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Abstract:
In recent decades, enhancements in computational power have led to large changes in aircraft design methodologies. It is now possible to use high-fidelity computational fluid dynamic (CFD) simulations to optimize an airplane's geometry and minimize fuel consumption. These optimization approaches have resulted in new, unconventional aircraft designs with beneficial aerodynamic attributes. However, despite such advancements in computational power, dynamic aeroelastic analysis based on high-fidelity CFD remains prohibitively expensive. Thus, aircraft optimization tools typically omit modeling dynamic aeroelastic behavior. One of the most important dynamic aeroelastic phenomenons is flutter, defined as large amplitude wing oscillations which result from the coupling of fluctuating wing motion and aerodynamic forces. The goal of my research is to develop a computationally efficient flutter prediction algorithm for use as a constraint in aircraft optimization.

A typical flutter analysis algorithm can be divided into two components: the structural model, which approximates the wing's deflection based on applied aerodynamic forces, and the aerodynamic model, which approximates these forces based on the wing's deflection. High-fidelity flutter analysis typically involves solving both these models simultaneously to determine if the transient oscillations of a perturbed wing will decay or grow, the latter resulting in flutter. However, due to the computational cost of the unsteady CFD simulations, each aeroelastic simulation is time consuming, and a large number are required to predict the onset of flutter for a complete flight envelope. Alternatively, one could couple both the structural and aerodynamic models into a single monolithic system and analyze the eigenvalues of the Jacobian for varying flight conditions. The point at which any eigenvalue crosses the imaginary axis (i.e. gains a positive real value) determines the onset of flutter. Unfortunately, due to the large number of degrees-of-freedom (DOF) in the high-fidelity CFD model, computing the eigenvalues is also computationally intractable. Therefore, it is evident that any increase in computational efficiency would stem from the aerodynamic model.

Recently, model order reduction techniques have been used to create fluid models with significantly fewer DOF than their full-order counterparts. The concept of model order reduction is as follows: in many cases, the solution to a system of equations lies on a manifold of fewer dimensions than the original system. If one were able to capture this manifold in a given space, and project the full-order model onto this space, the resulting system would have

fewer DOF but still be capable of capturing the correct solution. For the aerodynamic model mentioned above, the full-order system is the high-fidelity CFD model, and the solution we seek is a vector of flow states (mass, momentum, and energy) at each node in the CFD mesh. This solution is time dependent, and thus the “solution manifold” we seek represents the evolution of these flow states in time due to the motion of the airplane wing. For this research, the concept of model order reduction translates to assuming the solution to our flow model can be expressed as a linear combination of basis vectors with time-dependent coefficients.

The challenge now becomes to determine what flow behavior should be included in the basis vectors used to create our aerodynamic reduced-order model (ROM). For flutter analysis, the dynamic behavior of the structure is well approximated using a few structural mode shapes associated to the lowest natural frequencies. Knowing this, it becomes evident that the basis vectors used to create the aerodynamic ROM should thus span the unsteady flow solutions created by the excitation of each structural mode shape. This is exactly what is done in this work; during a full-order CFD simulation, each mode shape is separately given an impulse. At each time step, the vector of flow states in the full-order system is saved to memory; these are referred to as snapshots. Once all snapshots are collected for each flow simulation, a technique called proper orthogonal decomposition is used to process the snapshots into a usable set of basis vectors.

It becomes clear that, with its reduced number of DOF, the aerodynamic ROM is significantly more computationally efficient than the full-order CFD model. But, one still needs to run the full-order model in order to generate the snapshots used in the creation of the ROM. For this research, in order to reduce the computational costs of snapshot creation, the flow equations are linearized with respect to the flow state, aircraft wing position, and aircraft wing velocity. This linearized flow model is faster to solve compared to the nonlinear model because system matrices need not be recomputed during a simulation. Moreover, important flow characteristics, such as shock motion, are still captured for small wing motion; thus the linearized equations are still relevant for flutter analysis in nonlinear regimes.

Importantly, the full-order CFD model, and thus the resulting ROM, are nondimensionalized for free stream dynamic pressure. Dynamic pressure then becomes an external parameter, analogous to the level of influence the aerodynamic forces have on the structural deformation. Typically, the aerodynamic ROM contains no more than a few hundred DOF. Similarly, the structural system can be limited to tens of DOF. Coupling both these systems together, one can rapidly determine the eigenvalues of the coupled aeroelastic system for various values of

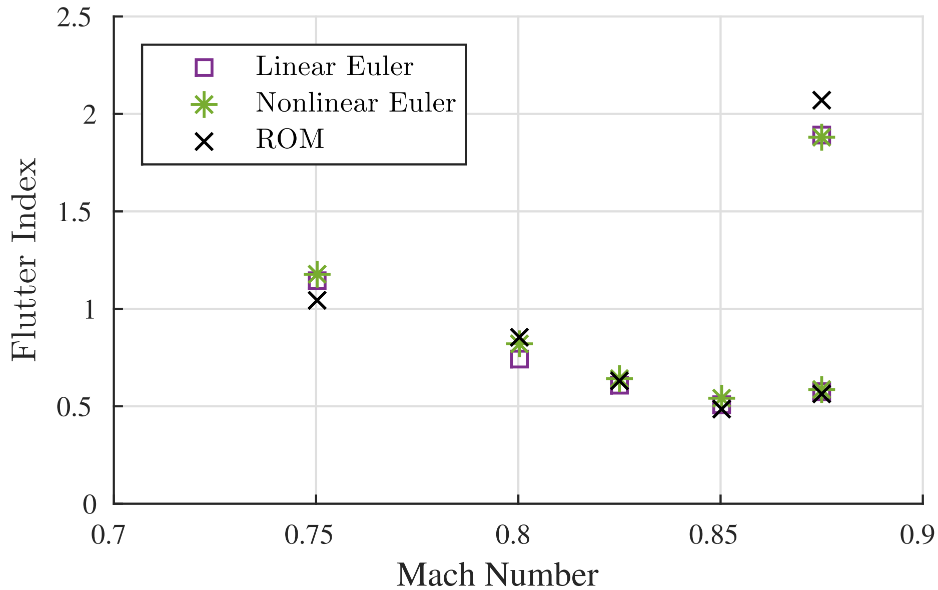

Figure 1: Flutter boundary for a two-DOF airfoil obtained the nonlinear and linearized Euler equations, and by the ROM.

dynamic pressure. As previously mentioned, the onset of flutter is indicated by any eigenvalue in the system gaining a positive real part.

Results for the flutter boundary of a two-DOF airfoil, capable of pitching and plunging in the transonic flow regime, are shown in Figure 1. It is observed that the ROM predicts the flutter boundary well compared to the full-order models. Notably, the ROM is capable of capturing the "dip" in the flutter boundary at Mach 0.85 caused by the motion of the shockwave on the upper surface. Currently, a new aerodynamic ROM is created for each Mach number of interest. Future work includes integrating a parametric framework which will allow the ROM to predict aerodynamic forces at various Mach numbers.

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