The interference aerodynamics caused by the wing elasticity during store separation

Yang Lei, Ye Zheng-yin

*National Key Laboratory on Aerodynamic Design and Research, School of Aeronautics,
Northwestern Polytechnical University, Xi'an 710072, P.R.China*

Abstract: Air-launch-to-orbit is the technology that has stores carried aloft and launched the store from the plane to the orbit. The separation between the aircraft and store is one of the most important and difficult phases in Air-launch-to-orbit technology. There exists strong aerodynamic interference between the aircraft and the store in store separation. When the aspect ratio of the aircraft is large, the elastic deformations of the wing must be considered. The main purpose of this article is to study the influence of the interference aerodynamics caused by the elastic deformations of the wing to the unsteady aerodynamics of the store. By solving the coupled functions of unsteady Navier-Stokes equations, six degrees of freedom dynamic equations and structural dynamic equations simultaneously, the store separation with the elastic deformation of the aircraft considered is simulated numerically. And the interactive aerodynamic forces are analyzed. The study shows that the interference aerodynamics is obvious at earlier time during the separation, and the dominant frequency of the elastic wing determines the aerodynamic forces frequencies of the store. Because of the effect of the interference aerodynamics, the roll angle response and pitch angle response increase. When the store is mounted under the wingtip, the additional aerodynamics caused by the wingtip vortex is obvious, which accelerate the divergence of the lateral force and the lateral-directional attitude angle of the store. This study supports some beneficial conclusions to the engineering application of the air-launch-to-orbit.

Keywords: Store separation; interference aerodynamics; elastic deformation; dynamic response; air-launch-to-orbit

I. Introduction

Air-launch-to-orbit is the technology that has stores carried aloft and launched the store from the plane to the orbit. Air-launch-to-orbit is economic and flexible. In the process of launching, the kinetic and potential energy of the plane are transferred to the store so that the initial velocity and height of the store are high. Besides, the launch platform can be reused, which could reduce the launch cost effectively ^[1-2]. Without the restriction of the launch site and launch window, air-launch-to-orbit can be taken place at everywhere and anytime. The air-launch-to-orbit technology, which provides new insights into space activities, can be used to launch space booster, space ship, satellite and space shuttle, etc, and has been attached great importance by more and more researchers.

The separation between the plane and store is one of the most important and difficult phases in Air-launch-to-orbit technology. The motion locus and attitude angles of the store should be under control strictly to insure the successful launching. However, during the separation, the unsteady

interaction aerodynamics between the plane and store are complicated, which will have effect on the dynamics responses of the store. When the aspect ratio of the plane is large, the elastic deformation of the plane should be considered, and the aerodynamics interference caused by the elastic deformations may have great influence on the unsteady aerodynamics of the store. Nowadays, a great deal of work has been taken in the dynamic responses prediction of the store separation, among which flight test^[3-5], wind tunnel experiment^[6] or numerical simulation methods^[7-13] are used. The flight test and wind tunnel experiment, which can model the store separation accurately, would take a long time and high cost. Therefore, many codes and numerical methods are developed. With the automated Chimera methodology or remeshing methodology, the multiple moving body problems that involve store separation are simulated^[7-11]. To improve the simulation efficiency, the parallel computing technology is widely employed^[12-13]. Most numerical investigations mentioned above have ignored the effect of the elastic deformation of the plane. M.T. Kozak, et al, have studied the effects of the plane elastic deformation on the store with simplified aerodynamics models^[14], which have lots of assumptions and limitations, thus cannot be employed for accurate simulations of these complex store separation problems.

The main purpose of this paper is to study the influence of the interference aerodynamics caused by the elastic deformations of the wing to the unsteady aerodynamics of the store. With the code developed by our research group, the store separation with the elastic deformation of the aircraft considered is simulated. Based on the frame of unstructured hybrid mesh and the method of dynamic chimera mesh and mesh deformation, the unsteady Navier-Stokes equations coupled with six degrees of freedom dynamic equations and structural dynamic equations are solved simultaneously. Besides, the structural dynamic equations based on modal method are considered to improve the computational efficiency. According to the simulation results, the dynamic responses of the store and the interference aerodynamics caused by the elastic wing are investigated.

II. Simulation method

By using the code developed by our research group, the coupled functions of Navier-Stokes equations, six degrees of freedom dynamic equations and structural dynamic equations are solved, and the store separation with the elastic deformation of the wing considered is simulated.

