

STRUCTURAL BLENDING FOR ACTIVE FLUTTER SUPPRESSION

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ABSTRACT

This paper presents a control design methodology for active flutter suppression. Flutter denotes a self-excited aeroelastic instability arising from the interaction of unsteady aerodynamics with structural dynamics. Traditional airframe design mitigates flutter risk by maintaining a large margin to the open-loop flutter boundary, which increases structural weight and constrains the use of high-aspect-ratio, lightweight wings (Livne, 2018). Active flutter suppression (AFS) aims to increase the damping of critical aeroelastic modes via feedback control, thereby relaxing those structural penalties (Butz, Friedrichs, Henke, & Hornung, 2025). A rectangular wing exhibiting bending-torsion flutter is modelled using the linear Finite Element Method (FEM) in combination with the Doublet Lattice Method (DLM) (Böhnisch, Braun, Koschel, & Marzocca, 2022). Modal analysis of the structural FEM submodule shows that both the bending and the torsion eigenmode are well observed by distributed vertical acceleration measurements. Dually both the bending and torsion mode can be independently acted upon through four spanwise distributed leading edge slats and four trailing edge flaps. Fig. 1 depicts the wing model used in this work. Red arrows indicate acceleration measurements.

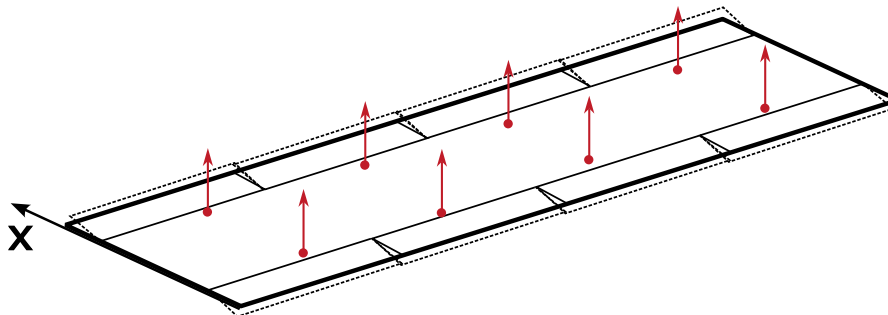


Fig. 1 Rectangular Wing Geometry

Leveraging this property, a linear combination of the eight accelerometer signals is computed to isolate the relevant structural eigenmodes in a two-channel virtual output. The eight control surface deflection commands are linearly combined into a two-channel virtual input. A low-order structured H_∞ controller is then synthesized on this reduced two-by-two interface, targeting robust stabilization up to a specified freestream velocity with prescribed gain and phase margins while minimizing control effort. The H_∞ synthesis scheme is inspired by works of (Theis, Pfifer, & Seiler, 2020). Relative to an H_2 -optimal SISO blending baseline introduced by (Pusch, 2020), the proposed approach achieves increased flutter damping and reduced control effort. In contrast to other blending schemes the proposed structural blending is independent of the freestream velocity. The architecture further supports sensor fault tolerance by precomputing blending matrices for alternative sensor configurations, enabling reconfiguration without modifying the controller dynamics.

The central idea is to retain only the relevant structural modal information on the sensor side and confine the actuation to the relevant structural modes.

Concretely this work includes:

1. A least-squares optimal structural blending framework that (i) constructs output and input blends as Moore-Penrose pseudoinverses of the dominant structural modes output and input matrices, (ii) preserves bending/torsion acceleration and minimum-effort actuation maps exactly on bending/torsion, and (iii) defines a well-conditioned, fault-reconfigurable virtual interface for structured H_∞ synthesis.
2. A Gram-determinant metric for controllability and observability of structural mode(shape)s that (i) quantifies the independent measurability and excitability of structural modes via the squared volume spanned by the corresponding output/input vectors, (ii) is insensitive to rotation and common rescaling, and (iii) predicts the conditioning (i.e., noise/effort amplification) of least-squares blends.
3. A structured H_∞ controller design (systune) on a reduced two-by-two virtual interface that balances active structural damping and actuator economy, while maintain robust stability up to a specified freestream velocity with prescribed gain and phase margins.
4. A benchmark comparison against the H_2 -optimal SISO blending method of (Pusch, 2020), demonstrating improved flutter damping and reduced control effort in simulation.
5. An open-source MATLAB/Simulink implementation for reproducibility and extension.

