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CFD/CSD approach to predict hypersonic aerothermoelastic response of a wing

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Abstract

A coupling numerical simulation technology which combined computational fluid dynamics (CFD) method with computational structure dynamic (CSD) is developed. The aerodynamic heating is calculated using CFD method. The thermo-structural response is calculated using CSD method. The thermal modal under aerodynamic heating is simulated and the influence of aerodynamic heating is discussed. The strategy of CFD/CSD approach used to simulate the aerothermoelastic response phenomenon is introduced. The simulation results indicate that aerodynamic heating obviously change the vibration mode of the wing. The contrast between normal temperature and high temperature response of a hypersonic wing under aerodynamic exciting is shown. The computed results indicate that aerothermoelasticity simulation using CFD/CSD approach is feasible and credible.

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Keywords: coupling calculation; aerothermoelasticity; thermal modal; CFD/CSD

1. Introduction

Researches on Hypersonic aeroelasticity problems and aerothermoelasticity problems were vibrant and active in the late 1950's and during the 1960's [1-4]. The research interest in this area was ignited again after the advent of the National Aero Space Plane (NASP). In recent years, vehicles like X-43A, X-37B flight in a typical hypersonic flight regime successfully. Vehicles in this category are based on a lifting body design. However, stringent minimum weight requirements imply a degree of fuselage flexibility. The serious aerodynamic heating condition is the critical problem for this kind of vehicles. Furthermore, the testing of aeroelastically scaled wind tunnel models which is a conventional practice in subsonic flow is not feasible in the hypersonic regime. Thus, the role of aerothermoelasticity simulations is more important for this flight regime.

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A realistic analytical model for the hypersonic regime must include aerodynamic heating effects. Aerodynamic heating significantly alters the flow properties [5]. The material properties also introduce thermal stresses [6-8]. Commonly, the heated structure has lowered stiffness due to material degradation and thermal stresses [7-9]. Recently, some approximate calculations are carried out by considering the effect of elevated temperatures on the structural stiffness and associated frequencies. Traditionally, the wind tunnel approach is used to support the design. Some hypersonic wind tunnel flutter experimental data are achieved by researchers [10]. But the real aerothermoelasticity properties of hypersonic vehicle can't be simulated using traditional wind tunnel because the failure of simulating real temperature conditional in flight.

In the near future, along with the development of the computer technique, the numerical simulation approach offers a new way to predict the dangerous flight conditions which helps the design. In paper [11], studies on grid convergence are used to determine the appropriate computational domain and resolution for a low aspect ratio wing in hypersonic flow, using both Euler and Navier-Stokes aerodynamics. Results indicate that the aeroelastic behavior is comparable when using Euler and third order piston theory aerodynamics [12]. A parametric study of offsets, wedge angles and static angle of attack is studied [13]. For the geometry used in this paper, differences between viscous and inviscid aeroelastic behavior are not substantial.

In this paper, a CFD/CSD coupling simulation method is used to predict the temperature response of a hypersonic wing model. The flow field and solid field are solved separately and the interaction surface data are exchanged in each time step. The Euler and Navier-Stokes equation is used to obtain the numerical solutions of the flow field. The CSD model is constituted and solved using finite element approach (FEA). The data exchange and interpolate is carried out at the domain of CFD/CSD coupling surface. Finally, the thermal modal and thermal response is calculated then the influence of aerodynamic heating is discussed.

2. Numerical simulation method

2.1. CFD model and solution

The Navier-Stokes equation is used to obtain the heat environment of the wing. The code uses an implicit, finite-volume algorithm based on upwind biased spatial differencing to solve the time-dependent Reynolds-averaged Navier-Stokes equations. Different turbulence models are available.

2.2. CSD model and solution

In finite element analysis, the transient thermal conduction equations can be written as follows:

$$C\dot{\phi} + K\phi = P \tag{1}$$

where C is the thermal capacity matrix, K is the thermal conduction matrix, ϕ is node temperature vector, P is temperature load vector.

2.3. Fluid-solid surface data interpolation

In the sending code, the data is defined on a mesh of some kind and shall be transferred to the mesh of the receiving code. These meshes describe the same geometric entity, but typically differ in element size and node location, which is referred to as “non-matching grids”. The exchange procedure can be split up into three steps: pre-contact search, association and interpolation. In flux interpolation, the value is adapted to the element sizes to preserve the integral. In field interpolation, the values are kept to ensure a conservative transfer.

