DOI:10.13434/j.cnki.1007-4546.2021.0202

Impact Analysis of Fluid-structure Coupling Embedded Weapon Bay

FENG Ruoqi, CHEN Xuemei, PU Keqiang, XIONG Qinlin

(AVIC Chengdu Aircraft Industrial(GROUP) Co., Ltd., Chengdu 610092, China)

Abstract: The coupling behavior of the imbedded weapon store occurring between the local unsteady flow field round the store and the structure response on the processing of opening its bay-door is simulated by using numerical method based on computational fluid mechanics (CFD). The transient aerodynamic behaviors when opening door under various flight altitudes and the corresponding structure deformation evolution in the unsteady flow fields are analyzed respectively and presented. The rules of aircraft attitude parameters' impacting to the responses of structure and the bay-door's opening process are obtained by comparing with the analysis results. These rules can be applied to the structure design of bay-door and route specification of missile when disengaged and launched from within store.

Keywords: embedded weapon store; CFD numerical simulation; unsteady air flow and structure coupling; aerodynamic characteristics analysis; structure behavior analysis

1 Introduction

The imbedded weapon store configuration is widely applied in the combat aircrafts of new generation in order to obtain high maneuverability, super-sound cruise and low detectability. Owning

Received February 15, 2021

to smoother exterior profile by removing external store for missiles, this kind of the configuration can achieve better aero-dynamic performances and reduce drag. The smoother profile also reduces RCS, and thus obtain the high capability of defense-penetration on field[1-5].

The opening of store′s bay-door, and missile′s disengaging with structure attachments when launching will cause the variation of flow at interior of store and exterior space round it. This variation will change the aerodynamic load acting on structure and trigger its deformation response. The coupling of the unsteady flow field and structure deformation furtherly impacts flow field characteristics and structure behavior, and thus affect the flight performance of aircraft, even the flight safety. The structure response of weapon store and local variation of flow field also impact the track and attitude at the moment when disengaging missile, and thus impact its launching. Obviously, the research of aerodynamic characteristics and structure response behaviors, and application the research results to the design of imbedded weapon store is very important to guarantee the structure integral and non-clashing between the aircraft and the missile body. The understanding of unsteady complex flow field is also very important to the design of bay-door, store configuration and structure, bay-door open/close actuation system, joining between store structure and missile to ensure its steady movement, normal track, ejection and launch[6-9].

The numerical simulation method by considering the coupling of unsteady flow and structure is used to analyze the flow field characteristics and bay-door structure response, and then obtain the impact rule of various flight attitude′s to the door structure behavior when opening bay-door.

2 Numerical simulation method

The 3-D Reynolds Mean N-S governing equations with Dimensional One is as follows[10]:

$$\frac{\partial \boldsymbol{Q}}{\partial t} + \frac{\partial(F_i + F_v)}{\partial x} + \frac{\partial(G_i + G_v)}{\partial y} + \frac{\partial(H_i + H_v)}{\partial z} = 0 \tag{1}$$

Where: $\boldsymbol{Q} = [\rho, \rho u, \rho v, \rho w, \rho E]^{\mathrm{T}}$ is the conservation variables vector; F_i、G_i、H_i are the flux variables vector with non-viscosity; F_v、G_v、H_v are the flux variables vector with viscosity.

By using finite volume method, the second order central difference and Roe-FDS second order upwind scheme are respectively utilized to develop the meshes of viscous and non-viscous terms. The Runge-Kutta explicit method is used to carry time steps forward.

3 Bay-door structure and flow field modeling

3.1 Structure configuration

The monolithic box-section structure is used in the bay-door of store, as shown in Figure 1. The lateral beams are made of 7075 Alloy; The skins and stiffeners are made of co-curing Carbon fiber composites. The power to open/close the bay-door is provided by actuation system which drives the rotation of bay-door along its hinge joints.

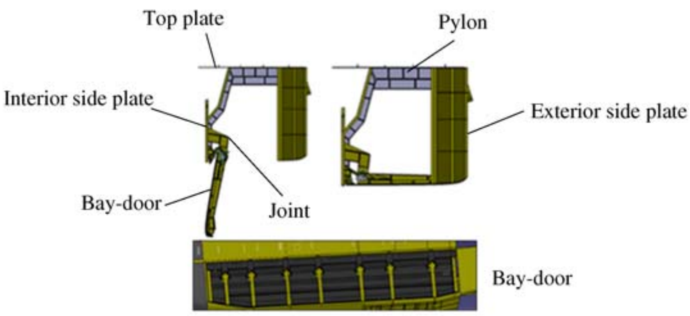


Figure 1 Structure of weapon store and bay-doors

3.2 Structure and flow field meshing

The non-structural mixing meshing is used. The boundary layer zone of solid surfaces is discretized with triangular prism grids, filling the space close to the boundary layer with tetrahedron meshes, bridging transition area with pyramid meshes, as shown in Figure 2. The configuration with right bay-door closed, left door being driven to open toward aircraft symmetry plane is supposed when simulating; hence, denser meshing applied on the movement envelop space of left bay-door, with more than 2.2 million meshes placed here. The structure is modeled with tetrahedron meshes.

