CFD/CSD APPROACH TO EVALUATE THE AEROELASTIC RESPONSE OF HYPERSONIC VEHICLE 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. Several kinds of mode to exchange data for CFD/CSD coupled computation is designed. Aeroelastic response of hypersonic wing under Ma 5 wind tunnel experimental condition is calculated as an example. The coupling of bending and torsion mode is captured. The computed result indicates that CFD/CSD method of aeroelastic simulation is feasible and credible.

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. Furthermore, the testing of aeroelastically scaled wind tunnel models, a conventional practice in subsonic flow is not feasible in the hypersonic regime. Thus, the role of aeroelastic simulations is more important for this flight regime.

A realistic analytical model for the hypersonic regime must include aerodynamic heating effects. Aerodynamic heating significantly alters the flow properties[9]. The material properties also introduces thermal stresses[10-12]. Commonly, the heated structure has lowered stiffness due to material degradation and thermal stresses[11-13]. 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[8]. 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[5], previous studies are separated into several groups. The 1st group consists of studies focusing on panel flutter[14-17]. It was noted that piston theory may not be appropriate for the hypersonic regime and that hypersonic studies might have to use unsteady aerodynamic loads based on the solution of the Navier-Stokes equations[18]. A review of this research can be found in this paper[19]. The 2nd group of studies was motivated by a previous hypersonic vehicle, namely the NASP[20-26]. Spain et al. [21] carried out a flutter analysis of all-movable NASP-like wings with slab and doublewedge airfoils. Besides, 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[5]. Results indicate that the aeroelastic behavior is comparable when using Euler and third order piston theory aerodynamics[6]. A parametric study of offsets, wedge angles and static angle of attack is studied[7]. For the geometry used in this paper, differences between viscous and inviscid aeroelastic behavior are not substantial.

In this paper, CFD/CSD coupling simulation method is used to predict the aeroelastic response of a wind tunnel experiment model. The aeroelastic response is simulated at the wind tunnel experimental condition, the influence of the coupling algorithm used in CFD/CSD coupling simulation is discussed. The CFD/CSD coupling simulation result is contrasted to the result predicted by piston theory. Finally, the simulation results are compared to the experiment data acquired by binocular vision measurement in hypersonic flutter wind tunnel.

2 NUMERICAL SIMULATION METHOD

2.1 CFD model and solution

The Euler equation is used to obtain the numerical solutions of the flow field. The equation of integral form is as follows:

$$\frac{\partial}{\partial t}\oiiint_{\Omega} W d\Omega + \oiint_{S} F \bullet \vec{dS} = 0 \tag{1}$$

Where $F = f\vec{i} + g\vec{j} + h\vec{k}$, $\vec{dS} = dS_x\vec{i} + dS_y\vec{j} + dS_z\vec{k}$, $W = \left(\rho, \rho u, \rho v, \rho w, \rho E\right)^T$,

$f = \left(\rho u, \rho u^2 + p, \rho uv, \rho uw, u(\rho E + p)\right)^T$, $g = \left(\rho v, \rho vu, \rho v^2 + p, \rho vw, v(\rho E + p)\right)^T$,

$h = \left(\rho w, \rho wu, \rho wv, \rho w^2 + p, w(\rho E + p)\right)^T$.

Where, W is conservative variable, F is flux tensor, ρ is density, p is pressure, (u, v, w) is velocity component, E is energy, $E = \frac{p}{\gamma - 1} + \frac{\rho}{2}(u^2 + v^2 + w^2)$.

2.2 CSD model and solution

The equations of motion can be written as follows:

$$M\ddot{q} + G\dot{q} + Kq = F \tag{2}$$

Where *q* is a vector of generalized displacements, *M* is the generalized mass matrix, *G* is the damping matrix, and *K* is the stiffness matrix, *F* is the vector of generalized forces.

2.3 Fluid-solid surface data interpolation

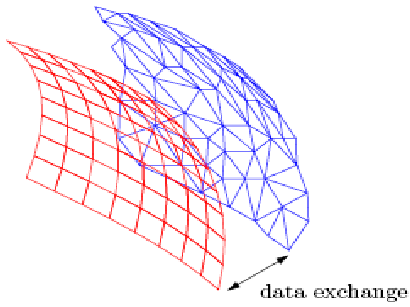

Figure 1: Data exchange sketch map

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”(shown in Figure 1).

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 Numerical simulation coupling mode

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.