2.4. Coupling algorithm

The loose-coupling mode is adopted in the simulation for this paper. The flow field and solid field are solved separately and the data of interaction surface are exchanged in each time step.

3. Computational results

In this section, the structural dynamics character of a hypersonic vehicle wing under aerodynamic heating is calculated. The computational free inflow condition is Ma5, static pressure 1200Pa and static temperature 100K.

3.1. Heat environment simulation

The steady heat environment of the wing is simulated using CFD method. The root of the wing is set to be symmetry condition. The adiabatic boundary condition is used. The far field and pressure outlet condition are used to consider the free flow condition. The steady heat environment temperature of the wing is simulated, see Fig. 1.

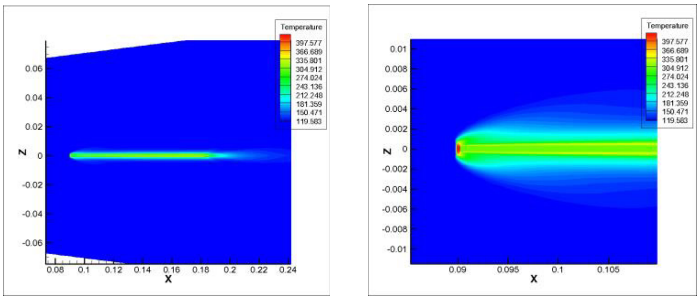

Fig.1. Film temperature contour under aerodynamic heating progressing

After the steady simulation is finished, the unsteady thermo-solid coupling simulation is applied for 2 seconds. The results show that the film temperature of the wing changes with the aerodynamic heating progressing. In the calculation time domain, the aerodynamic heating transfer from fluid to structure still happens which is to say that the heat transfer doesn't achieve to equilibrium.

3.2. Structure thermal modal calculation

The thermo-solid coupling simulation progresses use CFD/CSD method. The temperature of the wing is obtained and stored to calculate the thermal stress and thermal modal of the wing. The structure thermal modal under aerodynamic heating is calculated, see Fig. 2.

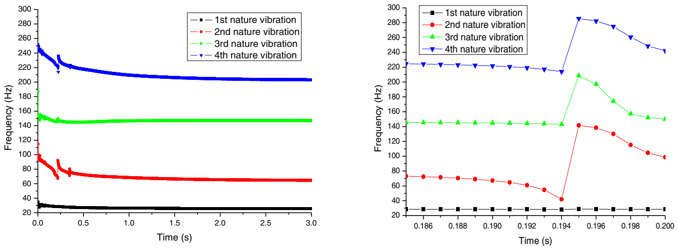

Fig.2. Nature vibration frequency changing with aerodynamic heating progressing

The results show that after 0.5 second, the disciplinarian of nature vibration frequency changing with aerodynamic heating progressing is obvious. The 1st, 2nd, 4th order nature vibration frequency decrease with time, but the 3rd order nature vibration frequency increase with time at the beginning but decrease with time latterly. The disciplinarian is complex before 0.5 second especially at 0.2 second. Before this time domain, the all first four order nature vibration frequencies decrease with time, but after 0.195 second, the 2nd nature vibration disappears.

The thermal modal shape calculation results (0.194s and 0.195s) of the wing are shown in Fig. 3. The results shown that the thermal modal of the wing is changed obviously along with the aerodynamic heating in this time domain, the 2nd nature vibration (torsion vibration) disappear.

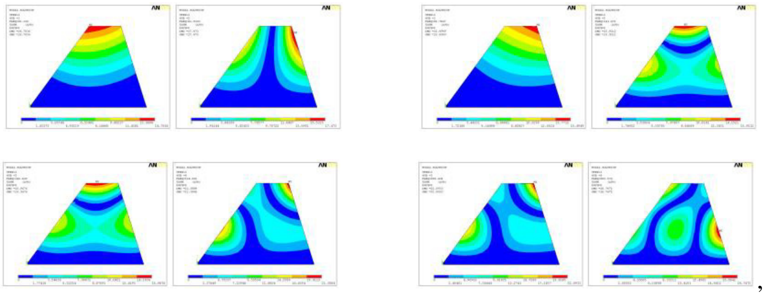

Fig.3.（a） Thermal modal shape at 0.194 second.（b） Thermal modal shape at 0.195 second

3.3. Normal temperature aeroelastic response prediction

Firstly, coupled structure-fluid is calculated. The wall-forces of the model are interpreted to the structural model as the force boundary condition. The displacements of boundary nodes of the structural model are interpreted and sent back to the flow field solver as the boundary condition. The unsteady flow field is calculated again under the new boundary condition and transfer new force data to the structural model.