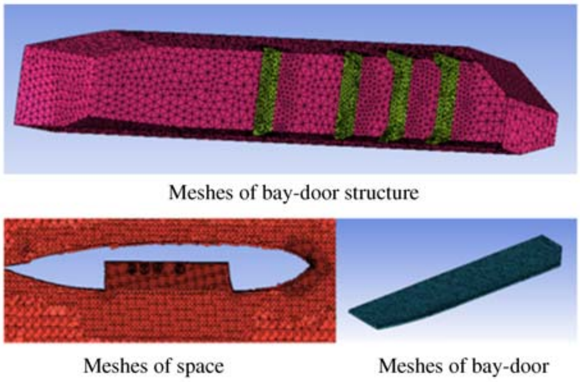


Figure 2 Meshes of bay-door structure and flow field on its symmetry plane

4 Simulation coupling characteristics between structure of bay-door and flow field

4.1 Bay-door structure configuration and material

Table 1 shows the material used in Bay-door structure.

Table 1 Material performances of material on bay-door

Material	Parameter	Value
	0 Compression Module/MPa	110 000
	0 Tension Module/MPa	120 000
	90° Compression Module/MPa	7 800
T700	90° Tension Module/MPa	8 700
	In-Plane Shear Module/MPa	4 000
	Poisson Ratio	0.32
	Density/(kg · mm^{-3})	1.7×10^{-6}
	Elastic Module	70 000
7050	Poisson Ratio	0.33
	Density/(kg · mm^{-3})	2.82×10^{-6}

4.2 Boundary conditions

The mechanism simulation same to actual bay-door rotation shaft and movement actuation is applied, with seven pin points placed in the interior of store on their movement planes, as shown in Figure 3. The "JOINT" is used to constrain the upper hinge joints, with anti-torsion coefficient 5 200 NM/° applied.

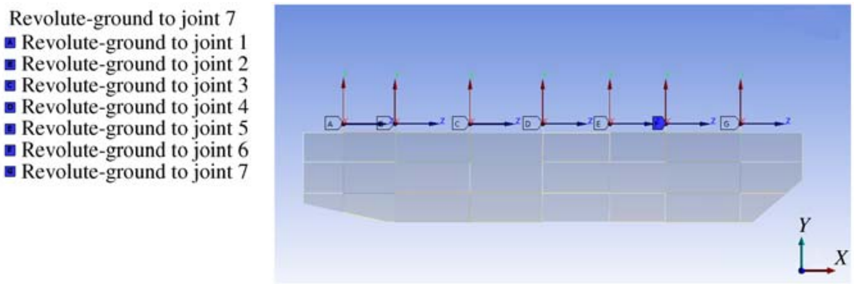


Figure 3 Joint on top of bay-door

4.3 Simulation of flow-structure coupling of door-bay

In the different conditions of side slip angles $\beta(0, 5°, -5°)$ taken respectively, the coupling between the unsteady flow round weapon store and its door structure is analyzed with numerical simulation. The cases are assumed as opening left bay-door toward aircraft symmetry plane at rotation rate 0.58 rad/s in time 3 s. In this paper, the displacement along the direction of closing bay-door is indicated as plus, along the direction of opening bay-door is indicated as minus.

Case 1 $M/\alpha/\beta/h = 0.8/3°/0/6$ km

Case 2 $M/\alpha/\beta/h = 0.8/3°/5°/6$ km

Case 3 $M/\alpha/\beta/h = 0.8/3°/-5°/6$ km

Where: M is the Mach number; α is the attack angle; β is the flight side slip angle; h is the altitude.

The simulation of the coupling unsteady flow with and structure when opening the bay-door gives the distribution plot of Mach numbers at the center line of store at three different side slip attitudes and different open locations of the bay-door. Figure 4 to Figure 6 show conditions Case 1 to

Case 3 respectively. As seen from Figures 6, the noteworthy variations of local Mach numbers occur at door surfaces and interior of store when door opens at the different locations in the conditions of different flight side slip angles.

