UPDATED AEROSERVOELASTIC MODEL OF AN ACTIVE FLUTTER SUPPRESSION DEMONSTRATOR AIRCRAFT

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ABSTRACT

Improving the aerodynamic efficiency of aircraft with high aspect ratio wings is a current trend for future designs. However, the slender wing structures are prone to suffer from an adverse interaction between aerodynamics and structural dynamics causing a destructive instability called flutter. Active Flutter Suppression (AFS) is a key technology to enable high aspect ratio wings by stabilizing the flutter behavior without weight penalties using an active control system. The EU funded projects FLEXOP and FliPASED addressed this topic and matured the technology up to a successful demonstration of the AFS control laws in flight tests with the P-FLEX UAV.

The P-FLEX technology demonstrator is a jet-engine-powered UAVs with 70 kg take-off mass and 7.1m wingspan with a 20 deg sweepback angle. The wing area is 2.54 m^2 which amounts to an aspect ratio of around 19.8. Overall, there are twelve control surfaces, four ruddervators at the V-tail for pitch and yaw control and four control surfaces on each wing, where the outermost flaps are used for the active flutter suppression system. The aircraft is equipped with an inertial reference system (IRS) system and an airdata boom for primary flight control and twelve inertial measurement units (IMUs) at the front and rear spar at 30%, 60% and 90% span locations to capture accelerations and rotational rates of the dynamic flexible deformation of the aircraft for secondary control functions like the active flutter suppression. The aircraft was designed intentionally to exhibit open-loop flutter within its operational envelope, with the AFS system tasked to suppress these instabilities. Flutter analyses with the FEM model predicted a symmetrical flutter mode at around 50 m/s and an unsymmetrical mode at around 53 m/s.

A Ground Vibration Test (GVT) campaign was conducted in March 2023 [1], revealing some discrepancies compared the Finite Element Model (FEM). The GVT data showed some frequency deviations in the unsymmetrical modes and a previously unmodeled in-plane mode, cf. table 1. More severely, the modal mass of the symmetric torsion mode was underestimated by the FEM model. Flutter analysis with the GVT modal data showed that the unsymmetrical flutter instability was pushed beyond 78 m/s and the symmetrical mode was delayed to about 55.5 m/s. Hence, the flight test clearance was done with a linear aeroelastic model directly using GVT modal data. This model was then connected with the AFS control laws. The safety aspects and the correct functioning of the AFS controller beyond the open loop flutter speed was verified and the go ahead to the flight test was granted.

Table 1: Modal frequencies and damping: FEM model vs GVT results

	FEM			**GVT**		
mode description	mode	f [Hz]	g [%]	mode	f [Hz]	g [%]
2n_wing_bend-s	7	2.899	1.0	6	2.938	1.10
3n_wing_bend-a	8	8.156	1.0	7	7.220	0.79
1n_wing_inplane-a				8	8.491	1.83
wing_tors-s	9	10.608	2.0	9	10.744	0.95
wing_tors-a	10	10.717	2.0	10	11.155	1.07
4n_bending-s	11	12.134	2.0	11	12.023	0.72
2n_wing_inplane-s	12	14.953	2.0	13	14.846	1.19
v-tail_rock	13	15.694	2.0	12	12.501	3.36
5n_wing_bend-a	14	19.482	2.0	17	20.383	1.78
bending-a	15	23.684	2.0			
6n_wing_bend-s	16	24.511	2.0	20	25.860	1.82

In May 2023 flight tests with active flutter suppression were conducted [2]. During the tests two AFS control laws by DLR and SZTAKI successfully extended the flight envelope by over 10% beyond the open loop flutter speed [3, 4].

However, the AFS controllers were designed with the aeroservoelastic model [5] based on the uncorrected FEM with the incorrect lower flutter speed. This paper addresses the updating of the nonlinear simulation model, which serves as a new baseline for controller design and performance assessments.

A numerical update of the physical mass and stiffness matrices of the FEM model was conducted to match the frequencies and mode shapes of the GVT data, cf. table 1. This includes the correction of the modal masses leading to the change of flutter behaviour, as well as the previously unmodeled in-plane mode.

Since the classical Doublet Lattice Method (DLM) is unable to account for in-plane effects, an enhanced DLM [6] was employed to capture those effects. The resulting model is shown in figure 1.

