Aerospace Science and Technology 78 (2018) 620–636

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Time-adaptive loosely coupled analysis on fluid–thermal–structural behaviors of hypersonic wing structures under sustained aeroheating

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ARTICLE INFO

Article history:
Received 29 August 2017
Received in revised form 22 March 2018
Accepted 11 May 2018
Available online xxxx

Keywords:
Time-adaptive
Thermal modal
Aerothermoelasticity
Multi-physics coupling
Hypersonic

ABSTRACT

With the mathematical and physical description of hypersonic intrinsic aerothermoelastic behaviors, the present paper proposes a time-adaptive multi-physics coupling strategy for fluid–thermal–structural modeling and analysis. A framework of hypersonic computational coupling dynamics (HyCCD) is developed for integrating an independently developed program solving hypersonic aerothermodynamics with a finite element analysis professional software. The embedded adaptive time-step approach, hybrid interpolation strategy and grid deformation method have taken into consideration the physical characteristics of coupling variables and their properties. A typical low-aspect-ratio hypersonic wing is considered as the simulation model to study the impact of sustained aerothermodynamic loads on the inherent vibrations, thermal modals and their variations. The time-adaptive loosely coupled analysis of aerothermoelastic behaviors along flight trajectory provides a reliable, applicable and efficient prediction for the thermal–structural–vibrational response of hypersonic wing structures.

1. Introduction

The hypersonic air-breathing vehicles in the near-space atmosphere experience a sustained long-range maneuverable flight in a wide range of Mach numbers (5–12). It makes the aerothermodynamic environment extremely complicated, which is characterized by high-enthalpy flow and long-duration (a time period that lasts from minutes to hours) aeroheating flux. There is a physical fact that strong interactions, which are often referred as multi-physics coupling problems, could occur between the external flowfield and the internal structure through a fluid–solid interface. Furthermore, the wings, rudders and other components with the massive application of lightweight flexible materials and thin-walled structures, will be subjected to urgent aerothermoelasticity problem. The efficient and safe design of lightweight structures for hypersonic wings depends largely on the accurate and reliable prediction of thermal–structural–vibration response as well as aerothermodynamic load, structural temperature distribution, and thermal deformation and stress.

To capture such a highly coupled problem involving all effects and their interactions, many efforts have been made to improve the computationally feasibility with high-fidelity modeling techniques. Murty et al. [1] simultaneously solved Navier–Stokes equations in fluid and transient heat transfer equations in solid with commercial software to get the variation of surface temperature and other flow parameters of high-speed aircraft along the flight trajectory. Tabiei and Sockalingam [2] developed a multi-physics coupling analysis framework based on loosely coupled strategy in combination with the CFD solver Fluent and the thermostructural solver LS-DYNA. Culler and McNamara [3,4] applied the third order piston theory for unsteady aerodynamics, reference enthalpy method for aeroheating, and commercial finite element software for thermal and structural responses to model and analyze fluid–thermal–structural coupling. Falkiewicz and Cesnik [5] developed a surrogate modeling technique and basis augmentation techniques to improve the computational efficiency and accuracy of a reduced-order aerothermoelastic simulation framework [6].

In order to minimize computational expenses, the selection of loosely coupled partitioned approach and suitable coupling time stepsize may further improve the efficiency without sacrificing accuracy. Ferrero and D'Ambrosio [7] proposed a hybrid coupling strategy in consideration of the characteristic time of thermal response much longer than that of flow response, which treated the unsteady problem as a series of "quasi-steady" problems. Miller et al. [8] proposed a loosely coupled time-marching method for high temporal accuracy of fluid–thermal–structural coupling analysis, which makes use of multicycling method with multiple time

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https://doi.org/10.1016/j.ast.2018.05.015
1270-9638/

stepsizes to ensure the global second order temporal accuracy. Birken et al. [9] turned out an adaptive time stepsize approach led to a significantly more efficient procedure than a fixed time stepsize approach by proposing a novel time-adaptive singly diagonally implicit Runge–Kutta time integration scheme for thermal coupling problems.

For practical engineering applications, it is crucial to characterizing the effects of fluid–thermal–structural coupling on the response prediction under the extreme environment with the presence of composite loads. Ho and Paull [10] provided a relatively simple coupled analysis strategy for predicting the thermal–structural–vibrational response of hypersonic engines by implementing aerodynamic heating models into a finite element code. Culler and McNamara [3,4] conducted a series of studies on the modeling and analysis of hypersonic skin panels under combined loading. Navazi and Haddadpour [11] studied the aeroelastic behavior of homogeneous and functionally graded flat plates under supersonic airflow. Huo and Yang et al. [12] conducted aerothermoelastic response analysis for C/SiC panel of ceramic matrix composite shingle thermal protection system for hypersonic vehicles. Soloveichik et al. [13] studied the thermoelastic behavior of composite made nose caps at different non-zero angles of attack with high time-variable thermal and mechanical loads during the flight of the hypersonic vehicle.