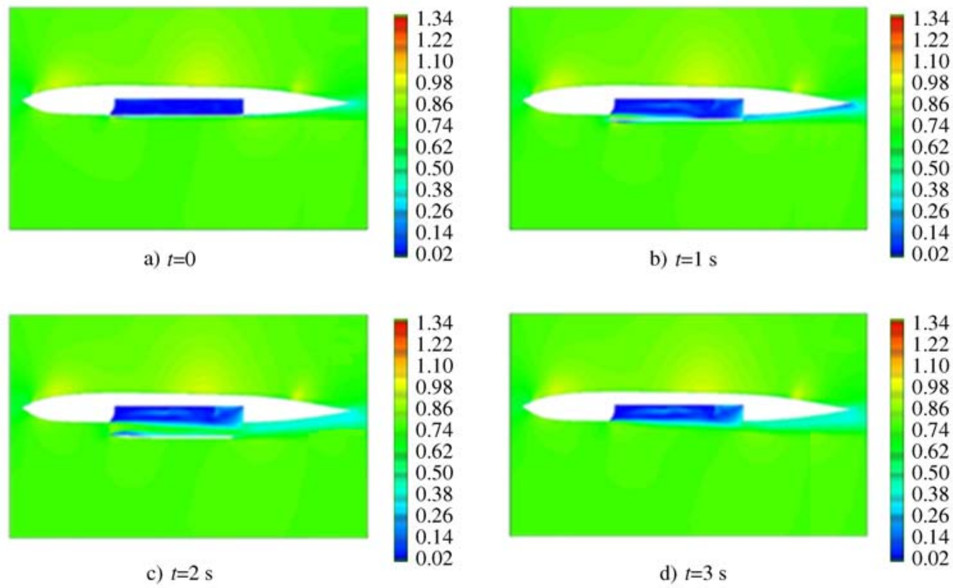


Figure 4 Mach number distribution at center line of store, Case 1 $M/\alpha/\beta/h = 0.8/3°/0/6$ km

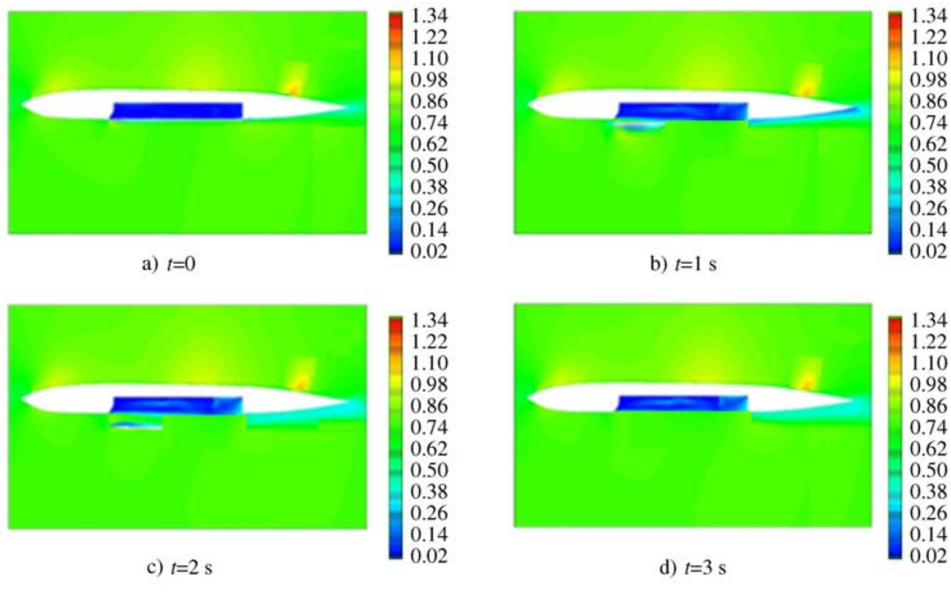


Figure 5 Mach number distribution at center line of store, Case 2 $M/\alpha/\beta/h = 0.8/3°/5°/6$ km

