Active Flutter Suppression – Plans for Assessing the Technology’s State of the Art

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Even though historically Aeroelasticity and the mathematical and experimental techniques associated with it developed separately from Flight Controls technology and its own analysis, design, and testing methods, the tight link between the two was always recognized (Ref. 1) as well as the possibilities for using active controls to suppress flutter instabilities and alleviate dynamic loads.

In essence the aeroelastic problem can be viewed as a dynamic system feedback problem, with the structural dynamic transfer function in the forward loop, and the aerodynamic transfer function providing both feedback and outside excitation forces (Fig. 1).

![The Aeroelastic (AE) Physical Feedback Loop and Associated Stability Static & Dynamic](image)

Figure 1: The Aeroelastic system as a structural dynamic / aerodynamic feedback system

The integration of an aeroelastic system with active controls (Fig. 2) provides additional sensing and actuation elements as well as control laws and control feedback loops, resulting in what is called an Aeroservoelastic system.
Factors that prevented active control technology from being used to control aeroelastic problems such as flutter, dynamic gust loads, and ride comfort, included the low bandwidth and nonlinearity of control surface actuation systems, the lack of theory and design tools for multi-input multi-output control systems subject to uncertainty and noise, and the corresponding inadequacy of control system hardware.

Early attempts to develop active control technology for gust loads suppression followed World War II into the 1950s (Ref. 2). With the rapid development of control systems theory from the 1950s to the 1970s and 1980s and the appearance of fast powerful actuators and rapidly improving control systems hardware, active flutter suppression (AFS) technology seemed to begin to be within reach. The late 1960s and years into the 1970s and 1980s were years of active R&D in the AFS area (Refs. 3-9). The following decades saw a tremendous increase in control systems technology theoretical foundations as well as hardware and software. Active control, from the beginning of the 1970s, became an integral part of aircraft design, development, and operations, through advanced flight control systems (FCS) for passively stable or unstable flight vehicles, maneuver load control (MLC), ride comfort (RC) improvement, and gust loads alleviation (GLA).

With the growing power and bandwidth of active flight control system, undesirable interactions and resulting aeroelastic instabilities were encountered in quite a number of advanced aircraft over the last four decades (Refs. 10-12). The problems had to be solved by modifying the control system, either by changing control laws, or adding control loops, or adding notch filters to filter out contributions of dynamic response at specific aeroelastic frequencies to the overall airframe / control system dynamics. But to count on an active control system to suppress flutter and to fly commercial aircraft, using active flutter suppression, at flight conditions where without the active control system a flight vehicle would suffer explosive flutter has not been allowed.

With the drive, however, to design and fly highly efficient aircraft and the growing body of active flutter suppression research and experience, it may be time, again, to review history and progress of the technology and assess its state of the art. Two major scenarios motivate a current state of the art assessment:
A need for an “AFS fix” scenario. In this case flutter problems may emerge late in the development of an airplane and can be found to be too costly or impractical to fix using passive airframe design change techniques compared with an AFS solution.

An integrated multidisciplinary design optimization (MDO) scenario. In this case AFS is taken advantage of and is harnessed from the beginning of the design process of a new airplane, leading, possibly, to major airframe weight savings due to relaxed stiffness and mass distribution constraints (Ref. 13).

A description in the open literature of a recent example of the first case – providing an effective active control solution to an undamped aeroelastic oscillation problem that was discovered late in its development process of a modern airplane – can be found in Ref. 14. In that case, however, it was demonstrated that there would be no degradation of safety if the active control system used becomes inoperative, except for unpleasant vibrations that can be quickly eliminated by changing flight conditions. This is not the same as using active flutter suppression to fly beyond the flutter speed of an airframe, where loss of the control system would lead to immediate divergent instability. Understandably, counting on active flutter suppression systems to clear the flight envelope of an airplane, where flutter would be encountered without those systems being active, is not authorized and has not been used in commercial aviation, even though the capacity of AFS to allow airplanes to fly without aeroelastic instability beyond the flutter speeds of their passive airframes has been demonstrated numerous times in analytical studies, wind tunnel tests, and even flight tests.

