delta \tau} + \sum_{i=1}^{N} \mathbf{H}(Q_{ri}^{rej}) - \sum_{i=1}^{N} \mathbf{H}(Q_{ri}^{rej})
$$

2.3. Overset Grid

Overset grid method is wildly used in the numerical simulation of multi-body movement which is difficult to simulate with a single mesh. In the overset mesh method the complex geometries are divided into several simple grid zones, every single mesh is generated independently for every zone, thus decreases the difficulty of mesh generation especially for structured grids and at the same time often improve the grid quality [12,13]. The flow fields are solved independently in every overset zone, and different zones get their boundary data by interpolation from neighboring zones [14].
For overset grid hole-cutting technique, determination of the hole boundary needs to be fully automated and of high efficiency and robustness. In this paper, the solid surface intersection criterion is selected as the boundary determination method. After determination of the hole boundary, the donor cells in other subzones are found for all interpolated cells. The Alternating Digital Tree method [15] is built for each zone by using the coordinates of the bounding box for a cell, which is a point in six-dimensional space. A conservative interpolation method for the hybrid overset mesh is used during the data transferring between overset sub-grids.

2.4. Geometry and Computational Grids

![Figure 1. Low-aspect-ratio flying-wing standard model and simplified cylindrical store.](image)

A standard model of low-aspect-ratio flying-wing aircraft, which is presented in Fig. 1, is developed by CARDC [16]. An internal cavity is created in the standard mode, the cavity is similar to M219 standard cavity model and has a long-depth ratio of 5:1 [17]. A simplified cylindrical store is separated from the cavity of flying-wing model. A leading edge spoiler is set at the front of cavity to control the separation characteristics of store (seeing Fig.2), the leading edge spoiler is described by 3 parameters, e denotes the height of plate, θ denotes the angle of plate, and h denotes the gas between plate and aircraft, δ denotes local boundary layer thickness.

Fig.3 shows the grids of flying-wing model and store, the computational grids are unstructured hybrid grids, including triangular prism, pyramid, and tetrahedral grid. The tri-angular prism grid and
tetrahedron grid are used to simulate the boundary layer and the isotropic region of the spatial flowfield, respectively, and the pyramid grid is used to transition the triangular prism and the tetrahedron. It can be seen from the symmetry plane that the grids near the leading edge spoiler and cavity are specially refined to simulate the shear layer, and grids where the store may go through under the cavity are locally refined to make sure the grids scale of store and its background grids is same, which can make a better data transferring between overset grids and achieve accurate simulation of store separation. The number of grid cells of flying-wing model is 18 million, and the number of grid cells of store is 4 million.

3. Results and Discussion

A standard model of store separation is used to verify the numerical method. The flow conditions for the cases in this paper are identical: Ma=1.2, attack angle $\alpha=1^\circ$, several groups of leading edge parameters of different height, angle and gas are used.

3.1. Methods verification

A wing/pylon/finned-store standard (WPFS) model is used to verify the numerical method. WPFS model is standard model used to verify the ability to simulate the store separation, and there a lot of wind tunnel results [18]. The flow conditions for the WPFS is: Ma=0.95, attack angle $\alpha=1^\circ$.

Fig. 4(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. 4(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 store separation.
3.2. Effects of leading edge spoiler on store separation

The separation characteristics with leading edge spoiler flow control and without flow control (clean cavity) are investigated. The thickness of boundary layer (δ) at the front of clean cavity is 60mm, and a leading edge spoiler with a height of 1.6δ is used to investigate the effect of leading edge spoiler on store separation.

![Graph showing pitch angle vs. time for clean cavity and spoiler-1.6δ](image)

**Figure 5.** Separation characteristics of the store separated from cavity.

Fig. 5 shows the pitch angle of a store separated from the cavity of flying-wing model, it can be seen that the store separated from clean cavity has a nose up pitch angle up to 45° when t=0.9s, and the pitch angle is getting larger and larger. The store would quickly tend to be vertical, and this is a bad situation in store separation. While the store separated from cavity with leading edge spoiler flow control has a little nose down pitch angle during the store separation, which is a good situation in store separation, because the trajectory of store would not threaten the safety of aircraft and it is good for posture control of store.

