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Invited Paper

The interference aerodynamics caused by the wing elasticity during store separation

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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.

1. 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

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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. 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.

2. 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.

2.1. 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 Eq. (1) at a control volume and it can be expressed as:

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

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