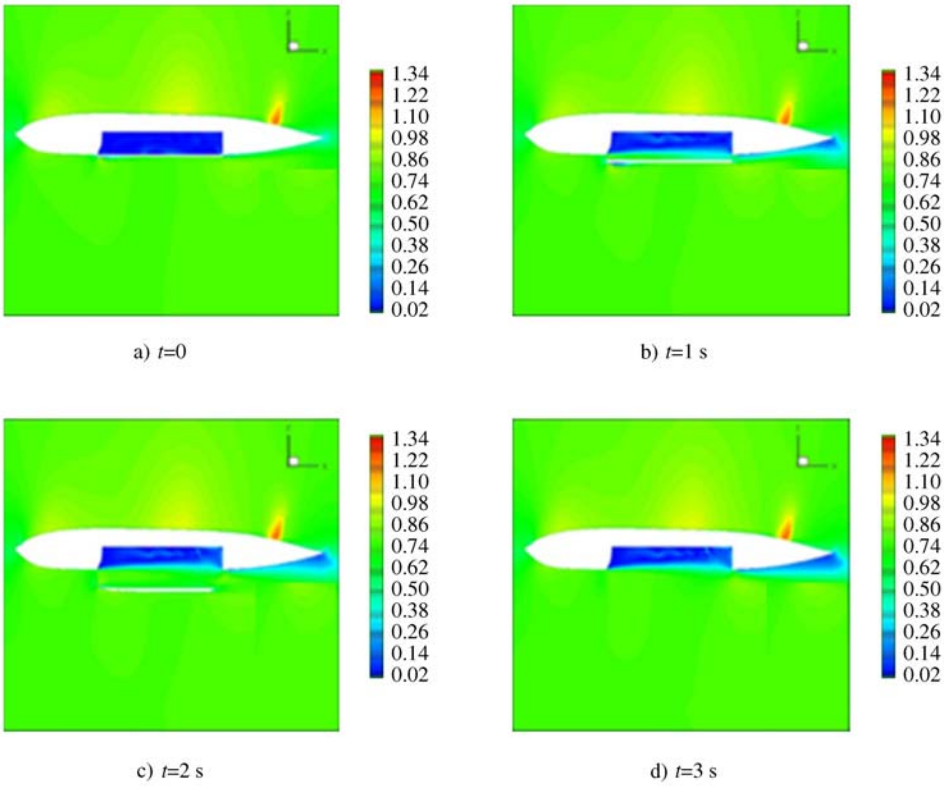


Figure 6 Mach number distribution at center line of store, Case 3 $M/\alpha/\beta/h=0.8/3°/-5°/6$ km

As seen from Figure 4 to Figure 6, with the increasing of door's open-angle, with the condition of weapon store altered from isolation to connection to exterior air flow, the air pressure of the interior space in store will change from the uniform distribution to the non-uniform: pressure raised at the rear section and decreased at the middle area.

The aero-dynamic moment to drive door open as plus and to drive door close as minus are supposed; the values of the aero-dynamic moment acted on bay-door at various side slip angles $\beta(0, 5°, -5°)$ are compared.

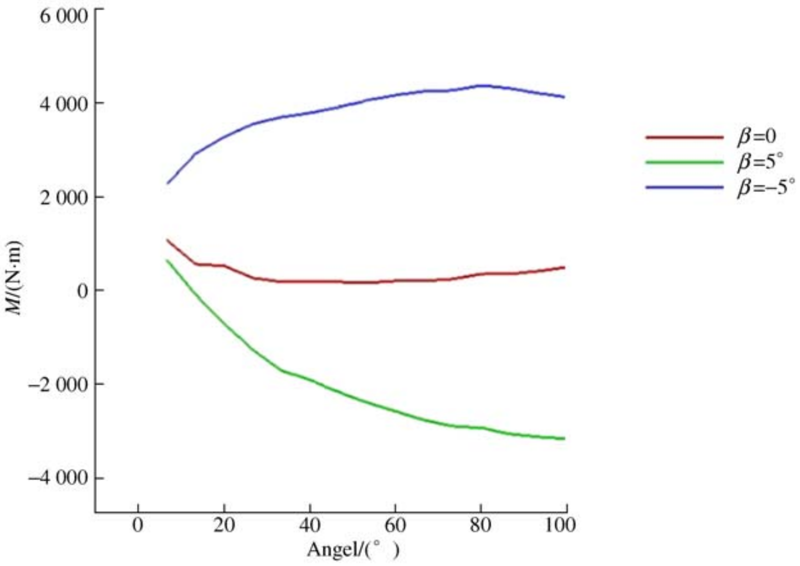


Figure 7 Aero-dynamic moments acting on door-bay versus open-angles of bay-door

As presented in this figure:

1) For $\beta=0$, the initial and subsequent aero-dynamic moment is always not less than 0 as bay-door opening, with its value being in [0,1 000] N · m. In this opening process, the air pressure variation in interior and exterior of store is small because the flight altitude gives the small impact to the air slow.

2) For $\beta=5°$, when air flowing toward right side of vehicle, the initial aero-dynamic moment is plus, namely to push the bay-door open. With left bay-door opening toward aircraft symmetry plane, this moment will change from plus to minus and its absolute value will increase quite largely. The aero-dynamic moment restrains the opening movement of bay-door, it varies at [700,−3 200] N · m, range 4 000 N · m approximate.

3) For $\beta=-5°$, when air flowing toward left side of vehicle, the initial aero-dynamic moment is plus, namely to push the bay-door open. With left bay-door opening toward the aircraft symmetry plane, this moment will increase further. The aero-dynamic moment drives the open of bay-door. The aero-dynamic moment varies at [2 000,4 500] N · m, with span about 2 500 N · m.

It can be seen that the side slip angle β greatly impacts the aero-dynamic moment acting on bay-door, even alters the direction of it. The driving moments provided by bay-door actuation system have to resist aero-dynamic moments varying in the range of [−3 200,4 500] N·m.

4.4 Structure behavior simulation of bay-door

Based on the simulation results of flow field at the side slip angles $\beta(0, 5°, -5°)$ respectively, the structural responses of the bay-door are simulated and analyzed, with the points given below.

