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Efficient aeroelastic reduced order model with global structural modifications

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ABSTRACT

Time domain aeroelastic analysis has high computing costs when using computational fluid dynamics. These costs become prohibitive when the structural model undergoes large changes from the baseline design, as within an aircraft design process. To overcome this realistic challenge, we have developed, implemented, and demonstrated an efficient method that is robust in the presence of global modifications of the structure. The method consists of: a) a reduced order model of the linearized Navier–Stokes equations generated around an aeroelastic equilibrium that depends, in turn, on the structural model; b) an approximate structural dynamic reanalysis method valid for global modifications of the structure; and c) a mechanism to exchange information between fluid and structural solvers without need for calculating at each iteration of the structural design an eigenvalue problem of the modified structure. The resulting aeroelastic reduced order model is demonstrated for the AGARD 445.6 wing, and material properties are varied up to 100% from their original values. It is found that: a) predictions of the time domain aeroelastic response and of the flutter speed are accurate for all modifications of the structure; and b) the computational efficiency of the proposed aeroelastic reduced order model is linearly proportional to the number of structural configurations considered. The method, therefore, is ideally suited for optimization and uncertainty studies.

1. Introduction

Aeroelastic analysis in the transonic regime is a critical aspect of today's aircraft design process. In transonic flow, linear aerodynamic theories fail due to the presence of flow nonlinearities (e.g. shocks, separation). Computational fluid dynamics (CFD) has become a feasible alternative method [1,2] to model flow nonlinearities. However, for the expensive computing time, CFD-based aeroelastic method is usually restricted to few flight conditions and mass configurations [3,4]. To overcome the expensive computational costs involved in solving complex fluid models with large size, the CFD-based unsteady aerodynamic reduced order models (ROMs) is proposed. These models extract key data of the fluid systems to generate a low dimensional system that retains similar accuracy of the full order model while reducing significantly the computational costs. System identification [5–7] and proper orthogonal decomposition (POD) are among the most popular ROMs for nonlinear aeroelastic analysis. For example, Dowell [8] and Lucia [9] demonstrated the use of ROMs to investigate transonic limit-cycle oscillation (LCO). Reference [10] documented a ROM for gust analysis in the transonic regime, providing a fast identification of the worst-case gust. The POD method, in particular, has been successfully applied to the aeroelastic analysis of turbine blades [11,12], helicopter rotor blade [13], wings [14–16] and complete aircraft configurations [17,18]. More recently, the POD has been exercised for transonic aeroelastic analysis [19], active aeroelastic control [20], LCO control [21], gust response analysis [22], and transonic flutter suppression with control delay [23].

Most of the efforts in the ROM community are addressed at improving the model prediction accuracy at a fixed flight condition for a frozen aeroelastic model configuration. Changes to either flight conditions (e.g. Mach number, angle of attack) or model configuration (e.g. mass, geometry) are neglected for the difficulty of accounting for these effects within a single ROM. The limited body of work on this topic consists of the following publications available in the open literature. Epureanu [24] and Lieu [25–27] used ROMs to predict the transonic aeroelastic responses with variations of the free stream Mach number and angle of at-

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tack. Chen [28] proposed a nonlinear POD technique, discussed a support-vector-machine based ROM [29], and presented a linear parameter-varying (LPV) method valid for bounded changes of the flow conditions [30]. Winter [31] presented a novel aerodynamic ROM approach for predicting generalized aerodynamic forces (GAF) based on local linear neuro-fuzzy models considering variations of Mach number. Even fewer studies have shown the ability to capture changes in the mass and stiffness distribution of an aircraft structure within a single aeroelastic ROM. As the mature stage of aircraft design process, with the outer shape being frozen at the early stages, the structural model undergoes multiple changes to guarantee the design target loads are met. Structural modeshapes and associated frequencies are dependent upon the mass and stiffness distribution, and this should be correctly included in an aeroelastic analysis [32].

When a structural modification was made, the structural model need to be updated and the new modeshapes and frequencies need to be recalculated. In an aeroelastic analysis, the influence of changes in the structural model will also propagate to the fluid solution, with both mean and unsteady flow components depending upon the structural model. One approach to update the aeroelastic ROM, referred to the direct method herewith, is the regeneration of the model. For every change of the structural model, this entails calculating: a) the new set of modeshapes and frequencies; b) the mean flow solution that guarantees the aeroelastic equilibrium for the modified structure; and c) the ROM around the new equilibrium position. To overcome the large computational expense, Fenwick [33] used a linear interpolation on a set of available ROMs to obtain a new ROM without regeneration. This approach was shown for the flutter boundary prediction with changes to the local mass distribution (e.g. fuel load distribution). Voss [34] used several synthetic modeshapes that were chosen to exhibit all realistic structural modes. Various unsteady CFD computations were run to generate the ROM database, including the effects on Mach number, reduced frequency and modeshapes. Zhang [35] demonstrated a method to obtain a new ROM using an existing CFD-based auto regressive with exogenous input (ARX) model based on radial basis function (RBF) interpolation for local changes of the root boundary condition. Winter [36] presented two novel CFD-based ROMs robust to variations in the structural modeshapes due to additional lumped mass.