Static blending matrices $M_y \in R^{n_c \times n_y}$ and $M_u \in R^{n_u \times n_c}$ are proposed. The *virtual output* and *virtual input* are

$$y_v = M_y y, \quad u = M_u u_v,$$

The resulting feedback loop is shown in Fig. 2.

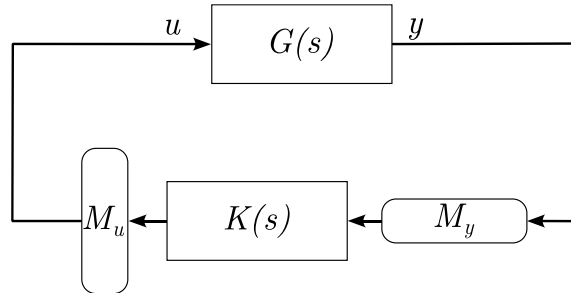


Fig. 2 Block Diagram of proposed Feedback Control

The approximation quality and robustness hinge on how independently the critical structural modeshapes are seen in y and excited by u . The proposed blending matrices for the rectangular wing model are computed as

$$\mathbf{B}_{fx} = \frac{1}{2} \rho V_{\infty, \text{ref}}^2 S_{fj} \left(\mathbf{Q}_{jj}^0 \mathbf{D}_{jx}^{Re} + \sum_{i=1}^{n_p} \mathbf{Q}_{jj}^{Lp_i} \mathbf{D}_{jx}^{Re} - \mathbf{D}_{jx}^{Im} \frac{2p_i}{c_{\text{ref}}} \right),$$

$$\mathbf{M}_{\mathbf{u}} = \mathbf{B}_{fx}^{(1:2,:)}{}^\dagger, \quad (\text{pseudo-inverse of the first two rows of } \mathbf{B}_{gx})$$

$$\Phi_{zf} = \Phi_{zg} \Phi_{gf},$$

$$\mathbf{M}_{\mathbf{y}} = ((\Phi_{zf})_{:,1:2})^\dagger, \quad (\text{pseudo-inverse of the first two columns of } \Phi_{zf}),$$

where S_{fj} is the aerodynamic force summation, $Q_{jj}^0, Q_{jj}^{Lp_i}$ reflect the unsteady aerodynamics, D_{jx}^{Re}, D_{jx}^{Im} map actuator deflections to aerodynamic downwash conditions, c_{ref} is the reference chord length, p_i are the unsteady aerodynamics poles, V_∞ the freestream velocity, ρ the air density and Φ_{zf} is the linear mapping from modeshapes to vertical displacement at the IMU positions.

The structural blending controller achieves robust stabilization across the required range of freestream velocities. Fig. 3 compares classical Vg-Plots of the Structural and the H_2 -optimal blending controllers.

