# ACTUATOR-INDUCED NONLINEAR DYNAMICS IN GUST LOAD ALLEVIATION AND ACTIVE FLUTTER SUPPRESSION

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## ABSTRACT

Load control functions will play a central role in next-generation aircraft, enabling the use of aerodynamically efficient high-aspect-ratio wings without compromising flight safety or increasing structural weight. Gust load alleviation (GLA) and active flutter suppression (AFS) are designed to alleviate the wing loads due to gusts and suppress flutter occurrence by increasing the damping of the affected aeroelastic modes. These functions require control surfaces to operate at high frequencies to effectively counteract atmospheric disturbances and aeroelastic instabilities. In practice, actuator limitations and nonlinear behaviour, can strongly reduce the effective bandwidth of the control functions and alter the dynamic stability of the resulting closed-loop aeroservoelastic systems, and must therefore be carefully accounted for in control design.

This contribution investigates the impact of actuator physical limitations on the performance of GLA and AFS control functions and their effect on dynamic stability of aeroservoelastic systems. Previous investigations, based on describing function analysis [1,2], have shown how frequency-dependent actuator nonlinearities, namely rate and acceleration limits, can alter the closed-loop dynamics of feedback control systems, limiting high-frequency performance and introducing sudden response variations via jump resonance. While describing function analysis provides valuable insight into the frequency-domain behaviour of the system and indications of actuator-induced limit cycle oscillations (LCOs), it does not allow to fully determine the global stability of the system or its long-term behaviour in response to gust perturbations.

This contribution focuses on exact analytical developments that extend and go beyond describing-function approximations. By exploiting piecewise analytical solutions of rate-limited closed-loop systems, the structure and stability of nonlinear periodic solutions can be assessed rigorously. This exact treatment reveals the existence of multiple coexisting periodic solutions, including stable, unstable and virtual LCOs, which play a central role in determining the long-term response of the system. In contrast to describing-function predictions, the exact analytical framework enables the direct assessment of the global stability and convergence in response to non-zero initial conditions and short-term excitations, which are of particular relevance in gust-driven and transient aeroelastic scenarios. The proposed framework is applied to representative GLA and AFS configurations based on aeroservoelastic models, demonstrating the effectiveness of the analytical approach for high-order multimodal dynamic systems.

In parallel, ongoing experimental activities are outlined, aimed at supporting the analytical findings through laboratory testing. A flexible cantilever beam excited by shakers is combined with a real-time controller and an actuator subject to realistic physical constraints. The experimental setup is intended to provide qualitative validation of the predicted nonlinear phenomena, while keeping the framework open to more extensive experimental investigations in future work.

### References:

[1] Marino L., Wang X., Sodja J.: Nonlinear analysis of combined rate and acceleration limits effect on actuator performance. IFASD–2024–183 (2024)

[2] Marino L., Sodja J., Nonlinear effects of actuator rate and acceleration limits on closed-loop systems: A describing function approach. Research Square (Preprint accepted in Nonlinear Dynamics) (2025)