4.4.1 Case 1 $M/\alpha/\beta/h = 0.8/3°/0/6$ km

The plot showing maximum deformation versus open-angle of bay-door is shown in Figure 8. The maximum displacement, 4.1 mm, occurs at $t=0$. At this moment, the aero-dynamic resultant force is to push bay-door open. Hereafter, the air pressure difference acted on door surfaces diminishes rapidly with the mixture of air flow external and interior store, which reduces the deformation of bay-door rapidly. The maximum deformation will be less than 1mm when open angle is greater than 20°.

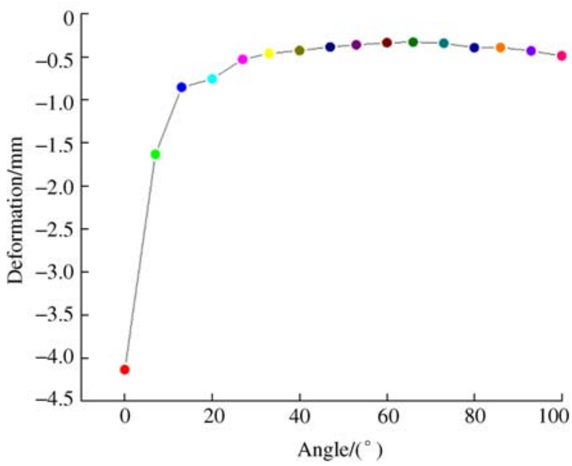


Figure 8 Maximum displacement versus open-angle in case 1

The color fringe plot of the door's deformation at $\beta=0$ is presented in Figure 9. It can be seen that the maximum deformation of door always occurs at the rear domain far away from hinge line, with the maximum displacement less than 1mm when bay-door opened at the final position. In the whole process, the skin deformation near to hinge line is always less than 1 mm.

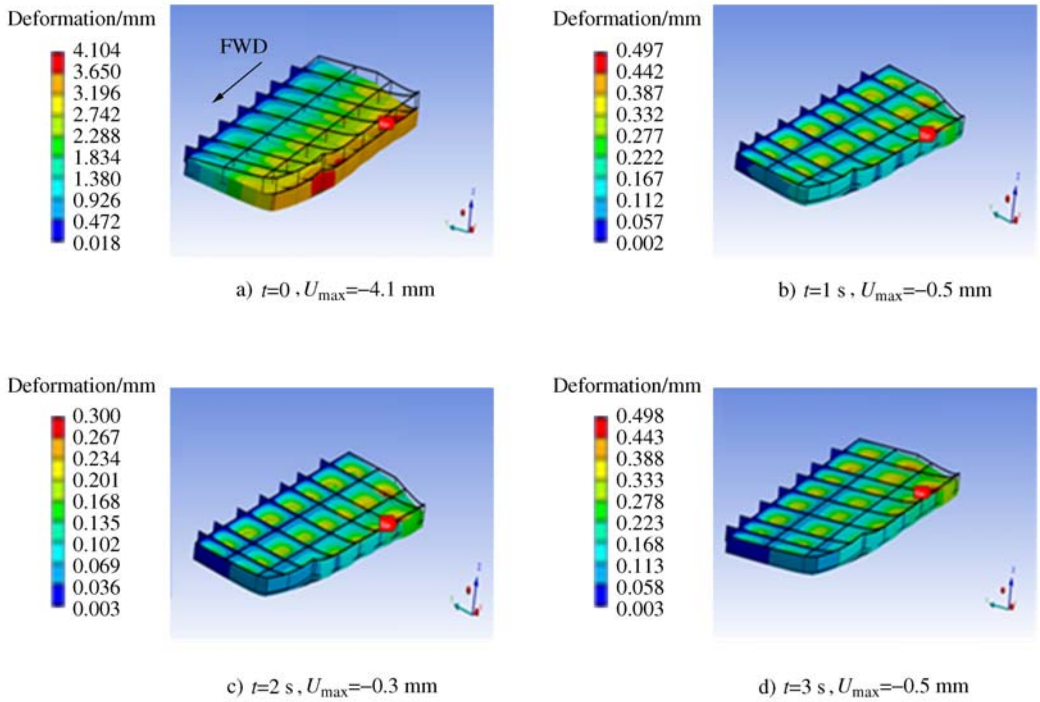


Figure 9 Deformation plot at different moments in case 1

4.4.2 Case1 $M/\alpha/\beta/h=0.8/3°/5°/6$ km

For $\beta=5°$, air flows toward right side of vehicle. With opening left bay-door toward the symmetry plane of aircraft, the air-flow acting onto the bay-door will change from pushing door open to restraining its opening movement. The reversion of the aero-dynamic forces will impact the displacement direction of door.

The maximum deformation plot obtained by simulating the process of opening door is presented in Figure 10. It shows in the whole process that the maximum deformation is 3.9 mm occurring at $t=0$. With the open-angle increasing of the door, the maximum displacement will reduce to zero and then reversely enlarge to 3.4 mm, with door deformed from expanding the bay to closing the bay.

