

STATE-SPACE AEROELASTIC FLUTTER ANALYSIS OF A FIXED-WING EVTOL AIRCRAFT WITH ROBUST MODAL TRACKING AND CONTINUATION TECHNIQUES

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ABSTRACT

Flutter prediction based on the stability of state-space system matrices remains a significant challenge in aeroelastic design and certification, particularly due to mode-switching phenomena that occur in conventional fixed-wing configurations. These effects frequently lead to inconsistent state identification when classical eigenvalue sorting techniques are applied. This study aims to enhance the robustness and reliability of flutter analysis via state-space realization for fixed-wing unmanned eVTOL aircraft by employing advanced modal tracking and continuation-based eigenvalue analysis techniques. A global finite element model (GFEM) of the aircraft is developed, incorporating the flexible airframe, control surfaces, and is validated through modal analysis prior to aeroelastic investigation. Unsteady aerodynamic forces are modelled within MSC NASTRAN software, which uses double-lattice method (DLM), and flutter analysis is first performed using the classical p-k method to establish a reference solution and extract generalization aerodynamic force matrices over the reduced frequency range of interest. The aerodynamic matrices are subsequently approximated using a Least-Squares Rational Function Function Approximation (LS-RFA), enabling the formulation of a velocity-dependent state-space aeroelastic model suitable for eigenvalue-based stability analysis. Flutter predictions obtained from the state-space formulation showed very good agreement with the classical p-k results, with both approaches predicting flutter speed at approximately 9.3 m/s. The instability mechanism is identified as coupling between the first symmetric wing bending mode and a rigid-body aileron rotation mode. Despite the agreement in flutter speed, conventional eigenvalue sorting based solely on frequency and damping is shown to be insufficient for consistent modal tracking across the velocity sweep, resulting in mode switching and discontinuities, particularly in regions of strong modal interaction. To address this limitation, a robust modal tracking algorithm based on combined left- and right-eigenvector orthogonality is implemented within the state-space framework, significantly improving modal continuity. However, residual issues were still observed at low speed resolution and when a large number of modes were included. These are mitigated through the application of a continuation-based eigenvalue tracking method applied directly to the velocity-dependent system matrix, enabling smooth and continuous modal trajectories and allowing larger velocity step sizes without loss of accuracy. The results demonstrate that the combined use of LS-RFA-based state-space aeroelastic modelling, robust eigenvector-based modal tracking, and continuation techniques substantially enhances the robustness of the flutter prediction and provides a reliable framework for aeroelastic stability assessment using state-matrix in complex aircraft systems.