Abstract for IFASD 2026

June 16–18, 2026, Göttingen, Germany

Prediction of Critical Aeroelastic Damping Using Dynamic Eigen Decomposition of Sensor Measurements

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During the design and test phases of aircraft structure, to ascertain stability and structural integrity of the airplane aeroelastic damping coefficients are computed using analysis tools such as the p-k iterations and eigenvalue solvers. Also, for certification of the airplane aeronautical industry typically undergoes aeroelastic damping extrapolation during flight flutter test (FFT). The flight testing tailored for the task requires conducting multiple tests at multiple different flight conditions making it time-consuming and expensive. Furthermore, the technique cannot estimate the damping beyond the test points, that is, it lacks the critical ability to predict the damping at points that have not been tested yet. In this paper, to remedy these shortcomings a new frequency domain approach for aeroelastic damping estimation and prediction is introduced based on the Dynamic Eigen Decomposition (DED) of the test data with an artificially imposed structural damping. Previously, the DED was used to develop a new theory of flutter prediction [1] and later it was modified for applications with limited actuators and sensors [2] and for prediction of limit cycle oscillation (LCO) [3].

Assuming a damping coefficient ζ_i for the i-th aeroelastic mode and the corresponding aeroelastic eigenvalue as $-\zeta_i \omega_{Ni} \pm j\omega_{Ni}\sqrt{1-\zeta_i^2}, g_i \equiv 2\zeta_i$, aeroelastic EQM in the modal coordinates $\boldsymbol{q}$ can be written as follows,

$$\boldsymbol{M}\ddot{\boldsymbol{q}} - g_i \omega_{Ni} \boldsymbol{M}\dot{\boldsymbol{q}} + \boldsymbol{K}\boldsymbol{q} = q_D \boldsymbol{Q}(k)\boldsymbol{q}$$

where the second-order term, $\zeta_i^2 \omega_{Ni}^2 \boldsymbol{M}$ is ignored. This approximation will be accurate if the mode being investigated is *lightly damped*. Practically speaking, it is not a serious drawback because if a mode is heavily damped it will not be threatening to the safety of the aircraft. The analysis of the EQM is carried out following a constant Mach line but by changing altitude, that is, by allowing dynamic pressure to vary. In reality, one can only work with sensor outputs rather than the modal responses and hence the above EQM will be replaced with another equation described in the sensor degrees of freedom. From the dynamically decomposed data modified with the artificial structural damping, neutrally stable solutions are sought by applying the Multi-Inputs Multi-Outputs (MIMO) Nyquist stability criterion and varying the two parameters, dynamic pressure and artificial damping. Then, the amount of the negative structural damping added is interpreted as the true aeroelastic damping at the subcritical point.

In the upcoming IFASD presentation and paper, the proposed scheme will be demonstrated using computational simulations of a tapered straight wing with four flaps along the trailing edge. It will be shown that the proposed method can yield and predict accurately aeroelastic damping of critical modes, i.e., lightly damped modes, at all subcritical conditions all the way up to the flutter point and beyond without the need for multiple tests, and hence it is ideal for flight flutter testing.

References

[1] Kim, T., Flutter Prediction Methodology Based on Dynamic Eigen Decomposition and Frequency-Domain Stability, Journal of Fluids and Structures 2019; 86; 0-13.

[2] Kim, T., Progressive Flutter Prediction Using Flight Data with Limited Actuators and Sensors, Journal of Fluids and Structures, 138 (2025) 104372.

[3] Kim, T., Prediction of Limit Cycle Oscillations Based on Dynamic Eigen Decomposition of Flight Data, International Forum on Aeroelasticity and Structural Dynamics, The Hague, Netherlands, June 17-21, 2024.

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