For different mechanic problems, several coordinate systems and the coordinate transformations should be considered. According to the flight dynamics, the origin of the body-fixed coordinate is located at the mass center of the aircraft. The positive x_b -axis is parallel to the fuselage axis of the aircraft and pointing forward. The positive z_b -axis is always pointing down. The positive y -axis is normal to the x_b - O - z_b plane and points to its right. In this paper, the earth-fixed coordinate is the same as it is defined in CFD. The origin of earth-fixed coordinate is located at the mass center of the aircraft in the initial time, which does not move with the aircraft. If the earth-fixed coordinate $Ox_gy_gz_g$ rotates ψ with z_g -axis, then spins θ around y' -axis, finally it rotates ϕ degree with x_b -axis, we can see that $Ox_gy_gz_g$ is overlapped with body-fixed coordinate $Ox_by_bz_b$.

The hybrid unstructured grid is used for spatial discretization, which is flexible to handle the geometrically complex models^[15]. The grids near the wall are prism cells and the others are

tetrahedral cells. The dynamic chimera mesh technique is adopted to treat the large rigid-body displacement. The combination of neighbor-to-neighbor algorithm and alternating digital tree method is employed to search for contribution cell, and an efficient algorithm proposed by Nakahashi is used to treat hybrid unstructured overset grids. In this paper, the mesh deformation method is used to deal with the elastic deformation. And the weighted distance method is employed to distribute the displacements of surfaces. More details are given in Reference [15-16].

In order to solve different dynamic problems flexibly, the framework of the solver code is modular design, which is divided into several parts, such as Navier-Stokes equations solver (CFD module), six degrees of freedom dynamic equations solver (RBD module) and structural dynamic equations solver (CSD module). By calling different solver modules, the corresponding coupled equations are initiated in time-domain.

CFD module

The CFD module is used to calculate the aerodynamic forces of the aircraft. The governing equations are unsteady, three dimensional Navier-Stokes equations, and are described by the Arbitrary Lagrangian–Eulerian (ALE) method [15-16]. The conservation form of Navier-Stokes equations written in earth-fixed rectangular coordinate system is as follows:

$$\frac{\partial}{\partial t} \iiint_{\Omega} \mathbf{Q} dV + \iint_{\partial\Omega} \mathbf{F}(\mathbf{Q}, \mathbf{V}_{grid}) \cdot \mathbf{n} dS = \iint_{\partial\Omega} \mathbf{F}^V(\mathbf{Q}) \cdot \mathbf{n} dS \quad (1)$$

Where $\mathbf{Q}$ is the vector of conservative variable, $\mathbf{V}_{grid}$ is the velocity vector of the control volume, $\mathbf{F}(\mathbf{Q}, \mathbf{V}_{grid})$ is inviscid flux vector, $\mathbf{F}^V(\mathbf{Q})$ is the viscous flux vector, Ω means the control volume, $\partial\Omega$ means the boundary of the control volume, $\mathbf{n}$ is the normal vector of the boundary face of a control volume.

The state equations of ideal gas are expressed as follows.

$$P = (\gamma - 1) \left[e_0 - \frac{1}{2} \rho (\|\mathbf{V}\|)^2 \right] \quad (2)$$

$$T = \frac{P}{\rho R} \quad (3)$$

Where $\mathbf{V}$, P , ρ , T and e_0 are velocity vector, pressure, density, temperature and total internal energy per unit volume of the incoming flow respectively. γ means the specific heat ratio of the gas. The S-A turbulence model is employed to enclose the N-S equations [21].

A cell-centered finite volume method is employed based on unstructured hybrid meshes. Discrete equation (1) at a control volume and it can be expressed as:

$$\frac{d(\mathbf{Q}_n V_n)}{dt} = - \left[\mathbf{R}(\mathbf{Q}_n, \mathbf{V}_{grid}) - \mathbf{R}^V(\mathbf{Q}_n) \right] \quad (4)$$

Where V_n is the volume of the control volume signed as n , $\mathbf{R}(\mathbf{Q}_n, \mathbf{V}_{grid})$ and $\mathbf{R}^V(\mathbf{Q}_n)$ are residual values of the inviscid flux and the viscous flux respectively. The time derivative term

$\frac{d(\mathbf{Q}_n V_n)}{dt}$ represents the unsteady characteristic of the control volume n . In this paper, the dual-time stepping method is used. While the pseudo-time variable τ is introduced, equation (4) becomes:

$$\frac{d(\mathbf{Q}_n^{k+1} V_n^{k+1})}{d\tau} = -\frac{3\mathbf{Q}_n^{k+1} V_n^{k+1} - 4\mathbf{Q}_n^k V_n^k + \mathbf{Q}_n^{k-1} V_n^{k-1}}{2\Delta\tau} - \bar{\mathbf{R}}(\mathbf{Q}_n^{k+1}, \mathbf{V}_{grid}^{k+1}) \quad (5)$$

Where,

$$\bar{\mathbf{R}}(\mathbf{Q}_n^{k+1}, \mathbf{V}_{grid}^{k+1}) = \mathbf{R}(\mathbf{Q}_n^{k+1}, \mathbf{V}_{grid}^{k+1}) - \mathbf{R}^V(\mathbf{Q}_n^{k+1}) \quad (6)$$

Where, the superscript k means the number of the time step. The conservative variables of the current time step $\mathbf{Q}_n$ can be solved with pseudo time iterative method. And in this paper, the Gauss-Seidel method is used for pseudo time marching [15-16].

