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Fault Tolerance Analysis of a Double Ailerons Based Adaptive Flutter Suppression System

Carmelo Rosario VINDIGNI[1,a *], Giuseppe MANTEGNA[1,b], Calogero ORLANDO[1,c], and Andrea ALAIMO[1,d]

[1]Department of Engineering and Architecture, Kore University of Enna, 94100, Enna, Italy

[a]carmelorosario.vindigni@unikore.it, [b]giuseppe.mantegna@unikore.it, [c]calogero.orlando@unikore.it, [d]andrea.alaimo@unikore.it

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Abstract. This work presents a fault-tolerance analysis of an adaptive control scheme for flutter suppression using multiple control surfaces. The proposed architecture is designed to exploit the distributed actuation capabilities of modern wings to enhance performance and reliability in realistic flight conditions. By employing an adaptive control technique, the system continuously adjusts to variations in flight dynamics without requiring prior knowledge of the complete aeroelastic model. Practical challenges, such as actuator faults and external disturbances, are explicitly addressed, contributing to the development of more robust and fault-tolerant flutter suppression strategies. The methodology is demonstrated on a representative system modeled using a low-order aeroelastic beam formulation based on Euler–Bernoulli beam theory and strip theory aerodynamics, and is suitable for extension to higher-fidelity models.

Introduction

The aviation industry is moving towards lightweight, high-aspect-ratio wing designs to improve fuel efficiency and reduce CO_2 emissions. While slender wing structures offer aerodynamic advantages, they are also more susceptible to aeroelastic instabilities such as flutter, posing significant limitations on their operational envelope. Adaptive control strategies have attracted growing interest due to their capability to manage the highly dynamic, speed-dependent behavior of aeroelastic systems [1]. These methods offer robustness to modeling uncertainties and flight condition variations, but so far, their application has primarily been restricted to low-order aeroelastic models. Furthermore, only a limited number of studies have investigated the integration of multiple control surfaces in adaptive flutter suppression architectures [2]. This work contributes in this framework by presenting a fault-tolerance analysis of an adaptive control scheme for flutter suppression using multiple control surfaces. The architecture is designed to exploit the distributed actuation potential of modern wings, with a focus on improving performance and reliability in realistic flight scenarios. Relying on adaptive control techniques, the system dynamically adjusts to changes in flight conditions and structural properties without requiring full knowledge of the aeroelastic model in advance. Additionally, the proposed approach takes into account practical considerations such as actuator faults and external disturbances, contributing to the development of more fault-tolerant and robust flutter suppression systems. The methodology is suitable for application to higher-fidelity aeroelastic models, moving closer to implementation on actual aircraft configurations.

Materials and method

The aeroelastic plant, representing a modified Goland's wing [3] equipped with double aileron, is modeled exploiting a low order aeroelastic beam formulation [4] based on Euler-Bernoulli beam

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theory and strip theory aerodynamics which allows to cast the aeroelastic equations in the following state space form

$$\begin{cases} \dot{X} = \mathrm{A}X + \mathrm{B}u + \mathrm{B}^{g}w_{g} \\ Y = \mathrm{C}X \end{cases}. \quad (1)$$

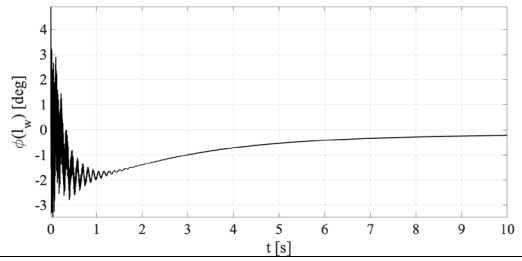
where A is the dynamic matrix, B is the control-state matrix, B^{g} is the gust influence matrix, C is assumed as an identity matrix in the hypothesis of ideal sensors that directly measure the structural displacements of interest, the control input vector u collects the ailerons commanded deflections, and w_g is the gust disturbance [5]. Loss of aileron effectiveness is taken into account by means of an effectiveness factor α_{f} that multiplies the transfer functions related to eq. 1 linking the inboard or outboard aileron deflection with the structural displacements. The Adaptive control scheme generates the control input by processing the wing tip torsion measurement $\phi(\mathrm{l_w})$, which is augmented with the output of a parallel feedforward compensator needed to fulfill the passivity requirements of the adaptive controller [6,7]. Specifically, the augmented plant meets the passivity requirements for velocity values below $U_f^{CL} = 190.6m/s$, which represents the ideal flutter boundary of the closed loop system.

