Aircraft Active Flutter Suppression

State of the Art and Technology Maturation Needs

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Abstract

Active Flutter Suppression, an important part of the group of flight vehicle technologies known as Active Controls, is an important contributor to the effective solution of aeroelastic instability problems when they pop up late in the development of a new aircraft or, if used from the start of the design process, it is a key element in multidisciplinary design optimization that would lead to more efficient aircraft. This work presents a thorough overview of more than fifty years of research and development in the active flutter suppression area. Along the way key historical development and the current state of the art in all supporting disciplines are surveyed. Technology gaps and R&D needs ae identified. Special attention is given to the vehicle safety issue and to research and development in the active flutter suppression area that would complement ongoing research and development in all areas of aeroelasticity, aeroservoelasticity, and active control. A thorough bibliography contains references that cover all building blocks of active flutter suppression technology. It would, hopefully, contribute to the preservation of the treasures of experience and knowledge in this area so that they would not be forgotten and lost and would remain available to professionals working in this field.

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1. Introduction, Goals, and Some Terminology

The interaction between the structure, dynamics, structural dynamics, and unsteady aerodynamics of the deformable moving airplane may lead to self-excited aeroelastic instabilities such as flutter, an oscillatory constant amplitude or divergent motion / deformation, and divergence, an exponential divergent motion / deformation, both with destructive potential and both functions of flight conditions such as altitude and Mach number, as well as, in some cases, load factor and other maneuver parameters. Flutter may also be encountered due to undesirable interaction between control systems and the aeroelastic behavior of an actively controlled airplane. The terms "aeroservoelastic instability" and "aeroservoelastic interactions" are used for such cases. The terms "flutter speed", "flutter dynamic pressure", and "flutter boundary" are often used to denote the flight condition boundary between stable and self-sustaining motions. The term "flutter region" is often used to describe the region in a flight vehicle's flight envelope where flutter oscillations occur. According to Ref. 1, "In the practical sense "flutter" means an oscillation which grows, and finally either breaks the structure or remains bounded at some amplitude whose value is dependent upon the departure from linear laws."

Aeroelastic instabilities can be categorized into different types regarding the way stability is lost with increase in dynamic pressure or any other change in flight conditions. Divergent flutter can be "explosive" or "violent". A small increase of speed in this case from just below the flutter speed to slightly above the flutter speed would lead to highly divergent oscillations and to airframe failure within a fraction of a second. Divergent flutter can be of the "moderate" type. Here, loss of stability (as reflected by reduced aeroelastic damping in the system) can be identified well below the flutter speed, and, based on such gradual "slide" towards instability, flutter speeds can be more reliably predicted by tests using extrapolation. Flutter of the "mild" type is characterized by loss of overall aeroelastic damping way before the flutter speed is reached, while the system is stable but lowly-damped. Beyond the flutter boundary the system is unstable, but its rate of growing divergent oscillation is slow, allowing test pilots often to slow down back into the stable region of flight. A flutter mechanism of the "hump mode" type will see gradual loss of damping towards the flutter speed, then very low negative damping, and then, with additional increase in speed and dynamic pressure, an increase in damping back to the stable region. Whether a system would actually flutter or not in such a case may be very sensitive to the levels of damping in the structure and other parameters affecting the structural dynamic and aerodynamic behavior. The stability concepts above are based on linear aeroelastic and aeroservoelastic theories. When significant nonlinear effects become important, such as freeplay control surface nonlinearities, stiffness nonlinearities due to large deformation, loading dependent engine or external store pylon nonlinearities, structural damping nonlinearities, or aerodynamic nonlinearities involving shock wave motion and flow separation, additional types of self-excited modes of behavior may occur, including Limit Cycle Oscillations (LCO) – sustained constant amplitude oscillations due to aeroelastic interactions. LCO may appear in an aeroelastic system way below the flight conditions that would lead to divergent destructive oscillation. As dynamic pressure and speed are increased, LCO amplitudes may become larger. But well below the divergent oscillation flight conditions an airframe may be able to tolerate LCO of limited amplitudes for quite some time, affecting ride comfort, maybe, but not compromising safety. Like many other nonlinear dynamic problems, nonlinear aeroelastic and aeroservoelastic behavior can be complex and surprising in nature (Refs. 2-4). It should be noted here that a linear system with very low damping in one of its modes of motion (or "states") may serve as a narrow-pass filter when excited by wide-spectrum inputs such as atmospheric gusts and display continuous oscillation at the system's frequency associated with the very low damping as long as the excitation persists. In the LCO case a nonlinear system can display continuous oscillation at finite amplitudes without any external excitation.

The possibility of suppressing airplane flutter instabilities through the actively-controlled closed-loop action of control surfaces and other control effectors has been known for years (Ref. 5) and became feasible with the appearance of high-bandwidth actuators and developments in control systems theory and hardware. Active Flutter Suppression (AFS) can provide a powerful and effective solution to flutter problems discovered late in the course of development of new airplanes, or encountered as a result of major modifications of airplanes during their service life, where elimination of flutter through passive means – structural stiffening or mass distribution changes – may be impractical. When harnessed and included in the airplane design process from its inception, AFS has the potential to lead to major weight savings and more efficient and versatile airframes (Ref. 6).