The dual-time stepping method translates the unsteady equations into steady equations masterly. Thus, the key of the computing of the unsteady equations is the pseudo time marching in each real time step. And the accelerating convergence such as local time step, residue averaging can be employed in the unsteady N-S equations.

In the viscous fluid, we assume that the relative velocity between the solid wall surface and the fluid is zero. Then the noslip boundary condition of cell-centred scheme is used for the solid wall [16, 21].

The Riemann non-reflection boundary is employed in the farfield. [21]. For the supersonic inflow, the variables on the boundary are only determined by the freestream values. Thus, for physical quantity q :

$$q_b = q_{input} \quad (7)$$

For the supersonic outflow, the variables on the boundary are determined by the solution inside the domain. Thus,

$$q_b = q_e \quad (8)$$

For the subsonic inflow, the boundary conditions are determined by the following equations:

$$\left\{ \begin{array}{l} P_b = \frac{1}{2} \left\{ P_{input} + P_e + \rho_e c_e \left[\mathbf{n} \cdot (\mathbf{V}_e - \mathbf{V}_{input}) \right] \right\} \\ \rho_b = \rho_{input} + (P_b - P_{input}) / c_e^2 \\ \mathbf{V}_b = \mathbf{V}_{input} + \mathbf{n} \cdot (P_b - P_{input}) / \rho_e / c_e \end{array} \right. \quad (9)$$

And for the subsonic outflow, the boundary conditions are determined by the following equations:

$$\left\{ \begin{array}{l} P_b = P_{input} \\ \rho_b = \rho_e + (P_e - P_b) / c_e^2 \\ \mathbf{V}_b = \mathbf{V}_e + \mathbf{n} \cdot (P_e - P_b) / \rho_e / c_e \end{array} \right. \quad (10)$$

Where, the subscript b means the boundary values; the subscript $input$ means the freestream values; the subscript e means the solution values inside the domain. The parameter c means speed

of sound.

RBD module

Derived from the momentum theorem, centroid dynamics equations of the aircraft in body-fixed coordinate can be expressed as:

$$\mathbf{F} = m \left(\frac{\partial \mathbf{v}}{\partial t} + \boldsymbol{\omega} \times \mathbf{v} \right) \quad (11)$$

Where, $\mathbf{F}$ is the total external force vector, m is the mass of the aircraft, $\mathbf{v} = [u \ v \ w]^T$ is the centroid velocity vector, $\frac{\partial \mathbf{v}}{\partial t}$ is the centroid acceleration vector of the body-fixed coordinate related to the earth-fixed coordinate, $\boldsymbol{\omega} = [p \ q \ r]^T$ is the angular velocity vector. $\boldsymbol{\omega} \times \mathbf{v}$ is the convective acceleration vector.

The total external force can be decomposed as:

$$\mathbf{F} = \mathbf{F}_{aerodynamic} + \mathbf{F}_{external} + m\mathbf{g} \quad (12)$$

Where, $\mathbf{F}_{aerodynamic}$ is the aerodynamics force vector, $\mathbf{F}_{external}$ is the external force vector, $\mathbf{g}$ is the gravity acceleration vector.

Derived from the moment of momentum theorem, the centroid rotation equations of the aircraft in body-fixed coordinate can be expressed as:

$$\mathbf{M} = \frac{\partial \mathbf{h}}{\partial t} + \boldsymbol{\omega} \times \mathbf{h} \quad (13)$$

Where, $\mathbf{M}$ is the total moment vector, $\mathbf{h}$ is the moment of momentum vector of the aircraft.

The total moment vector can be decomposed as:

$$\mathbf{M} = \mathbf{M}_{aerodynamic} + \mathbf{M}_{external} \quad (14)$$

Where, $\mathbf{M}_{aerodynamic}$ is the moment vector of the aerodynamics force, $\mathbf{M}_{external}$ is the moment vector of the external forces.

The six degrees of freedom dynamic equations are composed of the equation (11) and (13), and are solved by the second order Semi-Implicit Linear Multi-step Scheme (SILMS)^[16-17]. SILMS is the improvement of the Hybrid Linear Multi-step Scheme (HLMS)^[18], and has advantages of higher calculation precision, efficiency and robustness.

