

BUFFET ONSET PREDICTION WITH THE LINEARIZED FREQUENCY-DOMAIN METHOD

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ABSTRACT

A method to predict transonic buffet onset using a linearized frequency-domain computational fluid dynamics (CFD) solver is presented. A state-space aerodynamic model is built from linearized frequency-domain (LFD) data by means of the Loewner framework, and buffet stability is determined from the eigenvalues of this model. Results indicate accurate prediction for the NACA 0012 and ONERA OAT15A airfoils and the CRM configuration.

Transonic buffet is an aerodynamic instability over a wing that generates vibrations, occupant discomfort and structural fatigue; predicting its onset is essential to avoid buffet at specific flight conditions. Although time-domain CFD can characterize buffet, Crouch et al. [1] showed that buffet onset can be formulated as a linear stability problem and computed with global stability analysis (GSA), using the real parts of the eigenvalues of the linearized aerodynamic system. LFD, widely used for aeroelastic flutter [2,3] and gusts, is a linearized approach. Instead of computing stability directly from the full-order system, LFD computes frequency-domain generalized aerodynamic forces (GAFs) in response to harmonic perturbations of the flow equations linearized about a nonlinear equilibrium.

Quero et al. [4] constructed a state-space model from LFD outputs using Loewner tangential interpolation and computed flutter responses with the p - L method. In Quero et al. [5], this LFD-based aerodynamic model was coupled with the structural equations to capture instabilities of a fluid mode from pre-buffet conditions (a type-II instability on the fluid mode [6]). The present work extends this process to predict buffet onset for rigid configurations, i.e. a purely aerodynamic instability.

The eigenvalues of the state-space aerodynamic model define its aerodynamic, or fluid, poles and thus its stability. The reduced number of aerodynamic states, compared with the full CFD model, makes eigenvalue computation cheaper than in GSA. Dominant fluid modes are identified by residues from the two-sided Rayleigh quotient, computed for each mode j :

$$\mathbf{R}_j = \frac{(c_a \phi_j)(\psi_j^* B_a)}{\psi_j^* E_a \phi_j},$$

where ϕ_j and ψ_j are the right and left eigenvectors associated with eigenvalue $\lambda_{a,j}$ and $*$ denotes complex conjugation. The significance of the pole j is quantified by

$$\delta_j = \frac{\|\mathbf{R}_j\|_2}{\text{Re}(\lambda_{a,j})}, \quad j = 1, \dots, n_a.$$

Buffet onset is identified when the eigenvalue of the dominant fluid mode crosses the imaginary axis, i.e. when its real part changes from negative to positive.

A key novelty is to allow physically unstable fluid poles in the realization of the aerodynamic

data in the frequency domain. Unstable fluid poles are defined as those with $\text{Re}(\lambda_{a,j}) > 0$. To distinguish physical unstable fluid poles (associated with buffet) from spurious ones introduced by interpolation of the GAF matrix, only unstable poles satisfying

$$\frac{\delta_j}{\delta_{\max}} > \delta_u, \quad \text{Re}(\lambda_{a,j}) > 0, \quad j = 1, \dots, n_a,$$

are retained, where $\delta_{\max} = \max(\delta_j)$ and $\delta_u \in (0, 1)$ is a prescribed threshold.

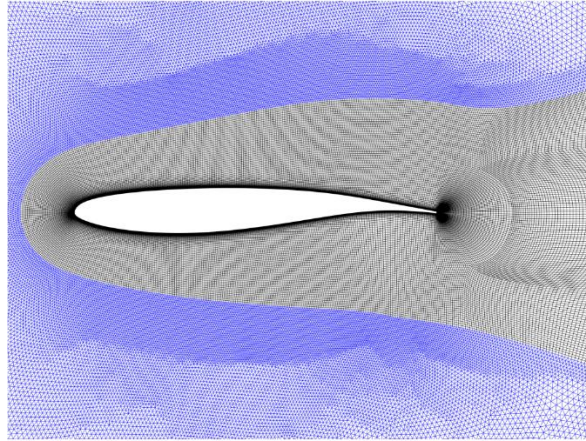


Figure 1: OAT15A airfoil computational mesh.

For the OAT15A airfoil [7], Figure 2 shows the evolution of the dominant fluid eigenvalue, defined as the one with maximum δ_j , as the angle of attack increases. Buffet onset is predicted between 3.1° and 3.2° , in good agreement with the dominant eigenvalue from GSA. In this case, the Loewner realization is built from the lift coefficient associated with a pitch degree of freedom whose rotation axis lies at 40% of the chord, but other aerodynamic quantities computed with LFD lead to the same dominant eigenvalue.

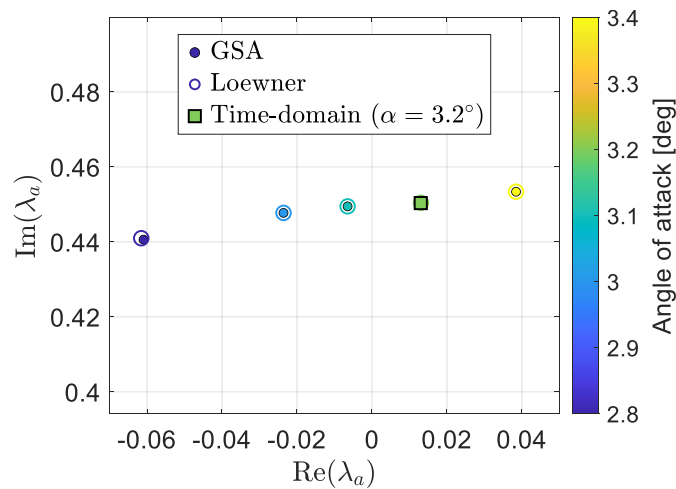


Figure 2: Dominant fluid eigenvalue from Loewner-LFD model vs GSA for the OAT15A airfoil.

