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Effect of elastic deformation on the trajectory of aerial separation

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ABSTRACT

Uncertain serious threats to fight vehicle exist during the process of releasing objects or launching weapons. Reynolds-averaged Navier–Stokes equations are solved through CFD technique in this paper. Based on the frame of unstructured mesh, techniques of dynamic chimera mesh and inverse-distance-weighted morphing mesh are adopted to treat the multi-body separation and flexible structure deformation caused by aeroelasticity respectively. Moreover, the six-degree freedom dynamic equations are solved with static aeroelastic equations by means of the modal approach. Effect of elastic deformation on the trajectory of aerial separation is intensively researched. Numerical results of store-separation case and static aeroelastic case calculated using the in-house code both agree well with the experimental data respectively, which validates of the numerical method. An air-to-air missile model of X–X configuration is constructed to research the effect of elastic deformation on the trajectory of the releasing body. Comparison results of flexible and rigid models show that the longitudinal and course trajectory of centroid is affected by the elastic deformation, and the oscillatory cycle of the orientation angle increases. Furthermore, the trajectories of rigid models with various centroid locations are computed, illustrating that the elastic deformation could move the aerodynamic center forward and weaken the margin of the stability. This study demonstrates that more attention should be paid to the effect of elastic deformation during the fining design of the trajectory of aerial separation.

1. Introduction

Aerial separation involved in multi-body relative motion including weapon delivery, shrapnel spreading, stage separation of launch vehicle, fairings separation from space shuttles or rockets and so on, is a crucial issue of aerospace engineering field. Since there is severely nonlinear aerodynamic interference between the separated components, the trajectories of these separated components are complicated and thus difficult to predict, which may pose serious threat to flight safety [1,2]. Accordingly, it is of high importance to regard behaviors of the objects released from an aircraft to ensure the flight safety and accurate arrival of the munitions at the target. The early missiles and projectiles with smaller ratio of slenderness and denser structures can be reasonably regarded as rigid models for dynamic analysis, while the elastic deformation of the newly practical missile due to aerodynamic loads cannot be ignored with the increasing of flight speed and high maneuverability, which might be beyond the range of common tolerance introduced in manufacturing [3–6]. Since the structural rigidity and natural frequencies of free vibration is lower, it is easier for the air-to-air missiles and rocket missiles with larger slenderness ratio to deform during the process of maneuvering rapidly or separating from aircrafts, which not only has adverse effect on the trajectory and firing accuracy, but also causes uncertain threat to the carrier. Moreover, fairings of large carrier rockets are more prone to aeroelastic problems such as breathing deformation due to light and thin-wall structures [7], which makes it more difficult to predict the trajectory of the separated components suffering from serious aerodynamic interference caused by large windward sides.

Since aerial separation is concerned with physical phenomena involving significant mutual interaction among aerodynamics, flight mechanics, elastic forces and control systems [8,9], it cannot be calculated easily and accurately by engineering methods. Previous studies have handled the problem with simplified models which have lots of assumptions and limitations. Reis addressed the problem of aeroelastic bending of spinning sounding rockets using a simple two-rigid-body model and pointed out that traverse bending of the free-flight rocket could lead to obvious lateral angular velocity [10]. Womack discussed the use of a more complex model based on the use of normal modes to model the flexibility of such rockets [11]. Based on the Euler–Bernoulli beam model and Hamilton's principle, Feng undertook the simulation of the

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trajectory of a rocket and found that the range of the rocket could be increased while the flight level became lower compared to the results of rigid-body models [12]. Ma has carried out a simulation of the process of large elastic fairing separation with flexible multi-body dynamics analyses and suggested that the "breathing vibration" point position depended on the low order modes of the fairings as well as external excitations, while the elastic deformation had little effect on the position of the centroid [13]. Long reported the results of computational fluid dynamics (CFD) investigation using dynamic unstructured mesh technique on the trajectory of the fairing and showed that elastic deformation would make the fairing fail to separate from the aircraft under the ejection forces and moments designed for the assumption of rigid models [14].

Although a great deal of work has been expanded to test the effect of flexibility on the stability of the launch vehicle, simplified models are always adopted to analyze the process of multi-body separation. The aerodynamic forces which dominate the trajectory are normally predicted with lifting-line method or perturbation method. Additionally, more researches related to the coupling of elastic deformation and flight dynamic characteristics focus on the flight vehicle itself, while the investigation about the effect of aeroelasticity on the process of aerial separation is very limited.

