HIGH PERFORMANCE COMPUTATIONAL NONLINEAR AEROELASTICITY

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1. Introduction

Aeroelasticity is the study of the effect of aerodynamic forces on elastic bodies. Because these effects have a great impact on performance and safety issues, aeroelasticity is one of the most important considerations in aircraft design.

The basic mechanism of a fluid/structure interaction phenomenon for an aerospace vehicle can be explained as follows. The aerodynamic forces acting on an aircraft depend critically on the attitude of its lifting body with respect to the flow, which in turn depends on the flexibility of the aircraft. It follows that neither the external load acting on an aerospace vehicle, nor its elastic deformation can be evaluated until the coupled aeroelastic problem is solved.

If one notes that the external aerodynamic forces acting on an aircraft structure increase rapidly with the flight speed, while the internal elastic and inertial forces remain essentially unchanged, one can imagine that there may exist a critical flight speed at which the structure becomes unstable. Such instability may cause excessive structural deformations and may lead to the destruction of some components of the aircraft. Panel or wing *flutter*, which is a sustained oscillation of panels or wings caused by the high-speed passage of air along the panel or around the wing, is an example of such instability problems.

An aeroelastic problem can also associate with a performance rather than a stability issue. For transonic flows, small variations in incidence may lead to considerable changes in the pressure distribution, shock position, and shock strength. Consequently, there are some margins within the Mach number and incidence that can be varied around the design condition of a supercritical airfoil without a serious deterioration of the favorably low-drag property of the shock-free flow condition [1]. Determining whether an oscillating airfoil is within or outside these margins requires determining its aeroelastic response.

Currently, the aerospace industry is engaged mostly in linear aeroelastic analyses where the structure is assumed to undergo a *harmonic* motion and *small displacement amplitudes*, and the flow is assumed to be inviscid, irrotational, isentropic, and is approximated by a linearized theory [2–4]. However, in the transonic regime, the mixed subsonic-supersonic flow patterns and shock waves are such that there are no reliable theoretical linear means for predicting the unsteady aerodynamic forces. In that case, the linear aeroelasticity theory simply breaks down. This is most unfortunate because of the current renewed interest in transonic flight for both military and civilian aircraft.

Besides transonic flights, there are many other important cases where the linear aeroelastic theory cannot be used for predicting the dynamic response or stability of an aircraft. These include, to name only a few, problems where the structure undergoes large displacements and/or rotations — as an example, we note that the maximum upward deflection of the wing of the B52 bomber is 22 feet [2] — parachute dynamics, bluff body oscillators, airfoil oscillations in separated flow, buffeting, and high-G and high angle of attack maneuvers such as those performed by the X-31 and F16-MATV fighters. The pressing need for understanding and solving such nonlinear aeroelastic problems is the main motivation for designing nonlinear aeroelastic numerical simulation capabilities such as the one pursued at the University of Colorado and described in this lecture.

2. Formulation of coupled nonlinear aeroelastic problems

Here, the structure is no longer restricted to a linear behavior, and the aerodynamic forces acting on it are no longer predicted by a linear aerodynamic approximation. The motion of the aircraft is allowed to have large displacements and rotations, and the unsteady aerodynamic forces are determined from the solution of the compressible Euler or Navier-Stokes equations.

As in most flow problems with moving boundaries, a body-conforming mesh has to be regenerated at each time-step of an aeroelastic analysis, or the existing grid has to be allowed to deform to follow the computational domain geometries. The former option is rather cumbersome and computationally expensive, especially for three-dimensional problems. The latter option introduces the concept *dynamic meshes* [5] that can be handled by the arbitrary Lagrangian/Eulerian (ALE) formulation [6,7]. Furthermore, a moving mesh can also be viewed as a pseudo-structural system with its own dynamics [8], and therefore, the coupled transient aeroelastic problem can be formulated as a *three-* rather than two-field problem — the fluid, the structure, and the dynamic mesh — and is governed by the three-way coupled semi-discrete equations

$$\boxed{\begin{aligned} \frac{\partial}{\partial t}(\mathbf{V}(x,t)\ \mathbf{W}(x,t)) + \mathbf{F}^c(\mathbf{W}(x,t),x,\frac{dx}{dt}) &= \mathbf{R}(\mathbf{W}(x,t)) \\ \mathbf{M}\frac{d^2\mathbf{q}}{dt^2} + \mathbf{f}^{int}(\mathbf{q}) &= \mathbf{f}^{ext}(\mathbf{W}(x,t),x) \\ \widetilde{\mathbf{M}}\frac{d^2\mathbf{x}}{dt^2} + \widetilde{\mathbf{D}}\frac{d\mathbf{x}}{dt} + \widetilde{\mathbf{K}}\mathbf{x} &= \widetilde{\mathbf{K}}_c\ \mathbf{q} \end{aligned}} \tag{1}$$

where x is the *displacement or position, depending on the context of the sentence* of a moving fluid grid point, $\mathbf{W}$ is the fluid state vector, $\mathbf{V}$ results from the finite element/volume discretization of the fluid equations, $\mathbf{F}^c$ is the vector of convective ALE fluxes that depend on the fluid grid velocity, $\mathbf{R}$ is the vector of diffusive fluxes, $\mathbf{q}$ is the structural displacement vector, $\mathbf{f}^{int}$ denotes the vector of internal structural forces, $\mathbf{f}^{ext}$ the vector of external forces acting on the structure, $\mathbf{M}$ is the finite element mass matrix of the structure, $\widetilde{\mathbf{M}}$, $\widetilde{\mathbf{D}}$, and $\widetilde{\mathbf{K}}$ are fictitious mass, damping, and stiffness matrices associated with the fluid moving grid and constructed to avoid any parasitic interaction between the fluid and its grid, or the structure and the moving fluid grid [8], and $\widetilde{\mathbf{K}}_c$ is a transfer matrix that describes the action of the motion of the structural side of the fluid/structure interface on the fluid dynamic mesh. For example, $\widetilde{\mathbf{M}} = \widetilde{\mathbf{D}} = 0$ includes as particular cases the spring-based mesh motion scheme introduced in [5] and the continuum based updating strategy advocated by several investigators.

3. Computational mechanics issues

In this lecture, the following computational mechanics issues which pertain to the solution of Eqs. (1) will be discussed and illustrated with the solution of real aeroelastic problems

- discrete geometric conservation laws for second-order time-accurate flow solvers
- mesh motion schemes that are robust for large displacements and/or rotations of the structure
- turbulence models for the computation on dynamic meshes of flows at high-angle of attack
- intelligent inputs to the control surfaces of an aircraft to drive its motion during a three-dimensional maneuver
- conservative load and motion transfer algorithms for fluid/structure interaction problems with non-matching discrete interfaces
- partitioned procedures for time-integrating Eqs. (1) and their assessment for accuracy, stability, heterogeneous computing, I/O transfers, subcycling, and parallel processing
- numerical/experimental correlations and finite element model updating

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