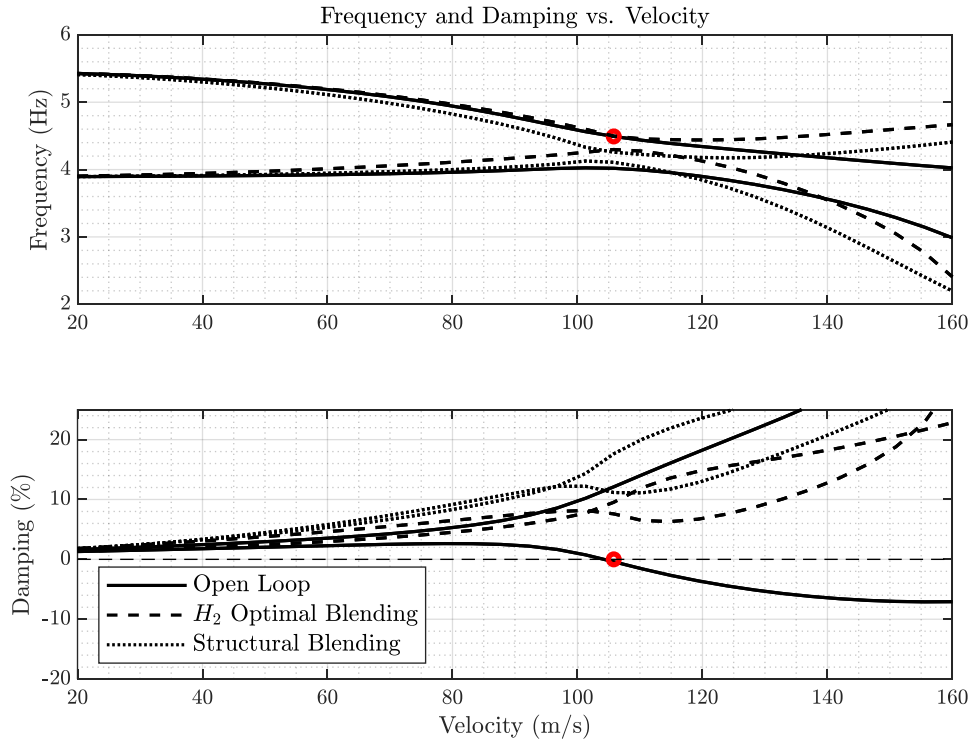


Fig. 3 V-g-Plot H_2 vs. Structural Blending

Modal damping performance is quantified through singular value analysis of the closed-loop transfer function from disturbance forces to structural deformation outputs.

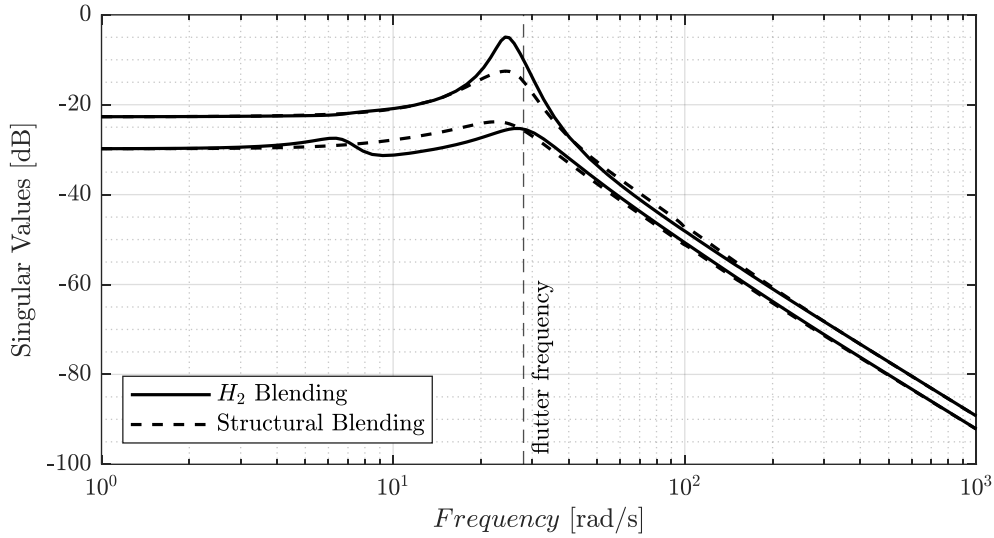


Fig. 4 Disturbance to Structural Deformation

Fig. 4 shows that the structural blending controller significantly attenuates the peak response to disturbances, in the flutter-critical frequency band around 4.5 Hz. This indicates effective suppression of flutter-induced structural oscillations. The H_2 -optimal controller exhibits slightly improved performance in non-critical bands, but the proposed controller outperforms it decisively in the flutter band. The residual sensitivity is spread evenly across adjacent frequency bands.