Since the accuracy of the engineering method is limited and will lead to more cumulative errors of the separation trajectory, it is necessary to develop more exact methods to predict the trajectory of aerial separation. Schütte at DLR simulated the unsteady aerodynamics of a free-flying aeroelastic combat aircraft by use of coupled aerodynamic, flight mechanics, and aeroelastic computations with the flow-solver TAU [15]. The CREATE-AV Project established by the DoD (the United States Department of Defense) is tasked to develop, deploy and support a set of multidisciplinary, physics-based simulation software products for the engineering workforces supporting air vehicle acquisition programs, and the project could handle the problems related to flexible aircraft with six-degree-of-freedom (SDOF) motion and moving control surfaces [16,17]. In this paper, based on the frame of unstructured hybrid mesh, the method combining dynamic chimera mesh with mesh deformation is applied to the problem coupling rigid body motion and structural elasticity. Unsteady Navier–Stokes (NS) equations are solved to obtain the aerodynamic forces and moments at different times. Flight dynamic equation based on SDOF motion and static aeroelastic equation based on the modal approach are solved to investigate the interaction of the flight dynamics and elastic deformation. Afterwards, the effect of the deformation on the trajectory of elastic separation object can be indicated. The frame of the solving methodology is shown in Fig. 1.

2. Overview of the framework for aerial separation coupled with aeroelasticity

As illustrated in Fig. 1, the methodology presented in this paper mainly consists of three modules including grid-treating module, CFD solver module and fluid–solid interaction module. The grid-treating module is capable of adapting elastic deformation of the meshes caused by aeroelasticity and adjusting the new computational domains according to the large rigid displacement caused by SDOF motion. The flow solver module is used to obtain the numerical results of the governing fluid equations at each time step. With the solution in CFD solver module, the aerodynamic forces and moments on the store are computed by integrating the pressure over the surface. Meanwhile, the generalized forces needed for the modal approach could also be obtained [18,19]. The rigid motion and the elastic deformation of the separated object can be computed by the SDOF trajectory codes and the aeroelastic codes in the fluid–solid interaction module respectively.

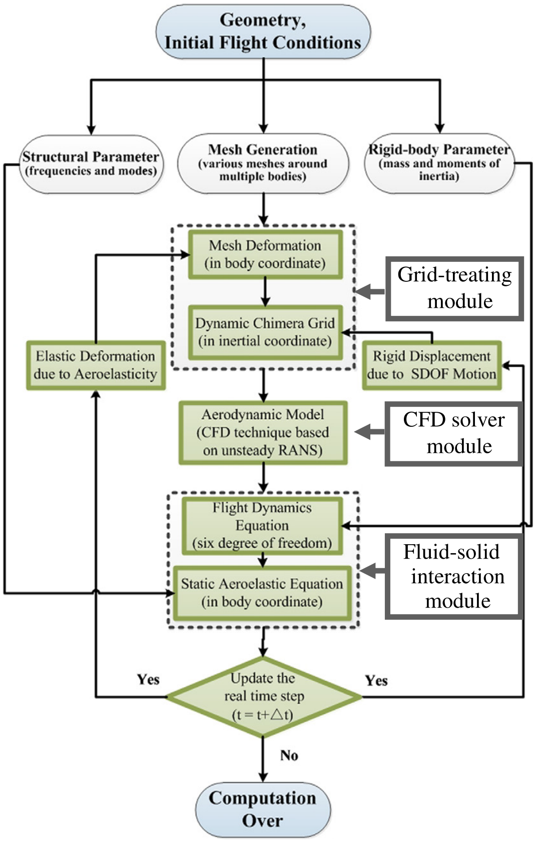

Fig. 1. Flow chart of the solving methodology.

The method is a loosely coupled system, and the effect of the aeroelasticity on the trajectory of aerial separation is embodied in the new location of the nodes of the moving zone. That is to say, compared to the displacement only due to the rigid SDOF motion, the combined mesh node movement in this paper is the summation of the rigid displacement and the elastic deformation from the fluid–solid interaction module. Correspondingly, the result of the flow field is composed of the effect of both flight dynamics and aeroelasticity. Various components of this framework are described next.

2.1. *Dynamic mesh technique*

With the rapid progress in the field of computer science and technology, more detailed and complicated configurations can be treated. It is widely acknowledged that unstructured meshes are more convenient and flexible than structured grids to handle complex models. Here hybrid unstructured meshes are selected for the simulation of the flow fields in this paper. The dynamic chimera mesh technique is adopted to treat the large rigid-body displacement due to multi-body separation, while the flexible structure deformation caused by aeroelasticity is dealt with by an inverse-distance weighted morphing mesh method.

2.1.1. *Dynamic chimera mesh technique*

The Chimera approach (overset-grid), in which several computational domains overlap and cover flow fields to handle complicated configurations, has showed good performance in dealing with multi-body moving problems mainly because remeshing is not required [20–22]. Furthermore, when unstructured meshes are used for the overset concept, the number of sub meshes can be significantly reduced compared with the overset-structured mesh. Moreover, it is simple to generate interpolation stencils between