Aerospace Science and Technology 71 (2017) 347–359

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Effect of elastic deformation on flight dynamics of projectiles with large slenderness ratio

Hua RuHao *, Ye ZhengYin, Wu Jie

School of Aeronautics, Northwestern Polytechnical University, Xi'an, 710072, China

ARTICLE INFO

Article history:
Received 12 September 2016
Received in revised form 23 July 2017
Accepted 18 September 2017
Available online 21 September 2017

Keywords:
Elastic deformation
Flight dynamics
Six degree of freedom motion
Large slenderness ratio

ABSTRACT

The elastic deformation of modern projectiles with large slenderness ratio cannot be ignored with the increasing of flight speed and maneuverability. Unsteady Reynolds-averaged Navier–Stokes (URANS) Equations are solved through CFD technique in this paper. Based on the frame of unstructured mesh, techniques of rigid-motion mesh and inverse-distance-weighted (IDW) morphing mesh are adopted to treat the rigid motion caused by flight dynamics and flexible structure deformation due to aeroelasticity, respectively. Moreover, the six degree of freedom (SDOF) dynamic equations and static aeroelastic equation are solved through the aerodynamic coupling. Numerical results of both free flight case and aeroelastic case calculated by the in-house code agree well with the experimental data, validating the numerical method. A projectile model with X–X configuration is constructed to investigate the effect of elastic deformation on the flight dynamics. Comparison results show that the longitudinal oscillation is more affected by the elastic deformation than the centroid motion, and the oscillation cycle of the orientation angle increases. Furthermore, the trajectories of rigid models with various centroid locations are simulated, illustrating that the elastic deformation could move the aerodynamic center forward and weaken the margin of the static stability margin. In the end, detailed analysis and comparison of the pressure distribution indicates the mechanism by which the elastic deformation leads to the movement of the aerodynamic center and changes the flight dynamic characteristics of the flexible projectile.

1. Introduction

High thrust–weight ratio and large length-diameter (slenderness) ratio are needed for the design of projectiles to reduce the aerodynamic drag, launch heavier payloads and increase the range. As the slenderness ratio increases, the structure of the projectile becomes more and more flexible, and the natural frequencies of longitudinal and transverse vibration decrease. Moreover, in order to improve the maneuverability and agility, stability margin of modern aircrafts is limited or even unstable configuration is adopted. These requirements lead to more attention on the research of dynamic response and vibration characteristics of flexible flight vehicles. The early missiles and projectiles with smaller slenderness ratio and denser structure can be reasonably regarded as rigid models for dynamic analysis. Unfortunately, the elastic deformation of the new practical missile cannot be ignored, which might be beyond the range of common tolerance introduced in the process of manufacture [1–5]. Besides, fairings of large carrier rockets are more prone to aeroelastic problems such as breathing deformation due to thin-wall structures, which makes it more difficult to predict the trajectories of the separated components suffering from serious aerodynamic interference [6]. Since the structural rigidity is lower, it is easier for the air-to-air missiles and rocket missiles with large slenderness ratio to deform during the process of maneuvering rapidly, which not only has adverse effect on the trajectory, but also causes uncertain threat to the carrier. Accordingly, it is of great importance to regard the objects as flexible models to ensure the flight safety and firing accuracy.

Since flight dynamics of flexible flight vehicles has been involved in severely mutual interaction among aerodynamics, flight mechanics, elastic forces and control systems [7–15], previous studies mainly handled the problem with simplified models which had various assumptions. Reis [7] addressed the problem of aeroelastic bending of a spinning rocket using a simple two-rigid-body model and pointed out that the transverse bending of the free–flight rocket could lead to obvious lateral angular velocity. Womack [8] developed a new "integrated method" based on normal modes to model the flexibility of sounding rockets and investigated the coupling of the vibratory and roll motions. Based on the Euler–Bernoulli beam model and Hamilton principle, Wang [9] undertook the trajectory simulation of a rocket and found that the range

* Corresponding author.
E-mail address: huaruhao@mail.nwpu.edu.cn (R.H. Hua).

https://doi.org/10.1016/j.ast.2017.09.029
1270-9638/© 2017 Elsevier Masson SAS. All rights reserved.

of the rocket could be increased while the flight level became lower compared to the results of rigid-body models. Tuzcu [10] investigated the stability of flexible aircraft with various dynamic models and assumptions. Oliveira [11] treated the sounding rocket as a mass-varying Euler–Bernoulli free–free beam and presented a mathematical model to calculate the trajectory, flight dynamic parameters and the elastic deformations. Li [12] addressed the rigid-elastic coupled equations of motion for trajectory simulation of a spinning symmetric vehicle with non-uniform free–free Euler–Bernoulli beam model and quasi-steady theory. Two typical related studies provided by Waszak [13] and Buttrill [14], developed the equations of motion for elastic aircraft to meet the compromise between the accuracy and the simplification in dynamic modeling. The emphasis of the first study, which could be referred to as the Waszak's study, was the assembly of a mathematical model which integrated "rigid-body" and "elastic" degrees of freedom with particular emphasis on the assumptions made at the various stages in the development and on obtaining a set of equations that constituted a literal model. The second study, which could be referred to as the Buttrill's study, focused on including effects of nonlinear inertial coupling between rigid-body angular rates and structural deformations and rates which were usually ignored in conventional aircraft modeling.