A pioneering design effort followed by wind tunnel and flight tests of a complex control configured vehicle (CCV) was carried out over the span of a few years in the late 1960s and early 1970s (Ref. 15). The flutter speed of a Boeing B-52 vehicle was intentionally degraded by installing ballast masses at the forward part of its external outboard wing fuel tanks. An array of control surfaces and sensors and an array of control laws were used to demonstrate active control technology that would address a number of design requirements separately and simultaneously (Fig. 3, taken from Ref. 15). The systems included: a Maneuver Load Control system (MCS), an Augmented Stability (AS) system, a Ride Control (RC) system, a Fatigue Reduction (FR) system, and a Flutter Mode Control (FMC) system. The surfaces and sensor locations used by the FMS (AFS) system are shown in Fig. 4.

Remarkably, despite the limitations of general control theory and controls design tools of the era plus the limitations of computer power and actuator performance, the CCV B-52 demonstrated safe operation of an actively controlled flight vehicle beyond its un-augmented flutter speed, with the control system taking care of simultaneously and without conflicts: flutter suppression, maneuver load control, ride control, and fatigue load reduction (Figures 5 & 6). Significant gains in damping were obtained with the only the FMS system on and with all active systems on.

The case involved flutter instabilities of the mild nature at a low frequency of about 2.4Hz. That is, the loss of damping in the critical aeroelastic roots was relatively mild as a function of airspeed. Thus, even if subject to a sudden loss of AFS when flown beyond the un-augmented airframe’s flutter conditions, the resulting divergent motion of the aircraft would have grown in amplitude slowly enough for the pilots to have enough time to reduce the speed below the flutter boundary. The CCV B-52 was not flown into flight conditions that were too far above the un-augmented flutter speed.

Careful consideration of failure modes and fail-safe design included redundancy in the control systems and the analysis of the time to wing failure following a failure of the active flutter suppression system, Fig. 7.
Figure 3 (from Ref. 15): The Control Configured B-52 and its control surfaces and active control concepts tested.

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Figure 4: B-52 CCV Control Surfaces used for flutter suppression (from Ref. 15)
Figure 5. Critical damping vs. airspeed at 21,000 ft: Basic, un-augmented vehicle and vehicle with active flutter suppression system on (Ref. 15).

Figure 6: Critical damping vs. airspeed at 21,000 ft. Basic, unaugmented vehicle and vehicle with ALL active systems operating: FR, MLC, FMC, and RCS (Ref. 15).
Figure 7: Level of wing tip acceleration as a function of time after sudden failure of the active flutter suppression system occurring when the airplane flies 15 knots above the airframe’s flutter speed. Two cases are shown: (a) the airplane continues to fly 15 knots above the un-augmented airframe flutter speed, and (b) the airplane is slowed down quickly using throttle and speed brakes after the AFS system fails. The design limit shows wing tip acceleration levels that would fail the wing (Ref. 15).

Assessment of the state of the art of Active Flutter Suppression (AFS) technology must be done in the context of flight vehicle active control technology in general and considering the rapidly developing integrated multidisciplinary design optimization (MDO) technology for flight vehicles that would lead to the capability to design airframes and their aerodynamic, structural, and active control systems simultaneously. The questions to answer include:

What has been done so far and what are the lessons (with special focus on test programs involving models and flight vehicles that, with their complexity, represent the real challenges that wide-spread AFS implementation faces).

What are the gaps in knowledge and experience that need addressing via R&D?

Can the technology be brought to the level of maturity and safety required to allow its usage, and if so, what are the design tradeoffs and gains it would make possible and how would it affect the efficiency of future flight vehicle designs?

The current project is aimed at exploring these questions. Its first stage – a comprehensive gathering of technical references and study of the literature on AFS to date – is about to be completed. The next stage – discussions with key industry and research leaders – is about to begin.
Acknowledgment

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References