CSD module

When the deformation of the elastic body is much smaller than the reference length, the elastic deformation can be regarded as linear and expressed by mode method. The elastic displacement vector can be written as follows, where the first N order modes are considered.

$$\mathbf{w}(x, y, z, t) = \sum_{i=1}^N \Phi_i(x, y, z) \xi_i(t) \quad (15)$$

$\mathbf{w}(x, y, z, t)$ is the elastic displacement vector of structural deformation, $\Phi_i(x, y, z)$ is the i th-order mode, $\xi_i(t)$ is the generalized coordinate of the i th-order mode.

Derived from the Lagrange equations, the final structure dynamic equations based on the mode method can be expressed as:

$$\mathbf{M}\ddot{\xi} + \mathbf{G}\dot{\xi} + \mathbf{K}\xi = \mathbf{Q} \quad (16)$$

Where, $\mathbf{M}$ is the generalized mass matrix, $\mathbf{G}$ is the generalized structural damping matrix, $\mathbf{K}$ is the generalized stiffness matrix, and $\mathbf{Q}$ is the generalized force.

The structure dynamic equations are calculated by the second order Semi-Implicit Linear Multi-step Scheme (SILMS).

Coupling simulation

The loosely coupled method is used to solve the coupled equations of CFD/RBD/CSD. Concretely, at the n th time step, the CFD module is called firstly to calculate the unsteady aerodynamic forces. And the aerodynamic forces are in earth-fixed coordinate system. Secondly, in terms of the CFD results, the aerodynamics forces in body-fixed coordinate system are computed through coordinate system transformation. Thirdly, with the aerodynamic forces solved above, call the RBD module or/and CSD module to calculate the rigid displacement or/and the elastic deformation of the aircraft. Finally, the rigid displacement or/and the elastic deformation of the elastic aircraft are transformed to the earth-axis coordinate system, and superimposed to the surface grids of the aircraft. Then, update the grids with dynamic mesh technology to get ready for the next time step.

III. Verification case

Verification of the coupled CFD/RBD method

To validate the coupled CFD/RBD code used in this paper, a widely used store separation case is calculated, and compared with the experiments results published in literature [19]. The separation event is simulated at the Mach number of 0.95 and the attack angle of 0 degree. The Reynolds number is 10 million. The mass of the store is 907.185Kg, the principal moments of inertia along the x, y and z axis are 27.116 kg/m², 488.09 kg/m² and 488.094 kg/m² respectively. The ejection forces are considered in the simulation, and are shown in Table 1. Here, the origins of the ejection forces are in body-fixed system, and the ejection forces and moments vectors are in earth-fixed system.

Table 1 the ejection force parameters

No.	origins of the ejection forces (in body-axis)	ejection forces vectors	ejection moments vectors
1	(0.1798,0,0)	(0,0,10676)	(0,-1920,0)
2	(-0.3292,0,0)	(0,0,42703)	(0,14057,0)

The dynamic chimera mesh technique is adopted during the coupled CFD/RBD simulation. Figure 1 show the grids of initial state, among which figure 1b shows the slice of the chimera grid. The volume cell number is 960 thousand. The dual-time stepping method is used and the real time step is 0.008s and the sub-iteration number is 300.

Figure 2 show the simulation results of motion locus of the store. Figure 3 show the comparison of the calculation results and experimental data. As shown in figure 3, the responses of the centroid locations and the orientation angles have good agreement with the experimental data. Therefore, the code and method used in the coupled CFD/RBD simulation is valid.

Fig 1 The grids of initial state

Fig 2 The motion locus of the store.

Fig 3 Comparison of the calculation results and experimental data

Verification of the coupled CFD/CSD method

The dynamic responses of the standard AGARD445.6 wing are simulated to evaluate the accuracy of the coupled CFD/CSD simulation method used in this paper. AGARD445.6 is designed by the Langley Research Center (NASA-LRC) to test the transonic flutter characteristics of elastic wing. At present, it is a standard verification case for dynamic simulation. The airfoil of AGARD445.6 is NACA65A004, and the aspect ratio is 1.644. The first four order modes are considered during the simulation^[20]. The incoming flow Mach number is 0.901 and the attack angle is 0 degree.

Figure 4 show the surface grids of initial state. The surface cell number is 28 thousands and the volume cell number is 330 thousands. The dual-time stepping method is employed. To ensure the simulation precision, the real time step is the twentieth of the natural period of the highest order mode. The sub-iteration number is 100.

The generalized displacement responses are shown in figure 5. The non-dimensional flutter critical speed is about 0.357, which agree well with the experiment result 0.37. Therefore, the code and method this paper used can give a reliable result for the fluid-structure coupling simulation, and can be used for similar problems.