Although a great number of researches have been expanded to investigate the effects of flexibility on the stability of projectiles and launch vehicles, the aerodynamic loads which dominate the trajectory were normally predicted with engineering methods such as lifting-line method and perturbation method. Furthermore, most researches involved with the coupling of elastic deformation and flight dynamic characteristics focus on the coupling phenomena itself, while the investigation for the mechanism by which the elastic deformation affects flight dynamics is very limited. Since the accuracy of the engineering method is limited and will lead to more cumulative errors, it is necessary to develop more exact methods to predict the characteristics of the flight dynamics for the flexible projectiles. With the rapid development of numerical methods and computer technology, computational fluid dynamics (CFD) has been widely used to investigate the aerodynamic performance of flight vehicles [15–21]. Schütte [17] at DLR simulated the unsteady aerodynamics of a free-flight aeroelastic combat aircraft by using the flow-solver TAU which coupled aerodynamics, flight mechanics, and aeroelastic computations. The CREATE-AV project established by the DoD (the United States Department of Defense) aimed to develop, deploy and support a set of multidisciplinary, physics-based simulation software products for the engineering workforces to support air vehicle acquisition programs, and the project can handle the problems related to flexible aircraft with SDOF motion and control surfaces deflection [18–21]. Abbas [22] developed a numerical method for the deformation calculation of a rocket and its influence on aerodynamic parameters was studied based on static analyzes using CFD/CSD workflow.

In this paper, based on the frame of unstructured hybrid mesh, the rigid-motion mesh technique and the mesh deformation method are applied to treat the large displacement due to SDOF motion and the elastic deformation due to aeroelasticity, respectively. URANS equations are solved to obtain the instant aerodynamic forces/moments at different time. Generalized flight dynamic equation composed of SDOF motion and static aeroelastic equation are constructed and solved to investigate the effect of elastic deformation on the flight dynamic characteristics.

2. Overview of the framework for flight dynamics coupled with aeroelasticity

The frame of the solving methodology presented in this paper is shown in Fig. 1, which mainly consists of three modules: grid-treating module, CFD solver module and fluid–solid interaction module.

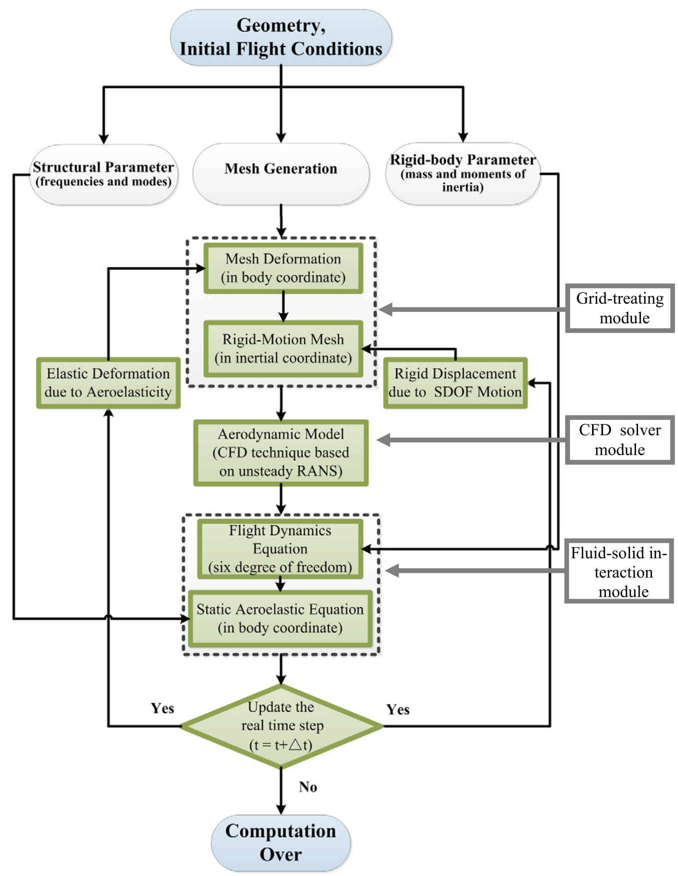

Fig. 1. Flow chart of the solving methodology.

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 displacement due to SDOF motion. The CFD solver module is used to obtain the numerical solution of the fluid governing equations at each time step. With the solution obtained in CFD solver module, the aerodynamic forces/moments on the projectile are computed by integrating the pressure and skin friction over the body. Meanwhile, the generalized forces needed for the solution of the aeroelastic equation can be obtained. The rigid motion and the elastic deformation can be computed by solving generalized flight dynamic equations for flexible aircrafts in the fluid–solid interaction module.

The methodology in this paper is a loosely coupled system similar with Waszak's study [13], and the effect of the aeroelasticity on flight dynamics is embodied in the new location of the mesh nodes. The combined mesh node displacement is the summation of the rigid displacement and the elastic deformation from the fluid–solid interaction module. Correspondingly, the flow field is composed of synthetic effect of both flight dynamics and aeroelasticity, and the focus of this paper is mainly on the aerodynamic coupling between rigid-body motion and structural deformation, while the effects of nonlinear inertial coupling between rigid-body angular rates and structural deformations and rates are not included in the flexible aircraft modeling. Various components of this framework are described as follows.

2.1. Dynamic mesh technique

With the rapid progress of computer science and technology, more detailed research of the flow field around complicated con-