In our study, different coupling algorithms are designed. The CFD-code is represented by "code B" and the FE-code by "code A". Two useful coupling algorithms are described in detail in Figure 2 named "serial coupling" and "parallel coupling".

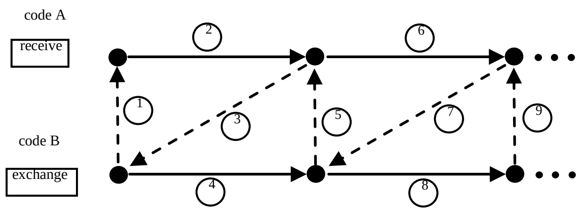

Figure 2: (A) Serial coupling algorithm

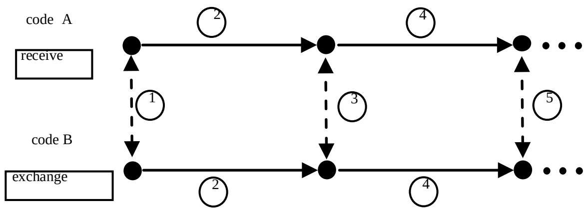

Figure 2: (B) Parallel coupling algorithm

3 COMPUTATIONAL RESULTS

3.1 A 3-dimensional wing model

In this section, the aeroelastic response of the wing of a hypersonic vehicle model are calculated. The wind tunnel experimental condition is used as the computational condition. The aerodynamic parameters are satisfied governing equations following:

$$p_\infty = \frac{p_0}{(1+0.2*M_a^2)^{3.5}} \tag{3}$$

$$q = 0.7 \times Ma^2 \times P_\infty \tag{4}$$

$$\rho = (\frac{1+0.2Ma^2}{287.1})\frac{P_\infty}{T_0} \tag{5}$$

$$a = \sqrt{(\frac{401.9}{1+0.2Ma^2})T_0} \tag{6}$$

Where, p_∞ is static pressure; p_0 is total pressure; q is dynamic pressure; ρ is density; T_0 is the total temperature. In wind tunnel experiment, the dynamic pressure is adjusted by adjusting total pressure. In this paper, the computational condition is Ma5, p_∞ : 1800~2200*Pa*, total temperature: 80*K*.

3.3 Numerical simulation results

The vibration mode of the hypersonic vehicle model is analyzed using commercial software ANSYS. The first four vibration frequencies and shapes are shown in Figure 3.