Fig 4 Surface grid of AGARD445.6 wing

Fig 5 The generalized displacement responses at different speed($Ma=0.901$)

IV. Store separation with the wing elasticity considered

Model and simulation states

For the simulation of the store separation, the elastic wing in this section employed is same with AGARD445.6, and the store is a tailless rigid delta wing aircraft designed by this paper. As shown in figure 6, the fuselage of the aircraft is revolution body with a length of 600mm and a diameter of 60mm. The wingspan is 364mm and the sweep angle is 70° . The distance between the mass center and nose is 600mm. The mass of the aircraft is 4.693kg, the principal moments of inertia along the x, y and z axis are 0.009kg/m^2 , 0.096 kg/m^2 and 0.103 kg/m^2 respective. Because the aircraft is symmetrical about $x_b\text{-}O\text{-}z_b$ plane and $x_b\text{-}O\text{-}y_b$ plane, the three products of inertia are all 0.

Fig 6 The three view drawing of the store

The store separation is simulated with the incoming flow of Mach number 0.7 and 2° attack angle. The Reynolds number is $1.58\text{E}6$. The ejection forces are considered in the simulation, and are shown in Table 2. The origins of the ejection forces are in body-fixed, and the ejection forces and moments vectors are in earth-fixed.

Table 2 the ejection force parameters

origins of the ejection forces (in body-fixed)	ejection forces vectors	ejection moments vectors
(0,0,0)	(0,0,50)	(0, 0,0)

This paper mainly studies the influence of the elastic deformation of the wing to the aerodynamics

of the store. The store has been viewed as rigid body and three situations have been designed: a. store separation with elastic wing; b. store separation with rigid wing; c. store free flight. The compute states of the three situations are described as follows. For the situation a, the AGARD445.6 wing maintain level flight and produce elastic deformation under the aerodynamics forces during the store separation. For the situation b, the AGARD445.6 wing, which has been supposed as rigid body, maintain level flight during the store separation. And no elastic deformation is produced. For the situation c, the dynamic responses of the store are purely the free flight responses without interference of the wing. The ejection forces, which are shown in table 2, are loaded on the store at initial state for the purpose of conducting the contrastive study.

In order to study the influence of the pylon position of the external store to the aerodynamics interaction, two different pylon positions have been design. As shown in figure 7, the store is carried under the middle of the wing (numbered 1) and under wingtip (numbered 2) respectively. Considering the leading edge of the wing root as the coordinate origin, the coordinate of the pylons are (-600, 500, 50) and (-800, 700, 50). The units is millimeter.

a. be carried at the middle of the wing b. be carried at the wingtip

Fig 7 two different pylon positions

The solver modules, which are needed for the simulation situations above mentioned, are shown in table 3. During the simulation, the dynamic chimera mesh technique is adopted to treat the rigid-body displacement and the mesh deformation method is used to deal with the elastic deformation. Considering the accuracy and efficiency of the Navier-Stokes equations, six degrees of freedom dynamic equations and structural dynamic equations, the time step of the coupled system is 0.001, which is about the tenth of the natural period of the highest order mode of the wing.

Table 3 the simulation situations

Simulation number	The wing			The store		
	CFD module	RBD module	CSD module	CFD module	RBD module	CSD module
a1	on	off	on	on	on	off
a2	on	off	on	on	on	off
b1	on	off	off	on	on	off
b2	on	off	off	on	on	off
c	none	none	none	on	on	off

Grid convergence study

The hybrid unstructured grid is used for spatial discretization. The grids nearby the wall are prism cells and the others are tetrahedral cells. For the grid convergence study, three grids with different resolutions are generated. The grid statistics are summarized in Table 4. The distance between the first prism cell and the wall is 10^{-5} m.

Fig 8 three grids with different resolutions

	Wall surface cell number (thousand)	Volume cell number (million)
course	30.39	0.73
medium	62.30	1.65
fine	106.48	2.75

The situation a1 mentioned above is selected as the simulation state for the grid convergence study. The store is carried at the middle of the elastic wing. For different mesh resolution, the simulation results of the dynamic responses are shown in figure 9. There are differences between the results of dynamics responses of the course grid and the other grids. Especially for the x-direction displacement response and orientation angles responses. But the results of the medium grid have good agreement with the fine grid. Thus, when the density of the grids is refined, the spatial resolution of the solver is enhanced, and qualitative consistency of the numerical results performs well. As the results of the medium grid and fine grid are almost same, and the medium grid has higher computing efficiency, the medium grid is selected for the following study.

Fig 9 results of dynamic responses of the store with different grids

The error estimates of the simulation

For unsteady problems, the accumulated error should be considered. For the given allowable value of total error $S_{\max}$, the allowable number of time steps can be estimated by the following equation [22-23]:

$$n_{\max} = (S_{\max} / S_{err})^2 \quad (17)$$

The code developed by our research group has 2-order numerical scheme [16]. As the hybrid unstructured grid is used, the mean ratios of the cell size in any directions are almost the same.

