

PREDICTION OF FREEPLAY-INDUCED AEROELASTIC LIMIT CYCLE OSCILLATIONS USING THE LOEWNER FRAMEWORK

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ABSTRACT

Nonlinear aeroelastic responses caused by structural freeplay remain a major challenge in predicting and certifying aircraft behavior. Even small freeplay gaps in control surfaces or hinge mechanisms can generate finite-amplitude limit cycle oscillations (LCOs) or chaotic responses, including subcritical cases in which LCOs appear below the linear flutter boundary, none of which can be captured by linear analysis. Over several decades, most research has examined simplified aeroelastic models based on two-dimensional typical sections and incompressible unsteady aerodynamics. Classical studies used low-order aerodynamic representations such as state-space realizations of the Theodorsen function, the equivalent Wagner formulation or Peters type finite-state models. These approaches have been widely applied to investigate the onset, amplitude and stability of LCOs induced by freeplay, as well as the sensitivity of the response to initial conditions.

Only a smaller portion of the literature has focused on developing efficient state-space aerodynamic models suitable for nonlinear aeroelastic computations. Most studies rely on the doublet lattice method [1] to obtain low-order unsteady aerodynamic models, while a more limited number use Euler-based formulations [2] and only a few employ URANS [3]. When CFD solvers are used, the usual strategy is to perform time-marching simulations followed by time-domain system identification using techniques such as ARX [3] or ERA [4]. Although effective, these methods require extensive time-domain sampling and become increasingly expensive when many flow conditions must be analyzed. In contrast, the present work uses frequency-domain aerodynamic data directly, ranging from DLM to the linear frequency-domain (LFD) implementation of the URANS equations, which enables the construction of efficient state-space realizations without time-domain identification.

Recent work has incorporated transonic effects into freeplay-induced LCO analysis using CFD-based solvers. However, the associated computational effort remains high. This highlights the need for modeling strategies that capture high-fidelity aerodynamic behavior while remaining suitable for nonlinear structural analysis.

The present work addresses this need through the Loewner framework, which is used to construct compact and accurate state-space realizations of unsteady aerodynamic forces. These realizations are generated directly from frequency-domain samples of the generalized aerodynamic forces, obtained from solvers ranging from DLM to the LFD formulation of the URANS equations. By relying solely on frequency-domain data, the Loewner realization avoids time-domain CFD simulations and eliminates system-identification steps. The resulting aerodynamic models are computationally efficient, suitable for nonlinear aeroelastic analysis and capable of incorporating high-fidelity transonic effects.

Once the aerodynamic contribution is represented in state-space form, the nonlinear structural behavior is introduced by adding a freeplay function in the selected degrees of freedom. This yields a nonlinear aeroelastic state-space model that retains the fidelity of the high-fidelity

aerodynamics while allowing localized structural nonlinearities to be represented explicitly. Other nonlinearities such as friction or piecewise stiffness laws may be included similarly, although the focus here is on freeplay in the control-surface rotation.

Limit cycle oscillations are computed using a harmonic balance (HB) method with a chosen number of harmonics. Compared to time-domain integration, HB offers two key advantages. First, it can determine both stable and unstable LCOs, which is essential for problems exhibiting subcritical bifurcations. Second, once an efficient aerodynamic realization is available, HB is significantly faster than time-marching. However, HB alone cannot capture chaotic responses, which may occur for certain parameter sets. Therefore, HB and time-domain integration are used in a complementary manner, with HB used to determine periodic solutions and time-domain simulations used to explore aperiodic or chaotic dynamics.

A suitable initial guess is required for the HB solver to converge. This initialization is obtained using the equivalent linearization approach, which corresponds to HB with a single harmonic and allows the use of standard flutter methods such as the p - k , g , p and p - L [5] techniques when the freeplay acts in a single structural degree of freedom. In this work, a modified p - L method is implemented that incorporates the Loewner aerodynamic realization together with describing functions. This nonlinear p - L method provides consistent initial conditions for the multi-harmonic HB solver. For configurations with freeplay in several degrees of freedom, further adaptations based on existing approaches in the literature must be applied.