Most of the previous studies focused on local structural modifications and neglected the global level structural modifications. Global changes to the structural parameters are routinely done in the aircraft design process such as optimization and trade-off studies. As the first step, the global level analysis initializes all the global quantities and responses, and then provides information to the local level sub-problem. At the global level, wing modifications generally consist of changes to the mass and stiffness distribution to meet the design target loads [37,38]. This specific problem requires an efficient ROM formulation that has the capability to investigate the impact of that structural modifications on aeroelastic analysis, uncertainty quantification, and optimization design. The novelty of the work in this paper is to develop and implement a time domain aeroelastic ROM which is valid for global structural modifications. The proposed new approximate methodology avoids the computational burden associated with the direct methods by introducing the structural dynamics reanalysis method, which is then embedded within a CFD-based aeroelastic ROM.

The paper continues in Section 2 with a description of the aeroelastic ROM generation. Section 3 provides a background knowledge on the structural dynamics reanalysis method for global structural modifications and discusses the CFD-based new aeroelastic ROM. Section 4 presents the impacts of the global structural modifications on the AGARD 445.6 wing for the time domain aeroelastic response and flutter boundary. Furthermore, the effectiveness, capability, and the advantages measured in terms of accuracy and computational cost of the proposed approach are discussed. Finally, conclusions are given in Section 5.

2. Reduced order model of large scale aeroelastic system

2.1. Flow and structural solvers

The nonlinear aeroelastic system is formulated using the two-field arbitrary Lagrangian–Eulerian (ALE) approach. The governing equations are

$$\frac{d(\mathbf{A}\cdot\mathbf{w})}{dt}+\mathbf{F}(\mathbf{w})=\mathbf{0} \tag{1}$$

$$\mathbf{M}\ddot{\mathbf{d}}+\mathbf{D}\dot{\mathbf{d}}+\mathbf{K}\mathbf{d}=\mathbf{f} \tag{2}$$

where Eq. (1) represents a finite volume discretization of the ALE non-dimensional conservative form of the Navier–Stokes equations. Here, $\mathbf{A}$ is a diagonal matrix containing the cell volumes, $\mathbf{F}$ is the nonlinear numerical flux function, $\mathbf{w}$ is the vector of conservative flow variables, and $\mathbf{d}$ is the vector of structural displacements. Eq. (2) is the finite element discretization of the structural dynamic equations. $\mathbf{M}$, $\mathbf{D}$, and $\mathbf{K}$ are the mass, damping, and stiffness matrices, respectively. $\mathbf{f}$ is the vector of aerodynamic loads calculated at the structural grid points which are derived from solving Eq. (1).

The CFD solver used a multi-block structured cell-centered finite volume discretization, and the second-order Van Leer scheme [39] is applied for the spatial discretization. The dual time-stepping [40] and Lower–Upper Symmetric Gauss–Seidel (LU-SGS) implicit method [41] are used for time integration.A modal representation of the structural model is assumed, without restricting the validity of the approach presented herein. Using generalized (or modal) coordinates, $\mathbf{u}$, the structural displacement field is expressed in the canonical form, $\mathbf{d}=\mathbf{\Phi}\mathbf{u}$, where $\mathbf{\Phi}=[\phi^1,\phi^2,\ldots]$ denotes the modal matrix. Using generalized coordinates, Eq. (2) becomes:

$$\bar{\mathbf{M}}\cdot\ddot{\mathbf{u}}+\bar{\mathbf{D}}\cdot\dot{\mathbf{u}}+\bar{\mathbf{K}}\cdot\mathbf{u}=\mathbf{f}_{gen} \tag{3}$$

where $\bar{\mathbf{M}}=\mathbf{\Phi}^T\mathbf{M}\mathbf{\Phi}$, $\bar{\mathbf{D}}=\mathbf{\Phi}^T\mathbf{D}\mathbf{\Phi}$ and $\bar{\mathbf{K}}=\mathbf{\Phi}^T\mathbf{K}\mathbf{\Phi}$ are the generalized mass, damping and stiffness matrices, respectively. $\mathbf{f}_{gen}$ is the vector of generalized aerodynamic forces:

$$\mathbf{f}_{gen}=\mathbf{\Phi}^T\mathbf{f}\ \text{or for vector element}\ i\text{:}\ \mathbf{f}^i_{gen}=q_\infty\cdot\int_{\mathbf{S}} c_p\cdot\phi^i\circ d\mathbf{S} \tag{4}$$

where $\mathbf{f}^i_{gen}$ is i-th generalized aerodynamic forces, q_∞ is the free stream dynamic pressure, and c_p is pressure coefficient.

2.2. CFD/CSD coupling simulation

A time-domain, fully-implicit, loosely-coupled partitioned approach is employed for the unsteady fluid–structure interaction (FSI) analysis. The process is depicted in Fig. 1. A converged steady-state flow solution is used to initialize the FSI loop. The transfer of the aerodynamic loads from the fluid to the structural field, and the transfer of the structural displacements from the structural to the aerodynamic field are performed using the infinite plate spline (IPS) method [42]. The radial basis functions (RBFs), combined with the transfinite interpolation (TFI) algorithm [43], are then used to warp the fluid volume mesh, based on the new deformed surface grid obtained by mapping the structural displacements onto the fluid surface grid. The iterative process continues to run until the change of the structural displacements between two consecutive iterations is below a given threshold, or the maximum number of iterations is reached. The coupled aeroelastic solver has been validated and applied to several two and three-dimensional aeroelastic models [19,23,44].

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