Then the mean ratios of the cell size can be expressed as $\Delta L = \sqrt[3]{V / c_n}$. There, V means the volume of the domain and c_n means the cell number. Then the S_{err} can be expressed as:

$$S_{err} = \left(\frac{\Delta L}{L_1}\right)^3 + \left(\frac{\Delta L}{L_2}\right)^3 + \left(\frac{\Delta L}{L_3}\right)^3 = \frac{V}{c_n} \left[\left(\frac{1}{L_1}\right)^3 + \left(\frac{1}{L_2}\right)^3 + \left(\frac{1}{L_3}\right)^3 \right] \quad (18)$$

The accumulated error is:

$$S = \sqrt{n} \times S_{err} \quad (19)$$

The ratio of maximal allowable number of time steps is defined by the following equation [22-23]:

$$R_s = n_{\max} / n \quad (20)$$

Consider the medium grid above mentioned, the error estimates are shown in table 5 when the time step number is 300. When the allowable value of total error is 1%, the allowable number of time steps is 10890000. Because the time steps number is less than 300 in the following simulations, the error is below the given value in this paper.

Table 5 Error estimates

cell number	time step number	allowable number of time steps (allowable value of total error is 1%)	accumulated error	R_s
1650000	300	10890000	0.00005249	36300

The influence of elastic wing to the dynamic responses of the store

The store is acted upon by the aerodynamic forces, ejection forces and gravity force during the separation. Here, the aerodynamics forces can be divided into two parts artificially: the aerodynamic forces caused by its geometry (expressed as F_s) and the interaction aerodynamics caused by the aerodynamic interference of the wing (expressed as F_i). Furthermore, F_i can also be decomposed into two parts: the interaction aerodynamics caused by the rigid wing (expressed as F_{ir}) and elastic deformation of the wing (expressed as F_{ie}). The aerodynamics forces can be written as follows.

$$F_{Aerodynamic} = F_s + F_{ir} + F_{ie} \quad (21)$$

In this section, the situations of a1, b1 and c are simulated. The aerodynamic forces of the store in a1 include F_s , F_{ir} and F_{ie} . However, because the wing in situation b1 is assumed as rigid body, the aerodynamics forces of the store in b1 include F_s and F_{ir} . Situation c is the event of the store free

flight, the aerodynamic forces of the store only include F_s .

Figure 10 show the simulation result of a1. It is clear to see the motion locus of the store and the elastic deformation of the wing. The aerodynamics forces responses and the displacement responses of the store in situation a1, b1 and c are shown in figure 11 and figure 12. As shown in figure 11, because of the aerodynamic interference of the wing, the amplitude of aerodynamics responses increase. The amplitudes of the normal force and pitching moment have increased by 70% and 45% respectively. Because the store is geometrically symmetrical, the lateral-directional orientation angles are small at the early time of the separation, then the value of lateral force and lateral-directional moments are small. During the fall of the store, the lateral force has tendency to increase. In figure 11a, it is easy to find that the aerodynamic interference of the wing accelerate the divergence of the lateral force of the store.

As shown in figure 12a, the difference of the displacements responses of the three situations are minor. This is because sum of gravity force (about 46N) and ejection forces (about 50N), which is 81% of the total external force, is larger than the aerodynamics forces, and the variation of the total external forces are not significant under the aerodynamic interference of the wing. As shown in figure 12b, the rolling angle responses in situation a1 and b1 are larger than that in situation c. The roll rate of a1 and b1 is about 17 times the value of c. Because of the influence of the wing, the interaction aerodynamic forces are unsymmetrical, which induce the rolling moment of the store. And the principal moment of inertia of the store along the z axis is small. Then the rolling angle increase quickly in situation a1 and b1. In figure 12b, the pitching angle response of the store oscillates in period, and the amplitude of the pitching angle response increase under the influence of the wing.

Fig 10 motion locus of the store and the elastic deformation of the wing

a. forces responses

b. moments responses

Fig 11 aerodynamics forces responses

a. rigid body displacements responses

b. orientation angles responses

Fig 12 displacement responses of the store

As shown in figure 11, it is interesting that, with influence of the elastic wing, the aerodynamics forces responses of the store is in cyclical variation at earlier time after separate (time ranges of 0~0.1s). Compare the aerodynamic responses of the store and elastic deformation responses of the wing, as shown in figure 13, the frequencies of the aerodynamics responses of the store are almost the same with frequencies of low order modes. This is the intuitive phenomenon which can be found in figure 13. For the further study, the approximate treatment on the aerodynamics responses of the store in situation a1 and b1, which is expressed in equation (22), is made to separate the interaction aerodynamics caused by the elastic deformation of the wing.

$$F_{ie}(t) \approx F_{Aerodynamic,a1}(t) - F_{Aerodynamic,b1}(t) \quad (22)$$

Where, $F_{Aerodynamic,a1}$ and $F_{Aerodynamic,b1}$ means the aerodynamics forces responses in situation a1 and b1 respectively.