For the CRM configuration at Mach 0.85, Reynolds number 5 million, and angle of attack 3.75° , Figure 3 shows the steady pressure distribution, with a shock on the upper wing surface and a separated-flow region downstream of the shock, characteristic of buffet conditions. Figure 4 compares the pitch–pitch component of the GAF matrix for the CRM configuration [8] obtained from the Loewner model including the unstable buffet pole with the reference LFD results in the frequency domain; this close agreement is only obtained when the unstable eigenvalue representing buffet is retained.

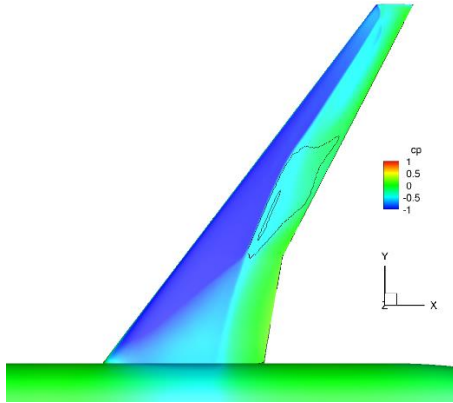


Figure 3: Steady pressure over the CRM wing at Mach 0.85, angle of attack 3.75° .

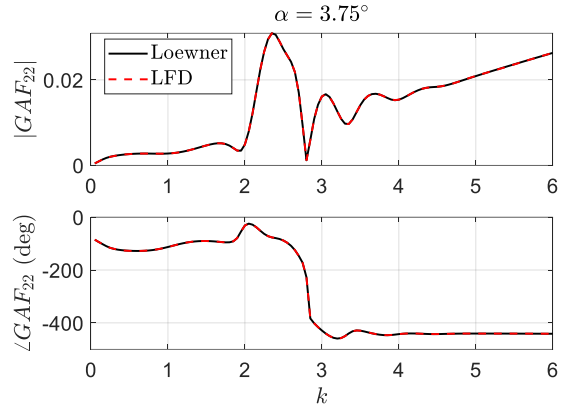


Figure 4: Pitch–pitch GAF component vs reduced frequency: Loewner realization vs LFD reference.

Different aerodynamic quantities, including GAF components and the lift coefficient, have been used to extract the dominant fluid eigenvalue. In all cases, the dominant fluid modes were insensitive to the chosen quantity, demonstrating a robust extraction of dominant fluid eigenvalues from LFD. Figure 5 shows representative subsets of the fluid eigenvalues obtained from the Loewner realization and from GSA, illustrating that for the 3D CRM configuration the LFD-based Loewner model captures the dominant buffet-driving eigenvalues. Dominant fluid eigenvalues lie close to the imaginary axis and strongly influence the transfer function along this axis, whereas eigenvalues with more negative real parts have little influence. Matching the transfer function on the imaginary axis therefore ensures that the Loewner realization captures the eigenvalues responsible for buffet onset.

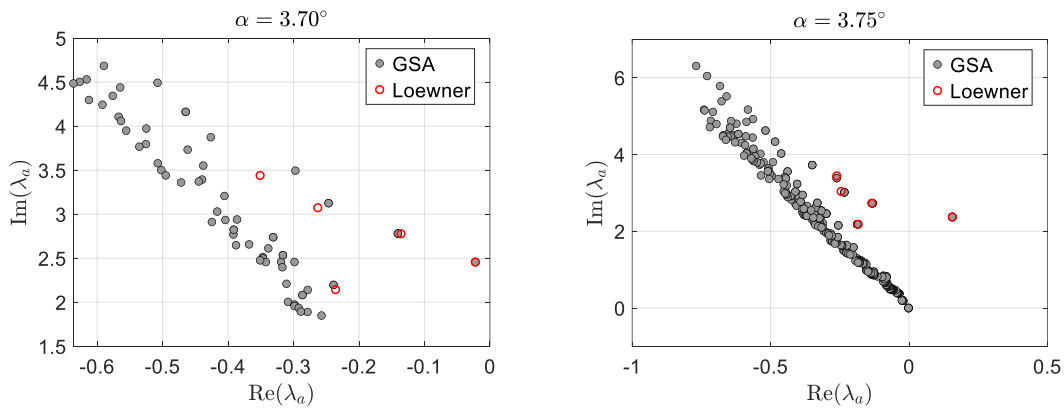


Figure 5: Dominant fluid eigenvalues from Loewner–LFD model vs GSA for the CRM configuration at two angles of attack.

Predicting buffet onset from LFD supports efforts toward a unified framework for flutter and buffet analysis. The present work demonstrates the applicability of this approach to unstable aerodynamic systems in buffet conditions and to realistic 3D configurations. The final paper will present NACA 0012 results, further discussion, and initial extraction of the dominant fluid eigenmode from LFD data.

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