The adaptive controller invariant gains were tuned by means of a Population Decline Swarm Optimization $\mathrm{P_DSO}$ algorithm [8]. The objective function was the Integral of Time Absolute Error ITAE of the wing tip torsion angle, which was computed considering the plant at the open loop flutter speed $U_f = 109.5m/s$ subjected to a pulse disturbance on the wing tip torsion rate of amplitude 100 rad/s and width 0.001 s. The optimized adaptive controller was then tested in a flight scenario involving a 1-cosine gust disturbance and loss of actuator effectiveness considering the wing flying at U_f^{CL}. The obtained results in terms of ITAE, maximum transverse displacement at the tip $w(l_w)$, maximum inboard aileron deflection δ^{in}, and maximum outboard aileron deflection δ^{out} are summarized in Table 1.

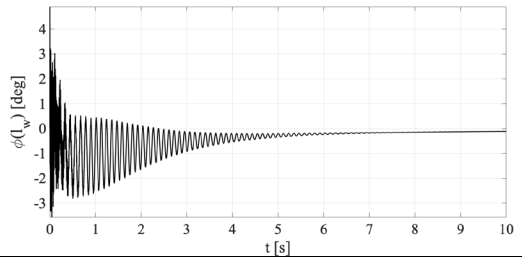
Table 1: Fault tolerance analysis results

Case	α_f^{in}	α_f^{out}	ITAE [rad-s]	Max$[w(l_w)]$ [m]	Max(δ^{in}) [deg]	Max(δ^{out}) [deg]
1	1.0	1.0	23.6	0.060	20	5.8
2	0.5	1.0	12.6	0.067	20	6.7
3	1.0	0.5	59.2	0.090	20	14.2
4	0.5	0.5	unstable	-	-	-
5*	0.0	1.0	245.0	0.200	52.3	40.0
6	1.0	0.0	unstable	-	-	-

The system maintains stable and acceptable performance when the inner aileron experience 50% loss of effectiveness. In this case, the reduction in ITAE observed between the first and second cases is attributed to the oscillatory nature of the response in the second scenario, as shown in Figure 1. Although the system exhibits increased oscillations, the error tends to decay more rapidly over time, resulting in a lower accumulated time-weighted error. In contrast, the first case presents a smoother, more damped response, but with a sustained deviation from the desired setpoint, leading to a higher ITAE.



(a) Fault-free scenario



(b) Inner aileron partial loss $\alpha_f^{in} = 0.5$

Figure 1: Wing tip torsion displacement

A reduction in the effectiveness of the outer aileron significantly degrades system performance, as indicated by the increase in ITAE and tip deflection. Simultaneous degradation of both ailerons and complete failure of the outer one lead to instability, demonstrating the key role of the outer control surface. It is worth noting that, in the case of complete failure of the inner aileron the system exhibits poor performance with large control surface deflections, but the system is still able to damp out the vibrations of the linear aeroelastic plant.

Conclusions

This work investigated the flutter suppression capabilities of a simple adaptive control strategy implemented on a wing configuration with double ailerons. The fault tolerance analysis demonstrated that the flutter suppression system exhibits greater robustness to partial loss of effectiveness in the inner ailerons than in the outer ones. While moderate inner actuator degradation may even improve the ITAE index due to a more oscillatory yet convergent response, outer actuator degradation significantly degrades performance and leads to larger wing-tip deflections. Complete or simultaneous failures ultimately result in instability, highlighting the critical importance of actuator redundancy. These findings emphasize that maintaining at least partial availability of both actuator groups is essential to ensure closed-loop stability and acceptable performance in flutter suppression.

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