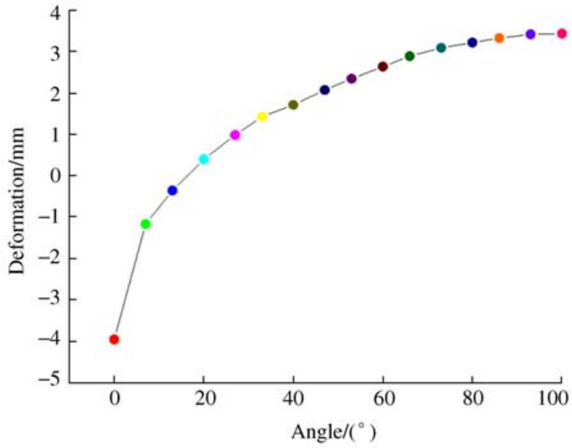


Figure 10 Maximum displacement graph of bay-door in case 2

The deformation patterns of the door at different moments are presented in Figure 11.

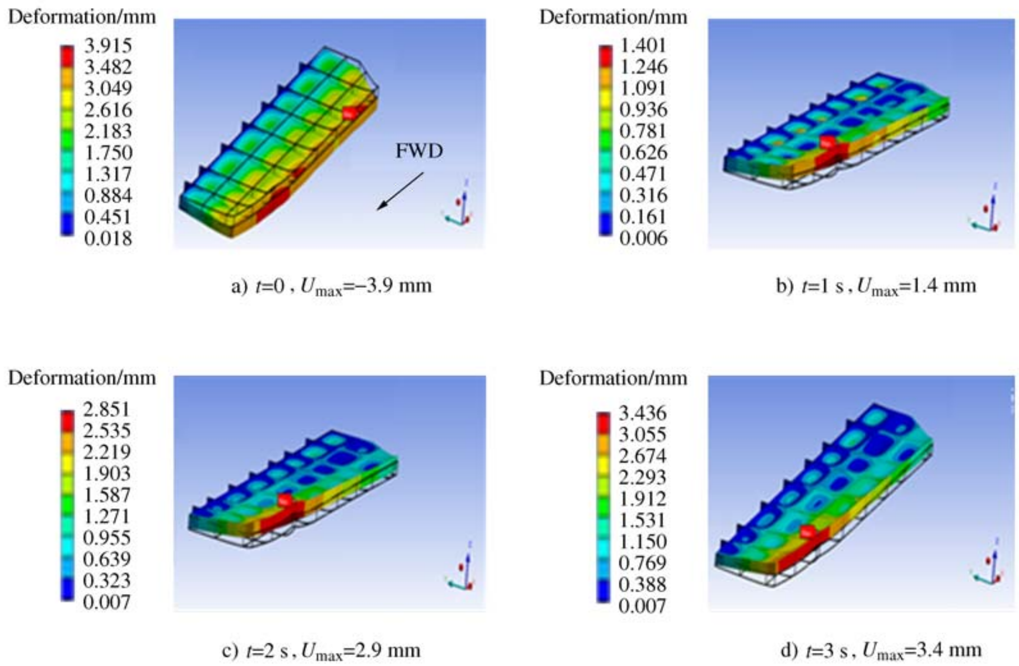


Figure 11 The deformation graph of bay-door at different moments in case 2

It can be seen, at $t = 0$, the resultant force of aero-dynamic pressure is driving the bay-door open, with the maximum deformation occurs at the rear area of the bay-door away from the hinge line. When opening to some certain angle, along with the entrance of air flow, the high-pressure domain will be stabilized gradually. And then, with the side slip angle 5°, due to the washing of coming stream, combined with the structure characteristics of door, the area of the largest deformation in door will move from the rear end to the front end. At rotation angle 20°, the trail edge of bay-door will be bent outwardly altered to deform inwardly, with the maximum deformation area maintained at the front end far away from hinge line.

4.4.3 Case1 $M/\alpha/\beta/h = 0.8/3°/-5°/6$ km

The maximum displacement on the opening of bay-door, for the side slip angle $\beta = -5°$ with coming air flow toward the left side of vehicle, is shown in Figure 12. The maximum value of displacement on the whole processes is 4.2 mm, occurring at $t = 2.4$ s and rotary angle −80°, with door's bending direction same as the opening direction of the door.