The methodology is demonstrated on a classical three-degree-of-freedom airfoil section with heave h , pitch θ and control surface rotation β . The freeplay nonlinearity is introduced in the hinge of the control surface. This configuration exhibits sustained LCOs when subjected to nonzero initial conditions, even in the absence of external forcing. Depending on the parameter set, the system may display multiple LCO branches or transitions to chaotic behavior. A schematic of the configuration is shown in Figure 1 [6].

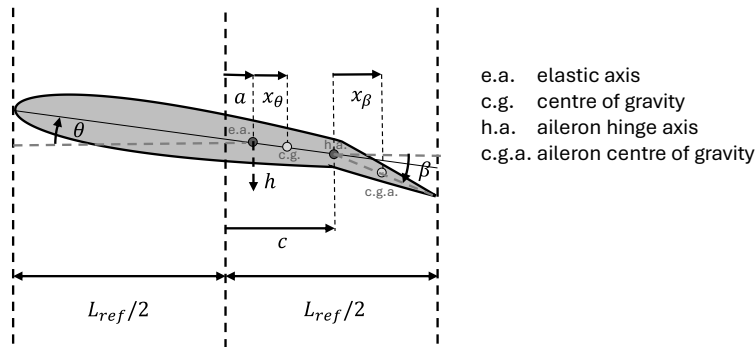


Figure 1: Typical airfoil section with three structural degrees of freedom.

Figure 2 presents the control-surface amplitude at the LCO condition, obtained with the modified nonlinear p - L method for several airspeeds U in incompressible flow. The airspeed is nondimensionalized by the flutter speed U_{F0} of the corresponding linear system without freeplay. The color scale indicates the dominant aeroelastic mode whose damping becomes zero at the LCO condition, revealing two distinct LCO branches. Figure 3 also shows a heave-dominated LCO obtained with the HB method using seven harmonics, initialized from the LCO predicted by the nonlinear p - L method, and compares it with time-domain integration of the nonlinear aeroelastic state-space model. In both cases, the unsteady aerodynamics are

represented by a Loewner realization. In the full paper, the analysis will be extended to transonic Mach numbers using unsteady aerodynamic forces computed with the LFD URANS solver.

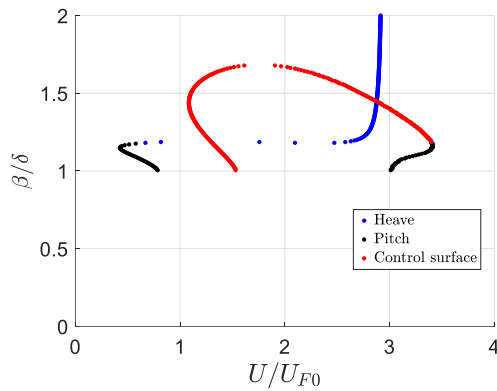


Figure 2: Control-surface amplitude at the LCO condition for different airspeeds, showing two branches.

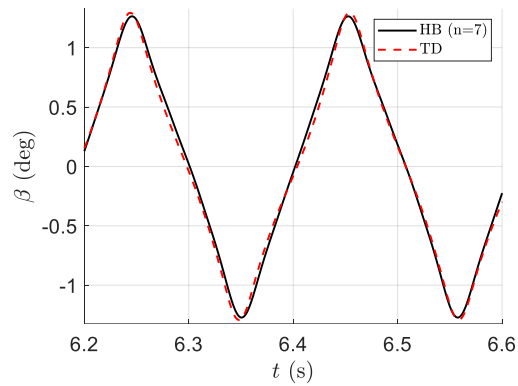


Figure 3: Control-surface amplitude of a heave-dominated LCO: HB with 7 harmonics vs time-domain results.

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