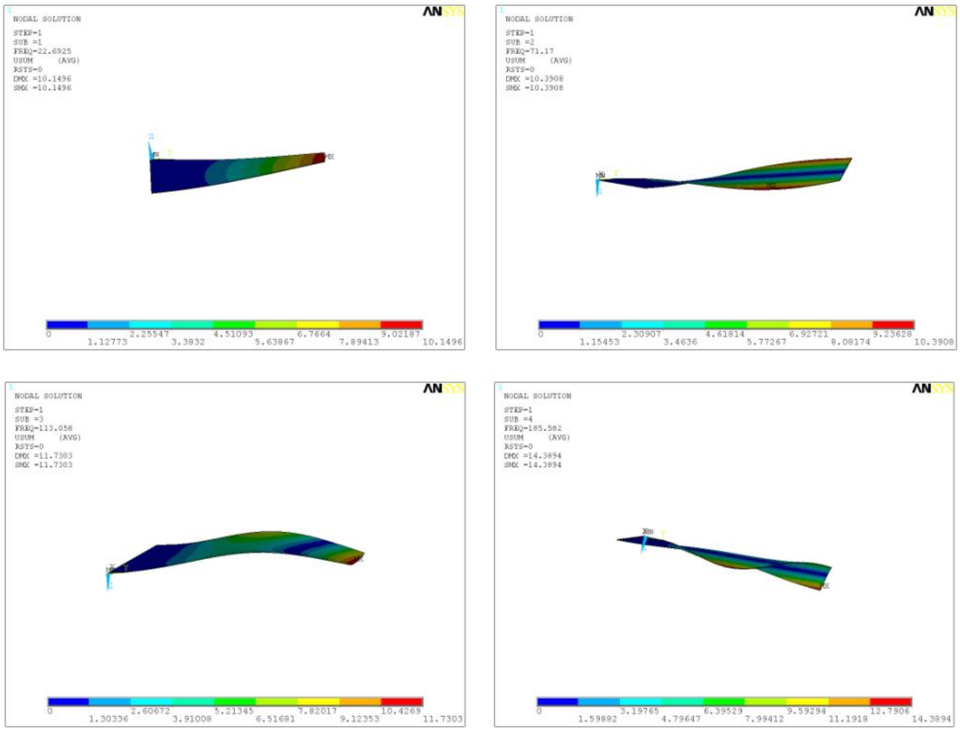

Figure 3: First four vibration mode

Firstly, the steady CFD simulation is done (see Fig. 4.) and applied as the initial condition of unsteady CFD/CSD coupling simulation. Velocity initial condition is applied to the element nodes of finite element model, in this example it is set to be 1m/s. The initial condition will not impact the time domain response results but larger velocity will cause the non-positive grid problem of CFD. 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. In this example, the structural damp is not considered.

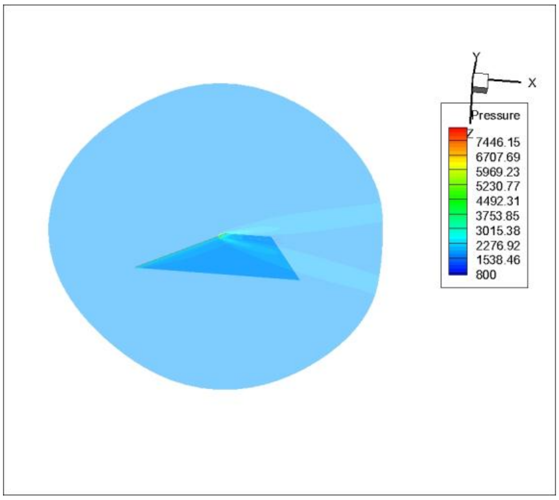

Figure 4: Steady pressure contour

The iteration continues in time domain. Four different dynamic pressures are used to capture the flutter boundary, results of displacements in time domain are shown in Figure 5.

For the Euler computations, the time step size was set to cover 50 steps per cycle of the torsion frequency mode, which corresponds to $\Delta T = 2*10^{-4}$ second.

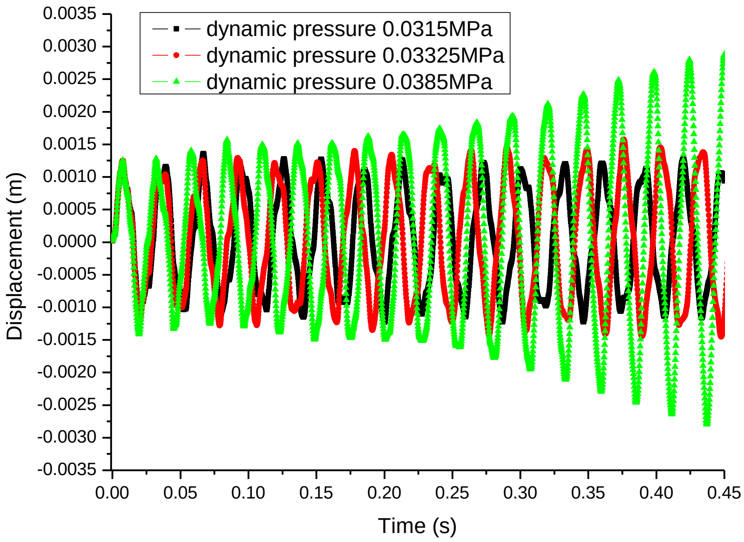

Figure 5: Deformed displacement of front node of the wing

The calculated results show that when the dynamic pressure grows from 0.0315MPa to 0.0385MPa, the vibration displacement of the wing appears divergent. The flutter appears in this region where the flutter dynamic pressure is between 0.0315MPa~0.03325Mpa (see Fig. 6.). The amplitude of vibration of the wing is about 1.3mm.

