# Reduced-Order Modeling for Transonic Wing Flutter Analysis Including Effects of Control Surface and Nonzero Angle of Attack

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#### Introduction

In the past much effort has been made to utilize advanced computational fluid dynamic (CFD) programs for aeroelastic simulations and analyses of military and civil aircraft. Although the use of CFD has become broad for static aerodynamic calculations nowadays, it is limited in the field of unsteady aeroelasticity due to enormous size of computer memory and unreasonably long CPU time associated with the large number of mode shapes in the structural model. While a military airplane model may need 20-50 modes, commercial aircraft models typically require as many as 200 modes to describe the motion of the structure with sufficient accuracy. Thus, both aeroelastic and CFD researchers have explored and developed various ways to reduce the size of the unsteady aerodynamic system and minimize the memory and CPU time. Unfortunately, although these reduced-order models (ROM) retain much of the characteristics of the original full-order models and reproduce the full responses quickly and faithfully, very few of them can be constructed in a time period short enough to justify such an effort, especially when faced with the multiple mode inputs.

In this paper, a new aeroelastic reduced-order modeling based on coupled CFD-CSD aeroelastic responses with a reduced set of state variables is presented. Recently, a novel system identification and model reduction technique, also known as "Aerodynamics is Aeroelasticity Minus Structure" (AAEMS) was developed for linear time-invariant, coupled fluid-structure systems [1]. The method has been successfully applied based on numerical simulations of a scaled Boeing Commercial Aircraft model and AGARD Wing model [1]-[2] (See Figs. 1 and 2), and experimental data obtained of a rigid wing in subsonic wind tunnel [3] (Fig. 3).

The objective of this paper will be to continue this effort and find flutter instabilities of the AGARD Wing in transonic flows including effects of control surface and nonzero angle of attack. Towards this end, a control surface will be attached to the trailing edge of the wing and deflected at an angle. Then, the entire wing plus control surface will be put at a nonzero angle of attack. It is noted that the effects the angle of attack including the deflected control surface on the flutter instability in transonic flow zone have rarely been explored in the literature.



Figure 1. The Twin-Engine Transport Flutter Model (TETFM) in the Transonic Dynamic Tunnel



Figure 2. AGARD 445.6 Wing



Figure 3. 3D Experimental Wing

### AAEMS

Unlike all of the previous ROM methods, the AAEMS works directly on time history data of the coupled aeroelastic system and therefore provides a realistic, easy and efficient tool to construct the aeroelastic ROM. Most importantly, the traditional mode-by-mode excitation of the unsteady aerodynamics is avoided saving a significant amount of model construction time and hence making the method very attractive for the practical applications. Assuming that structural properties are known a priori, and using linear transformations between the structural and aeroelastic states, it extracts and models the underlying unsteady aerodynamic system in discrete-time, state-space format with a finite number of state variables. The displacements and velocities of the structural coordinates are recorded in real time during the numerical simulations. In addition, unsteady pressures are recorded at various points on the lifting wing surface. All the responses are obtained for a fixed Mach, at a low sub-critical dynamic pressure value.

#### Method of Excitation and Static Condensation

To search for an efficient way to excite the aeroelastic model, various combinations of the structural coordinates as well as control surfaces can be used as potential inputs. It is important to make sure that all the important system modes

are perturbed by the excitation. If control surface inputs are not available, one can use initial conditions instead because a system response due to an initial condition is mathematically equivalent to a response due to an impulse input. Also, to find an optimum number and locations of the aerodynamic samples, different combinations of the pressures at different locations will be explored and the result will be reported in the paper. Considering that the aerodynamic flow will be highly nonlinear in transonic zone, it is critical to apply an input with a very small magnitude to extract only a statically nonlinear but dynamically linear (SNLDL) aerodynamic system. To this end, it is useful to check coherence functions of the various measurements and select only the responses that are linear or sufficiently linear for the system identification. Another issue encountered in the data processing is how to use the time histories that have mixed static/dynamic effects. Normally, unsteady CFD simulation is run after a steady-state equilibrium condition is established first because it might be different than the initial state at t=0. However, running the steady solution separately increases the CPU time significantly and therefore in this paper we will directly advance to the unsteady simulation without the steady calculation, mixing the steady and unsteady parts together. An analytic scheme will be developed such that the resulting time history contains only the effects of the unsteady part and hence is appropriate for the system identification. This so called 'static condensation' is necessary not only for extracting the unsteady solution part but also to avoid 'drifting' mode in the resulting reduced-order model. After the aerodynamic model is identified, an aeroelastic model can be constructed in discrete-time, state-space format by coupling the structural model and the aerodynamic system. The resulting reducedorder model is suitable for constant Mach, varying density (CMVD) analysis including flutter prediction and dynamic response calculation.

# **CFD Solver and AGARD Wing Model**

For application and verification of the method, the aforementioned AGARD Wing model with five structural modes will be studied. An in-house Euler solver developed by Temasek Lab will be used for the CFD part. Since the wing will be at nonzero angle of attack and produce nonzero static response, the static condensation method mentioned above will be critical in eliciting dynamic responses necessary for the system identification. It is also expected that the coupled responses will be highly nonlinear (the structural model is assumed to be linear) due to strong shock waves and numerical artifacts, so the optimum signal processing will be very important in constructing the SNLDL ROM successfully. Aeroelastic results including flutter speeds obtained from the reduced-order model will be compared to results of the full-order models, and whenever available will be compared with experimental results for various Mach conditions.

It is expected that the proposed new process will generate aerodynamic and aeroelastic ROMs that are useful for the analysis of flutter under the influence of nonzero angle of attack and deflected control surface with minimum amount of effort and time.

# **References**

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