Although the aforementioned works provided progress in the area of multi-physics coupling, few efforts focus on thermal modal analysis within a fully coupled fluid–thermal–structural framework. Additionally, to capture the highly coupled nature of hypersonic vehicles, the efficiency and computational expense of simulation approaches with high-fidelity modeling techniques must be considered despite the improvements in numerical algorithms and advances in computer power. The thermal modal analysis of the present work is a continuation of previous study on modeling and analysis of conjugate heat transfer (CHT) problems [14]. The time-adaptive, loosely coupled strategy developed by the authors is combined with thermal modal analysis method into a time-marching simulation framework of hypersonic computational coupling dynamics (HyCCD). To the knowledge of the authors, the time adaptivity in the context of hypersonic aerothermoelastic problems has been rarely investigated yet.

McNamara and Friedmann et al. [15] pointed out that the design demands of new-generation hypersonic vehicles have motivated researches on hypersonic aerothermoelasticity. Under the severe aerothermodynamic environment, the composite loads produce subsidiary thermal deformation and stress within the structures, and the resultant variation of structural stiffness and natural vibration performance could significantly affect the trim, flutter and control characteristics of hypersonic vehicles and these effects tend to be unfavorable. On account of the practical requirements, the present work focuses on the thermal deformation, stress, and first six modal parameters of a representative low-aspect-ratio wing at different angles of attack along the flight trajectory. The purpose is to further develop a credible and efficient approach for thermal modal analysis based on fluid–thermal–structural coupling by integrating with the time-adaptive, loosely coupled strategy and the relevant methods. The numerical results on hypersonic wing structures are expected to better understand the aerothermoelastic problems and then provide both theoretical and technical support to the development of hypersonic vehicles.

2. Characterization of multi-physics coupling

Multi-physics coupling problem mainly involves a complex physical process between aerothermodynamics in fluid and thermo-structural dynamics in solid through a fluid–solid coupling interface. In the multi-physics coupling system for hypersonic vehicles, aerothermodynamics is the active motivation including the composite of aerodynamic forces and aeroheating fluxes, while thermo-structural dynamics is the passive response such as heat transfer, thermal stress, and deformation. The high complexity of multi-physics coupling problem makes it very difficult to establish a complete coupling model simultaneously considering all the coupling relations and factors. It is necessary to split the problem into different coupling levels according to physical environment characteristics and the engineering application background. For some structures with low stiffness under severe thermal loads, they are mainly subjected to fluid–thermal–structural coupling in which the structural deformation induced by composite loads is no longer negligible. In particular, the aerothermoelastic behaviors become more prominently for the large thin-walled flexible structures such as the wings and flight control rudders.

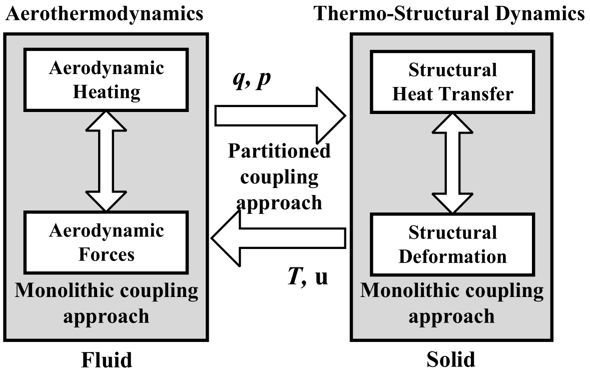

Fig. 1. fluid–thermal–structural coupling model.

The modeling mainly refers to constructing the mathematical-physical model of partial differential equation systems (PDEs) and the corresponding initial/boundary conditions to describe multi-physics coupling. And then, the analysis is to solve the PDEs by numerical simulation method to obtain the physical properties and behaviors. This modeling and analysis can generally be divided into two different types [16], that is, the monolithic coupling approach and the partitioned coupling approach. According to the coupling characteristics, the global strategy includes the monolithic coupling approach respectively for the aerothermodynamics in fluid and thermo-structural dynamics in solid while the partitioned coupling approach for the fluid–thermal–structural coupling problem through fluid–solid coupling interface.

The fluid–thermal–structural coupling model is shown in Fig. 1. It represents a strong two-way coupling relationship between the aerothermodynamic environment of external flowfield and the structural thermal response of internal solid structures. The volumetric coupling of aerodynamic forces and aeroheating fluxes in fluid is described by governing equations of aerodynamic flow, which is solved by computational fluid dynamics (CFD) to obtain the parameters of aerothermodynamic loads. The thermal loads (wall heat flux q) and aerodynamic force loads (wall pressure p) are imposed on the solid through fluid–solid coupling interface. The structural thermal response in solid is described by governing equations of structural heat transfer and thermoelastics, which is solved by finite element method (FEM) to structural/thermal coupling parameters. The temperature condition (wall temperature T) and structural deformation condition (surface displacement $\mathbf{u}$) are provided for the fluid through fluid–solid coupling interface to take into account the effects of temperature-deformation coupling.

2.1. Coupling strategies based on static flight trajectory

When the vehicle flies at a hypersonic speed within the atmosphere, the aerothermodynamic loads as active excitation changes