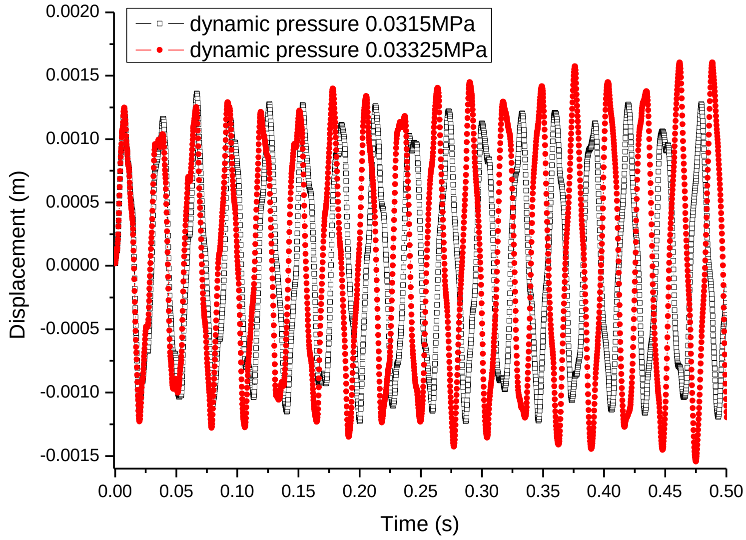

Figure 6: Flutter in time domain

The deformed wing in CFD codes and CSD codes are shown in Figure 7. The main deformed mode is coupling of bending and torsion of the wing. The results show that the spring dynamic grid method could solve this kind of deforming mode effectively.

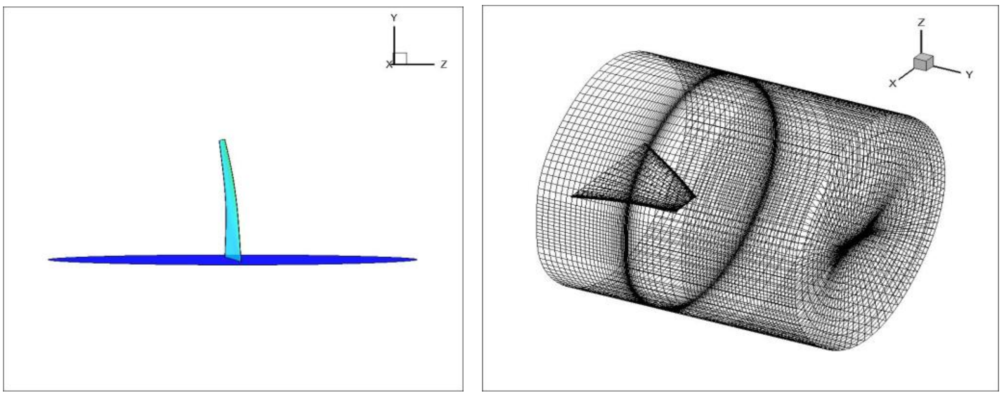

Figure 7: Deformed wing and grids

For the purpose to understand the physical problem of flutter, the data of time domain displacement response are analyzed using FFT method (see Fig. 8.). The red line shows the condition of dynamic pressure equals to 0.0315Mpa. The black line is 0.03325Mpa and the green line 0.0385Mpa. The blue lines show the natural frequencies of the model which the first natural frequency is about 23Hz (bending), the second natural frequency is 71Hz (torsion) and the third natural frequency is 113Hz.

As the dynamic pressure of inflow increases, the response spectrum of first bending and torsion weakens. The coupling of bending and torsion constitutes a new response spectrum peak which the frequency is about 35Hz. The results show that as the dynamic pressure of inflow increases, the vibration frequency of the model increases which is the effect of aerodynamic stiffness.

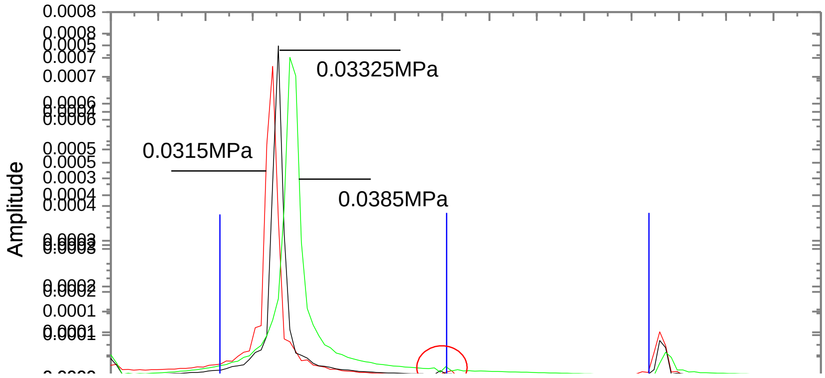

Figure 8: Displacement response spectrum

4 CONCLUSIONS

The CFD/CSD coupling numerical simulation method is introduced in this paper. The method is used for the simulation of the flutter problem of a hypersonic vehicle wing model. The flutter in time domain is simulated using this method and the physical phenomena of the coupling of bending and torsion mode is captured. The simulation results offer a efficient reference to the wind tunnel flutter experiment design.

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