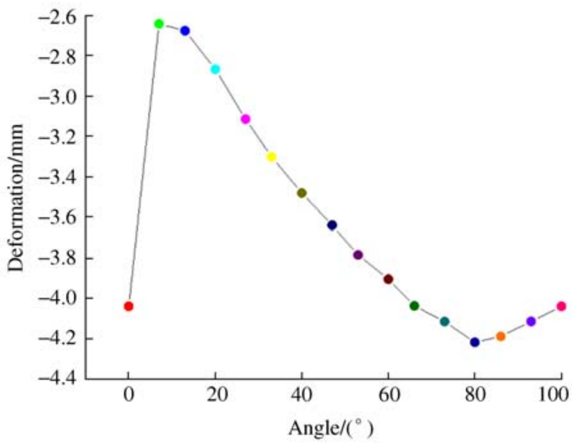
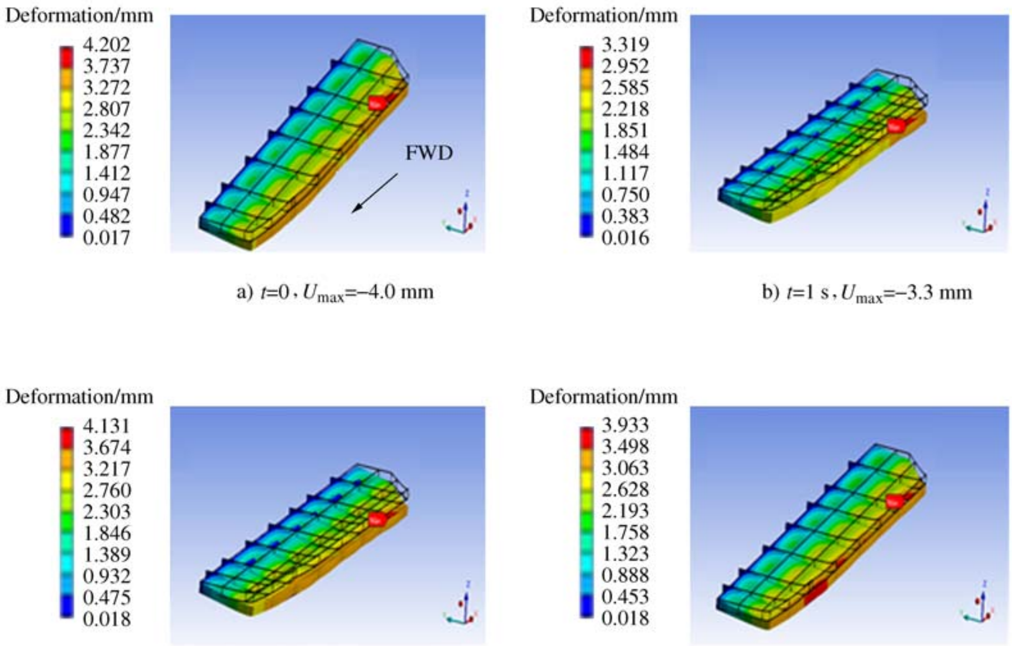


Figure 12 Maximum displacements of bay-door structure in case 3

The maximum displacement, 4.0 mm, occurs at $t = 0$, directing outwardly. As opening left bay-door toward the symmetry plane of aircraft, the deformation of door structure will decrease due to decreasing of air-pressure difference from the interior to exterior. When bay-door opened to 10°, the air-pressure difference of interior and exterior reaches the minimum; At this moment, the maximum displacement of door arrives at 2.6 mm, bent outwardly. However, with the opening of bay-door further, the air-pressure acting on the interior surface of bay-door will increase, which will drive bay-door open movement, and the maximum deformation value will increase as the increasing of aero-dynamic moment.

The fringe plots in Figure 13 present the deformation distribution on bay-door. At $t = 0$, the maximum displacement occurs at the rear domain far away from the hinge line of door. When opening to some certain angle, along with the entrance of the air flow, the high-pressure domain will be stabilized gradually. In this whole process, due to the washing of coming stream caused by the side slip angle $-5°$, bay-door always bends toward opening direction of the door, and the maximum deformation always occurs at the rear area and far away from hinge joints.



a) t=0, U_{max}=−4.0 mm b) t=1 s, U_{max}=−3.3 mm

c) t=2 s, U_{max}=−4.1 mm d) t=3 s, U_{max}=−4.0 mm

Figure 13 Deformation color-coded fringe plot at different moment in case 3

4.5 Analysis to bay-door reformation versus flight attitude

Maximum displacements to different side slip attitudes are shown in Figure 14.

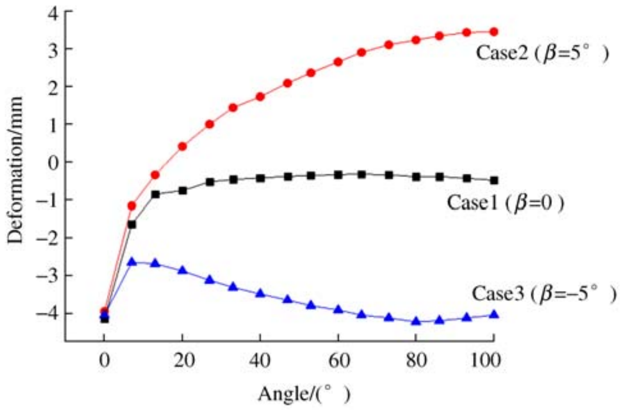


Figure 14 Graph of maximum deformation versus side slip angle

It can be seen from the figure that:

1) At $t = 0$, with bay-door at close condition, whether there is side slip angle or not, the maximum displacement on the door structure generated by the air-pressure difference between the interior and exterior of store is about 4 mm, and the aero-dynamic moment is to push bay-door open.