Fig 13 comparison of aerodynamics responses of the store and elastic deformation responses of the wing

Fourier analysis are made for F_{ie} and the generalized displacements of elastic wing, and the results are shown in figure 14 and figure 15. The frequencies of the first bending mode and first torsion mode are 20.45Hz and 23.55Hz respectively. However, the natural frequencies of the first bending mode and first torsion mode are 9.5992Hz and 38.1660Hz respectively. The first bending mode and first torsion mode of the wing have the tendency to couple with each other. In figure 14, the frequencies of F_{zie} , M_{yie} and M_{zie} are about 21Hz, which agree with the frequencies of the structure mode. It is clear that the elastic deformation of the wing will influence the aerodynamic forces of the store. At earlier time during the event of store separation, the frequencies of structure modes define the frequencies of the aerodynamic forces.

Fig 14 distribution of power spectra density of F_{ie} of store

Fig 15 distribution of power spectra density of generalized displacement of elastic wing

Influence of the pylon positions to the dynamic responses of the store

The simulation results of aerodynamics forces responses in situation a1, a2 and b2 are shown in figure 16. Comparing the results of situation a1, when the store is carried at the wingtip, the lateral-directional aerodynamics of the store are larger obviously. But the longitudinal aerodynamics between the two situations are almost the same. This is because the aerodynamic interference caused by the wing tip vortex increases the lateral-directional aerodynamics of the store and accelerates the divergence of the lateral force. As shown in figure 16b, with the influence of the wing tip vortex, the rolling moment of the store is about 9 times the value of a1 at the earlier

time during the separation. However, with the falling of the store, the roll damping moment caused by the roll rate increases, and the aerodynamic interference caused by the wing tip vortex weakened. Then the rolling moment decrease rapidly.

In figure 16, we can find that the lateral force and rolling moment of the store in situation a2 is only two thirds that of the values in situation b2. Therefore, the elasticity of the wing suppresses the divergence of lateral-directional aerodynamics of the store.

Fig 16 aerodynamics forces responses

Figure 17 show the displacement responses of the store in situation a1, a2 and b2. It is clear that pylon position has little influence on the displacement responses in x and z direction. When the store is carried under wing tip, the responses of lateral displacement, roll angle and yaw angle increase rapidly. The lateral displacement and yaw angle amplitude of a2 are 3.2 and 4.8 times the values of a1 respective. The roll rate of a2 is 3.6 times the value of a1. This is due to the influence of the wing tip vortex. Therefore, it is difficult to maintain the lateral-directional attitude of the store when the store is carried under wing tip.

Fig 17 displacement responses of the store

V. Conclusion

This paper numerically simulates the process of store separation with the elastic deformation of the wing considered. The interacting aerodynamic forces and the displacement responses of the store are analyzed. According to the simulation results, some conclusions are obtained as follows.

1. The aerodynamic interference caused by the elastic wing has great influence on the aerodynamic responses of the store at the earlier time during the separation. Compared with the store separation simulation results with rigid wing, the amplitudes of the normal force and pitching moment results of the store which is carried under elastic wing have increased by 70% and 45% respectively.
2. At earlier time during the event of store separation, the frequencies of structure modes of the elastic wing define the frequencies of the aerodynamic forces of the store.
3. Due to the influence of the wing and the unsymmetrical interaction aerodynamics, the divergence speed of the rolling angle of store separation is about 17 times the value of store free flight.
4. The aerodynamic interference caused by the wing tip vortex increases the lateral-directional aerodynamics of the store and accelerates the divergence of the lateral force. At earlier time during separation, the rolling moment of the store which is carried under wing tip is about 9 times that carried under wing middle. And the yaw angle amplitude and roll rate of the store which is carried under wing tip are 4.8 and 3.6 times that carried under wing middle respective. Thus it is difficult to maintain the lateral-directional attitude of the store when the store is carried under wing tip.
5. Contrasting by the store under rigid wing, the lateral force and rolling moment of the store which is carried under elastic wing tip will decrease by a third. Therefore, when the store is carried under the wing tip, the elasticity of the wing may suppress the divergence of lateral-directional aerodynamics of the store.
6. The effect of the elastic deformation of the plane should be carefully considered in the future air-launch-to-orbit project design.

Acknowledgments

This work is supported by the National Science Foundation of China, 11272262.

Thanks to Dr. Qing Zhang for his help on the grammar corrections.