![Images showing pressure and streamline for clean and spoiler cases](image)

**Figure 6.** Pressure and streamline at t=0.05s.

Fig. 6 shows the pressure and streamline of the flow passing through the cavity and store at the time t=0.05s, when the store is still inside the cavity. It can be seen that the leading edge spoiler lifts the shear layer and reduces the flux into the cavity, which significantly changes the pressure distribution inside the cavity. Fig. 6(a) shows that the air flows into the cavity and has a strong impact on the store, and the store generates a nose up moment of force, while we can see from Fig. 6(b) that the leading edge spoiler lifts the shear layer and prevents the air flowing into the cavity, which decreases the pressure distribution...
inside the cavity especially the pressure under the store, and the store generates a nose down moment of force.

Fig. 7 shows the pressure and streamline of the flow passing through the cavity and store at the time $t=0.35\text{s}$, when the store is going through the shear layer. Fig. 7(a) shows that the flow has a strong impact on the store when passing through the cavity, and generates high pressure in the lower surface on the head of store, and the store generates a nose up moment of force. Fig. 7(b) shows that the leading edge spoiler lifts the shear layer and prevents the air flow into the cavity, which makes a negative local attack angel and a downwash flow field at the head of store, and the store generates a nose down moment of force.

Fig. 8 shows the pressure and streamline of the flow passing through the cavity and store at the time $t=0.80\text{s}$, when the store has already left the cavity. Fig. 8(a) shows that the store already has a large nose up pitch angle, and the flow has a strong impact on the lower surface of store, the store generates a nose up moment of force and accelerates the process of raising its head. Fig. 8(b) shows that the store has a little nose down pitch angel. The leading edge spoiler generates a downwash shock wave and the shock wave strike on the store, the store generates a nose down moment of force.
3.3. Effects of leading edge spoiler with different parameters

The leading edge spoiler has a positive effect on the store trajectory separated from cavity, and makes store generate a nose down moment of force and effectively improves the separation characteristics. However, the effects of leading edge spoiler with different parameters on the store separated from the cavity is still unknown, so as shown in Fig. 2(b), a series of leading spoilers with different height, different distance of gas and different angle between spoiler and cavity are taken into numerical simulation to investigate the effects of leading edge spoiler with different parameters.

![Figure 9. Separation characteristics of different-height spoiler.](image)

In order to facilitate clear the effects of the height of leading edge spoiler on store separation, we compare the store trajectory separated from cavity with leading edge spoiler flow control and without flow control (clean cavity), the thickness of boundary layer (δ) at the front of clean cavity is 60mm, and e=0.5δ, e=δ, e=1.6δ and e=2.5δ are taken into consideration. It can be seen that the height of leading edge spoiler has a large effect on the pitch angel of store, when e=0 (clean cavity), the store has a large nose up pitch angel during separation, when the height of leading edge spoiler is small, the store has a little nose up pitch angel during separation, and with the increasing of the height, the spoiler has larger effect on the attitude control of store, the store has a larger nose down trend.

![Figure 10. Separation characteristics of spoilers with different angle](image)

![Figure 11. Separation characteristics of spoilers with different gas](image)
The angle of leading edge spoiler and cavity is also an important parameter, Fig. 10 shows the separation characteristics of spoilers with different angle, it can be seen that with the increasing of angel between leading edge spoiler and cavity, the spoiler has larger effect on the attitude control of store. There always a gap between the leading edge spoiler and cavity in practical engineering application, and a series of different gaps are take into numerical simulation. Fig.11 shows the separation characteristics of spoilers with different gas, it can be seen that the smaller gas makes larger effect on the attitude control of store.

4. Conclusion
Unsteady flow simulation of store separation from the cavity of flying-wing standard model is conducted by using a three-dimensional compressible flow solver based on dynamic overset grid. It is shown that the leading edge spoiler plays an important role in store separation from cavity:

(1) The leading edge spoiler lifts the shear layer and reduces the flux into the cavity, which significantly changes the pressure distribution inside and outside the cavity and makes the store generate nose down moment of force during separation.