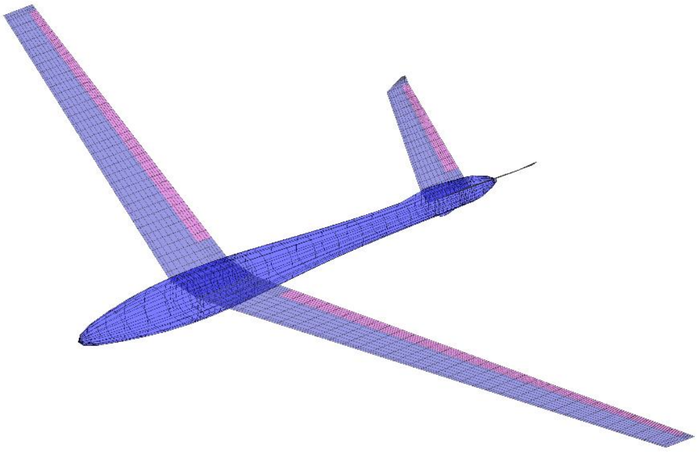

Figure 1: enhanced DLM model of the P-FLEX demonstrator

Furthermore, frequency-domain analysis of flight test data [3], depicted in figure 2, showed a pronounced peak in the range of 35 Hz which was attributed to the controller of the direct drive actuator. Therefore, the transfer function for the actuator for the flutter suppression control surface was updated.

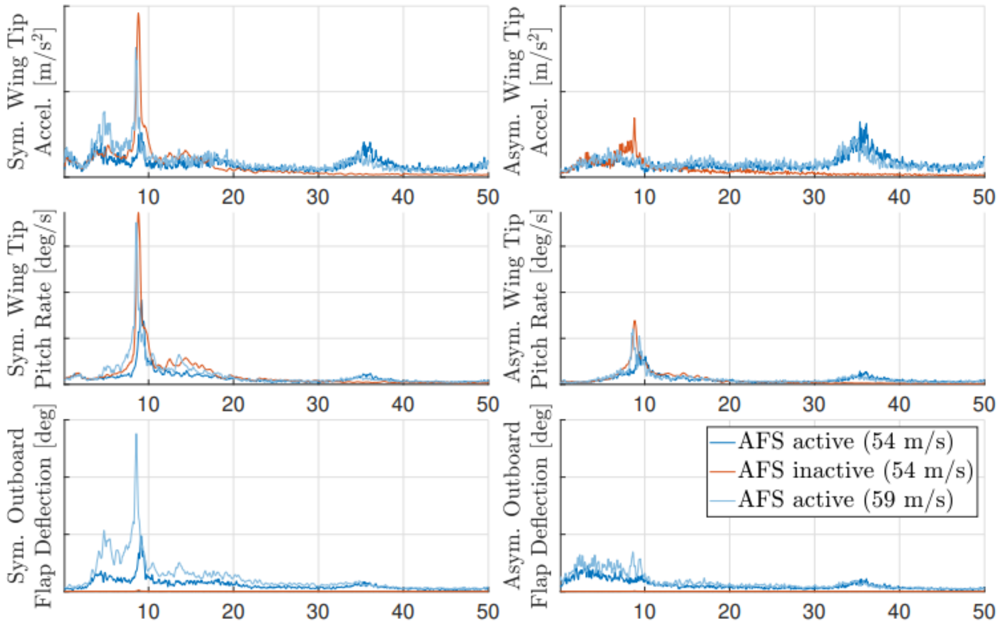

Figure 2: Frequency-domain analysis of flight test data comparing open-loop (AFS inactive) responses and closed-loop (AFS active)

With the refinements incorporated into the updated nonlinear simulation model, the measured flutter onset speed and the associated damping evolution observed in flight test are now accurately reproduced. This enhanced model fidelity enables a more rigorous evaluation of the test conditions through Software-in-the-Loop (SiL) simulations [7], in which the coupled nonlinear flight dynamics, the baseline flight-control architecture, and the AFS control laws interact under representative test-scenario conditions.

Because the AFS control law was originally synthesized using the pre-update model, its performance and robustness can now be reassessed against the improved aeroelastic representation. Moreover, the updated model provides a suitable basis for designing a new flutter-suppression controller and quantifying the achievable performance gains.

The flight-test data set has already been released publicly [8]. The updated aeroservoelastic model described in this paper, will likewise be provided in a form suitable for dynamic simulation and systematic linearization, enabling the community to evaluate and develop their own active flutter-suppression algorithms.

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