References

- [1]. S.M. Poth, M.A. Fisher, D.W. Levy, et al. Design of an airborne launch vehicle and an air launched space booster. AIAA Aircraft Design, Systems and Operations Meeting, Monterey, 1993. Paper AIAA1993-3955.
- [2]. S. Henri, P.L. Helene, J.L. Farges. Analysis and optimization of an air-launch-to-orbit separation. *Acta Astronautica*, 108(2015):18–29.
- [3]. S.K. Marti, S.K. Nesrin, M. Bob, et al. Flight Testing of a New Earth-to-Orbit Air-Launch Method. *Journal of Aircraft*, 43(2006):577-583.
- [4]. S.K. Marti, S.K. Nesrin, G.C. Hudson, et al. Trade Studies for Air Launching a Small Launch Vehicle from a Cargo Aircraft. 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, 2005. Paper AIAA2005-621.
- [5]. S.K. Marti, S.K. Nesrin, G.C. Hudson, et al. Gravity Air Launching of Earth-To-Orbit Space

- Vehicles. AIAA Space 2006, San Jose, 2006. Paper AIAA2006-7256.
- [6]. R.Q. Cheng, D.X. Zhou. Studies of experimental techniques of store-dropping in the wing tunnel. *Aerodynamic Experiment and Measurement & Control*, 3(1989):31-37.
 - [7]. Z.J. Wang, V. Parthasarathy. A fully automated Chimera methodology for multiple moving body problems. *Int. J. Numer. Meth. Fluids*, 33(2000):919-938.
 - [8]. Z.G. Tang, B. Li, M. Zheng, et al. Store separation simulation using overset unstructured grid. *Acta Aerodynamic Sinica*, 27(2009):592-596.
 - [9]. E.F. Charlton, M.B. Davis. Computational optimization of the F-35 external fuel tank for store separation. 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, 2008. Paper AIAA2008-376.
 - [10]. R.F. Tomaro, F.C. Witzeman, W.Z. Strang. Simulation of store separation for the F/A-18C using Cobalt60. *Journal of Aircraft*, 37(2000):361-367.
 - [11]. M. Jafari, A. Toloei, S. Ghasemlu, et al. Simulation of store separation using low-cost CFD with dynamic meshing. *IJE Transactions B: Applications*, 27(2014):775-784.
 - [12]. N.C. Prewitt, D.M. Belk, W. Shyy. Parallel computing of overset grids for aerodynamic problems with moving objects. *Progress in Aerospace Sciences*, 36(2000):117-172.
 - [13]. Z.Y. Xiao, X. Jiang, B. Mou, et al. Numerical simulation of dynamic process of store separation in parallel environment. *Acta Aeronautica et Astronautica Sinica*, 31(2010):1509-1516.
 - [14]. M.T. Kozak, E.N. Yildiz, Y. Yazicioglu, et al. Effects of aircraft aeroelastic deformations on external store separation dynamics. *Proceedings of the ASME 2013 International Mechanical Engineering Congress and Exposition*, San Diego, 2013. Paper IMECE2013-63772.
 - [15]. R.H. Hua, C.X. Zhao, Z.Y. Ye, et al. Effect of elastic deformation on the trajectory of aerial separation. *Aerospace Science and Technology*, 45(2015):128-139.
 - [16]. Y.W. Jiang. Numerical solution of Navier-Stokes equations on generalized mesh and its applications. Northwestern Polytechnical University, 2013.
 - [17]. W.W. Zhang, Y.W. Jiang, Z.Y. Ye. Two better loosely coupled solution algorithms of CFD based aeroelastic simulation. *Engineering Applications of Computational Fluid Mechanics* 1(2007): 253-262.
 - [18]. Y.W. Jiang, W.W. Zhang, Z.Y. Ye. Study of time-marching method for fluid/structure coupling solution based on CFD technique. *Journal of Vibration Engineering*, 20(2007):396-400.
 - [19]. E.R. Heim. CFD Wing-Pylon-Finned Store Mutual Interference Wind Tunnel Experiment. AEDC-TSR-91-P4, 1991.
 - [20]. E.C. Yates. AGARD Standard Aeroelastic Configurations for Dynamic Response I-Wing 445.6. AGARD Report No. 765, 1988.
 - [21]. J. Blazek. *Computational Fluid Dynamics: Principles and Applications*. Elsevier, UK, 2005.
 - [22]. N.N. Smirnov, V.B. Betelin, R.M. Shagaliev, et al. Hydrogen fuel rocket engines simulation using LOGOS code. *International Journal of Hydrogen Energy*, 39(2014): 10748-10756.
 - [23]. N.N. Smirnov, V.B. Betelin, V.F. Nikitin, et al. Accumulation of Errors in Numerical Simulations of Chemically Reacting Gas Dynamics. *Acta Astronautica*, 117(2015):338-355.