(2) The leading edge spoiler generates a downwash shock wave at the front of cavity, which have an impact on the store outside the cavity, accelerating the process of store separation.

(3) The height of leading edge spoiler, the angel of cavity and spoiler, and the gas between spoiler and cavity also have great effects on store separation from cavity. Higher height, larger angle and smaller gas have larger effects on the attitude control of store during store separation.

The leading edge spoiler greatly improves the separation characteristics of store separated from cavity, and more works will be carried out about the active flow control and other passive flow control method of store separation.

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References
[1] C. Coley, A. Lofthouse, Correlation of Weapon Bay Resonance and Store Unsteady Force and Moment Loading, 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 2012.
[2] K. Lee, B. H., Effect of Captive Stores on Internal Weapons Bay Floor Pressure Distributions, Journal of Aircraft, 47(2):732-736, 2010.
[3] G. N. Barakos, S. J. Lawson, R. Steijl et al, Assessment of Flow Control Devices for Transonic Cavity Flows Using DES and LES, Solid Mechanics & Its Applications, 14:77-87, 2008.
[4] S. J. Lawson, G. N. Barakos, Assessment of Passive Flow Control for Transonic Cavity Flow Using Detached-Eddy Simulation, Journal of Aircraft, 46(3):1009-1029, 2009.
[5] C. Lada, K. Kontis, Microjet Flow Control Effectiveness of Cavity Configurations at Low Speeds, Journal of Aircraft, 51(5):1391-1400, 2014.
[6] C. Lada, K. Kontis, Experimental Studies on Transitional and Closed Cavity Configurations Including Flow Control, Journal of Aircraft, 47(2):723-729, 2010.
[7] P. C. Cui, Y. Q. Deng, J. Tang, Adjoint-based grid adaptation and error correction, Acta Aeronautica et Astronautica Sinica, 37(10): 2992-3002, 2016.
[8] P. C. Cui, J. Tang, B. Li, A conservative interpolation method for overset mesh via supermesh, Acta Aeronautica et Astronautica Sinica, 39(3): 121569, 2018.
[9] D. Levy, K. Laflin, E. Tinoco, Summary of data from the fifth AIAA CFD drag prediction workshop, 51st AIAA Aerospace Sciences Meeting, DLR, 2013.
[10] P. L. Roe, Approximate Riemann Solvers, Parameter Vectors, and Difference Schemes, Journal of Computational Physics, 135(2):250-258, 1997.
[11] V. Venkatakrishnan, On the Accuracy of Limiters and Convergence to Steady State Solutions, 31st Aerospace Sciences Meeting & Exhibit, Reno, USA, 1993.
[12] M. J. Brazell, J. Sitaraman, D. J. Mavriplis, An overset mesh approach for 3D mixed element high-order discretizations, Journal of Computational Physics, 322:33-51, 2016.

[13] S. Völkner, J. Brunswig, T. Rung, Analysis of non-conservative interpolation techniques in overset grid finite-volume methods, Computers & Fluids, 148:39-55, 2017.

[14] J. Cai, H. M. Tsai, F. Liu, An Overset Grid Solver for Viscous Computations with Multigrid and Parallel Computing, AIAA Computational Fluid Dynamics Conference, 2013.

[15] J. Bonet, J. Peraire, An alternating digital tree (ADT) algorithm for 3D geometric searching and intersection problems, International Journal for Numerical Methods in Engineering, 31(1):1-17, 1991.

[16] Y. B. Zhang, N. C. Zhou, J. T. Chen, Numerical investigation of Reynolds number effects on a low-aspect-ratio flying-wing model, Acta Aerodynamica Sinica, 33(3): 279-288, 2015.

[17] L. Temmerman, B. Tartinville, C. Hirsch. URANS Investigation of the Transonic M219 Cavity, Progress in Hybrid RANS-LES Modelling, 2012.

[18] E. R. Heim, CFD Wing/Pylon/Finned Store mutual interference wind tunnel experiment: AEDC-TSR-91-P4, New York: AEDC, 1991.