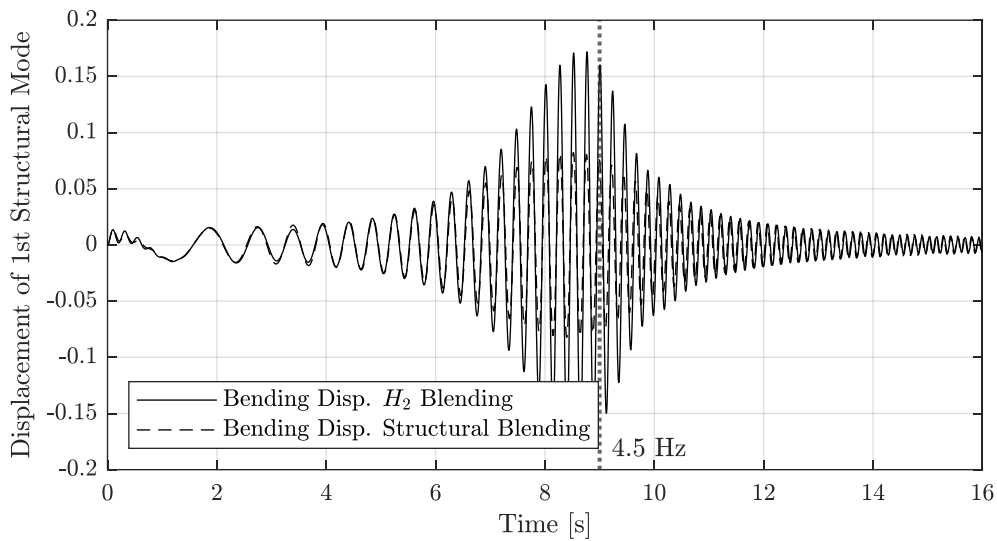


Fig. 5 Time-Simulation Bending Displacement

Time-domain validation is provided via a frequency sweep excitation applied to the bending mode. The disturbance input sweeps linearly from 0 to 8 Hz over a 16-second interval. The resulting structural response (Fig. 5) shows excellent damping of mid-frequency content.

To assess control effort, actuator deflections are extracted from the same time-domain simulations. Fig. 6 shows the corresponding aileron commands. As expected, actuator activity peaks near the flutter frequency. Notably, the structural blending controller achieves improved damping with less deflection compared to the H_2 -optimal controller. At frequencies away from resonance, however, the baseline controller demands less effort.

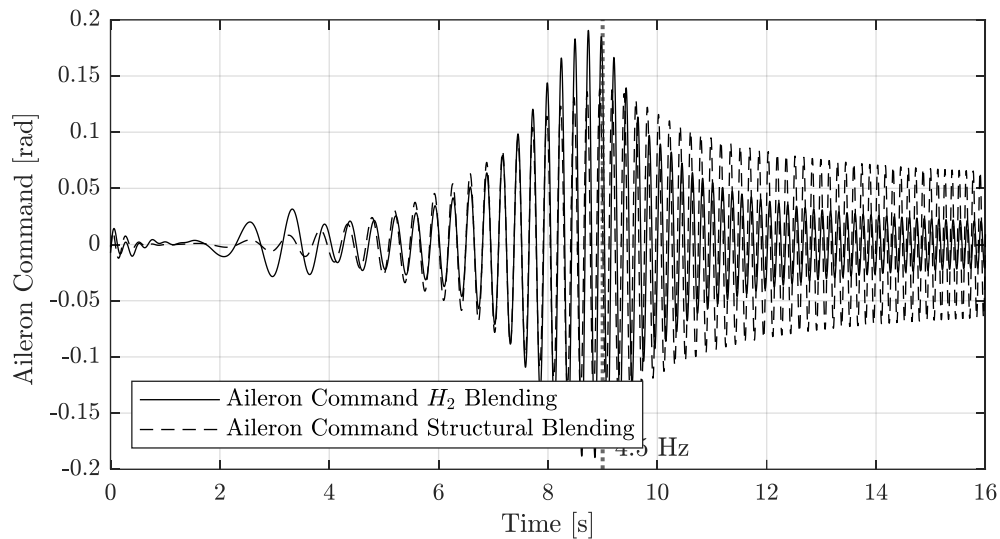


Fig. 6 Time-Simulation Aileron Commands

This work introduces a control synthesis strategy for active flutter suppression tailored to systems with (a large number of) distributed sensing and actuation. Open-source MATLAB/Simulink code accompanies the paper.

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