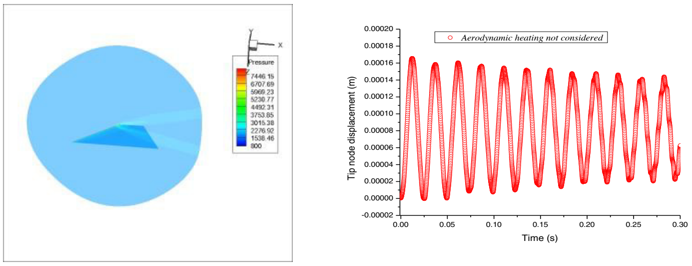

Fig.4. Pressure contour and wing deformation

The iteration continues in time domain. Dynamic pressure of 15km flight condition is used to capture the flutter phenomenon. Results of displacements in time domain are shown in Fig. 4. In this flight condition, the vibration of the wing is convergent. Flutter doesn't happen in this flight condition. The amplitude of the vibration is about 0.08mm.

3.4. High temperature aerothermoelastic response prediction

After the steady heat environment calculation finished, the coupling simulation of fluid and structure is carried out. The heat transfer is simulated using CFD/CSD approach in time domain. The temperature of structure is stored and used to calculate the thermal stress of the structure. Then the FE model considered the thermal stress effect is used to simulate the aerothermoelastic response phenomenon. The structure temperatures change with time (aerodynamic heating persisting for 0.1 second, 0.2 second, 0.3 second, 0.4 second, 0.8 second and 1 second) are shown in Fig.5.

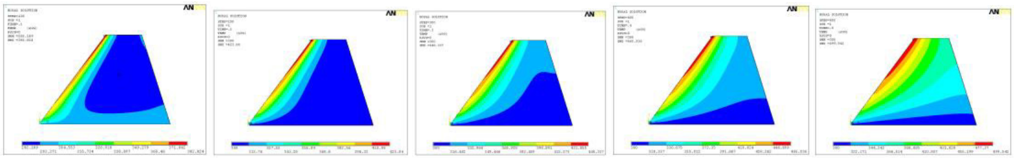

Fig.5. Structure temperature with aerodynamic heating progressing

Utilizing the finite element model considering the thermal stress, the high temperature aerothermoelastic response is simulated using CFD/CSD approach, see Fig. 6. Results show that the thermal stress caused by aerodynamic heating obviously weakens the stiffness of the wing. The vibration amplitude of the wing rises from 0.08mm to 8mm but the vibration form remains convergent, that is to say flutter doesn't happen in this flight condition also. In this example, the free flow static temperature is low, so the effect of aerodynamic heating is comparatively weak. The static temperature of real flight condition is higher than this example, so the effect of aerodynamic heating will be more obvious. The results show that aerodynamic heating effect can't be neglected in aerothermoelastic simulation.

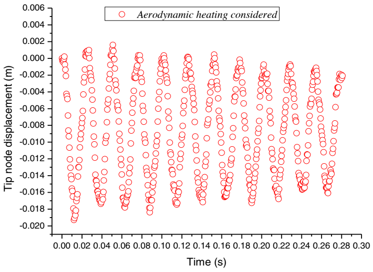

Fig. 6. Deformed displacement of front node of the wing considering aerodynamic heating

4. Conclusions

The CFD/CSD coupling numerical simulation method is introduced in this paper. The method is used for the simulation of the aerothermoelastic response problem of a hypersonic vehicle wing model. Aerodynamic heating effect weakens the structure stiffness and alters the nature vibration mode obviously. For the aerothermoelastic response problem, the influence of aerodynamic heating should be considered seriously.

Acknowledgment

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