2) At $\beta = 0$, the air-pressure difference between the interior and exterior of store will decrease rapidly with the opening of bay-door, and after that the variation range will become small, which makes the deformation small and steady on opening bay-door. The maximum displacement always occurs at the rear half area away from the door's hinge line.

3) At $\beta = 5°$, the air-pressure difference between interior and exterior of store will decrease rapidly with the opening of bay-door, and after that, until to some certain degree, the flow field retrains the open movement of the bay-door; its bending will alter from the direction of pushing door open to the direction of moving door close. The maximum deformation will move from the area of rear end toward the front end of door.

4) At $\beta=5°$, the air-pressure difference between interior and exterior will decrease with the opening of the bay-door. In this side slip attitude, the interior of store will become windward with the opening of the door, and the air-pressure in it will increase again. The air flow will push the bay-door open further. In the whole process, the variation range of maximum displacement is the smallest of all three cases including $\beta=0$ and $5°$; the area of maximum deformation is always at the door's rear end away from hinge line.

5 Conclusions

With numerical simulation method by considering the coupling the unsteady flow with the structure, the air-dynamic characteristic of flow field, the pressure distribution and door structure deformation on the process of opening the bay-door at different flight altitudes are analyzed. The rules obtained about the bay-door structure behavior and flight altitudes' impacting to bay-door's opening process can be applied as the input to the design of store configuration, its door's structure, actuation and mount system, can be used to specify the projectile route of weapons to launch from embedded store.

For the bay-door of weapon store, supported by and driven on rotation hinge and cantilever beams, the condition $\beta \leqslant 0$ facilities the steady open/close of bay-door, and the protection of structure integrality. In this condition, at the area far away from the hinge line, the deformation varies in a small range; this provides safer precondition to the weapon projectile and mount of weapons than β greater than zero.

References

[1] YAN P P. Study on aerodynamic characteristics and store safety separation for internal weapon bay[D]. Beijing Jiaotong University, 2018 (in Chinese)

[2] WR J F, WU L W, FAN Z L, et al. Investigation on aerodynamic characteristics of internal bay's door[J]. Acta Aerodynamica Sinica, 2012, 30(6): 744-748 (in Chinese)

[3] WR J F, WU L W, FAN Z L, et al. Investigation on dynamic simulation technology of internal weapons bay's doors opening and closing[J]. Journal of Experiments in Fluid Mechanics, 2015, 29(4): 88-94 (in Chinese)

[4] YANG D G, FAN Z L, LI J Q, et al. Studies on flow characteristics of cavity by numerical simulation and wind tunnel test[J]. Acta Aerodynamica Sinica, 2009, 27(3): 378-383 (in Chinese)

[5] WU J F, LUO X F, XU L W, et al. Investigation on internal weapon separation characteristics and flow control methods[J]. Acta Aerodynamica Sinica, 2014, 32(6): 814-819 (in Chinese)

[6] FENG B M, NIE W S, CHE X K, et al. Effect of fixing angle to separation characteristics of internal store[J]. Acta Aerodynamica Sinica, 2010, 28(6): 672-675 (in Chinese)

[7] ZHANG P H, WANG M, DENG Y Q, et al. Numerical simulation of store separation and door operation[J]. Acta Aerodynamica Sinica, 2013, 31(3): 277-293 (in Chinese)

[8] FENG B M, NIE W S, CHE X K, et al. Simulation of the store separation from a cavity at supersonic speed[J]. Aircraft Design, 2009, 29(4): 1-5 (in Chinese)

[9] SHI A M, YE ZY, YANG Y N. Calculation and analysis for aerodynamic loads acting on interior weapon cabin's door[J]. Aeronautical Computing Technique, 2007, 37(3): 5-6 (in Chinese)

[10] WANYAN Z H, LIU J J, YANG L, et al. Static aeroelastic analysis of air-launched rocket using fluid-structure interaction method[J]. Computer Simulation, 2019,36(11):27-30,63 (in Chinese)

Brief Biographies

FENG Ruoqi is an engineer working in AVIC Chengdu Aircraft Industrial(GROUP) Co., Ltd.. Her research interest is in aircraft design and manufacture engineering. 247857189@qq.com

CHEN Xuemei is an engineer working in AVIC Chengdu Aircraft Industrial(GROUP) Co., Ltd.. Her research interest is in aircraft design and manufacture engineering.

PU Keqiang is an engineer working in AVIC Chengdu Aircraft Industrial(GROUP) Co., Ltd.. His research interest is in aircraft design and manufacture engineering.

XIONG Qinlin is an engineer working in AVIC Chengdu Aircraft Industrial(GROUP) Co., Ltd.. His research interest is in aircraft design and manufacture engineering.