Active Flutter Suppression may be considered as one technology in the group of technologies known, in the context of flight vehicles, as Active Control. Active Control also includes Flight Control (FCS), also known as Flight Stability Augmentation (SA), Gust Loads Alleviation (GLA) or Dynamic Loads Alleviation, active Ride Comfort control (RC), and Maneuver Load Alleviation (MLA). The terms "Stability Augmentation" and "Flight Control System (FCS)" are often used for that part of a flying vehicle's overall control system focused on the shaping of "rigid body" motions of the vehicle to achieve desired safe Handling Qualities (HQ). It should be noted here that in the case of highly deformable flight vehicles the separation of "rigid body" motions (some form of describing the overall motion of the vehicle in 3D space without structural deformation) and its elastic motions is not straightforward. The term Flight Control System may also be found being used to describe the complete active control system of a flight vehicle, covering all its functions, which must work in complete harmony.

Various active control systems have been accepted, certified, and used for years on commercial and military aircraft. Those include Maneuver Load Alleviation (MLA) (or Maneuver Load Control (MLC), Gust Load Alleviation (GLA), Flight Control systems (FCS) for desired and safe handling qualities (HQ), and active Ride Comfort systems (RC). What is common in all these cases, regarding safety, is that in addition to strict redundancy and reliability design requirements in place that those systems have to meet and provided that such systems do not interact with the airframe to produce aeroservoelastic instabilities or LCO, failure of the active control (loss of the primary control system) would not be catastrophic (to a required level of probability), and action by the flight crew would allow, within certain flight envelope limitations, safe operation of the airplane. Failure of an active flutter suppression system, however, when a divergent flutter instability is involved, may lead to a failure of the airframe that would happen too quickly to allow the flight crew to respond by any corrective action such as reducing flight speed. Moreover, the failure to address uncertainties, interactions, and to account for control system capability limitations during the design and development phase of an actively controlled airplane that is unstable without the action of active controls may lead to disasters during the development phase (Ref. 7).

Naturally, the willingness to accept any form of active flutter suppression may be linked to the type of flutter behavior involved. Active Flutter Suppression may be acceptable if the self-sustained aeroelastic behavior to suppress is of the LCO type and is of acceptable amplitudes. In such a case failure of the control system would lead to LCO which would allow adequate flight crew response and safe flight. The loss of an active suppression system in a case of explosive or moderate flutter at flight conditions beyond the passive (no-control) flight boundary would lead to immediate airframe damage.

An important characteristic of any flutter mechanism on any flight vehicle involves the number and nature of the motion degrees of freedom (system's "states" in dynamics and control jargon) that drive the instability. For an elastic airframe, degrees of freedom used to describe full motion may include rigid body translations and rotations plus contributions to the deformation by the natural modes of the structure or some other modes of motion capable of capturing airframe motions accurately. Flutter instability mechanisms may involve interaction of two or more modes of motion. Different flutter mechanisms may be present for the same airframe leading to different flutter speeds for each mechanism. Changes in the structure or in control laws of active control systems used may make one flutter mechanism more critical or another. Single degree of freedom flutter is also possible in certain cases. In general, mathematical models of the full aeroelastic behavior of an airplane and including many degrees of freedom must be used in order to capture all aeroelastic static and dynamic mechanisms accurately. Such mathematical models may consist, even after using model order reduction techniques, of hundreds of equations of motion or more, and such high order, together with the large variety of flight and loading conditions that need to be covered, are a challenge for current control law design methods and their implementation.

For any flight vehicle technology to be accepted as safe it must be thoroughly understood in all its aspects and be supported by reliable analysis tools, thorough testing, confidence in the correlation between analysis predictions and the real world, and by established uncertainty & reliability estimation capabilities that cover, in addition to sources of uncertainty in all aspects of aeroelastic and aeroservoelastic simulation, also hardware, operations, and maintenance aspects.

R&D work focused on the improvement of aeroelastic and aeroservoelastic analysis and simulation is still underway in the U.S. and worldwide, funded by government agencies and industry, and it is carried out by industry, university researchers, and government research laboratories.

A flurry of AFS research and development activity in the 1970s and 1980s, with major achievements (Refs. 8-12), led at the time to optimism regarding an expected imminent maturation and subsequent acceptance of the technology on manned flight vehicles. But while other active control technologies, as listed above, have been accepted for certification and have by now seen wide-spread usage on aircraft, Active Flutter Suppression is still viewed with reservation and caution, and except for very few special cases, it has not been allowed on commercial and even military aircraft.

The goals of the work presented here are to contribute to the development and maturation of active flutter suppression technology by (a) presenting its history, including an encyclopedic bibliography and a survey that would lead current and future engineers working in this area to key sources that cover all aspects of the active flutter suppression analysis, design, and certification problem; and (b) by discussing limitations and accomplishments to date and by identifying research and development needs and recommended research.

This work was initiated and supported by the US Federal Aviation Administration (FAA). It is exploratory and educational in nature and presents no intention of the FAA at this stage to change any regulations or certification requirements or any interpretation of regulations and certification requirements that cover Active Flutter Suppression (AFS) technology. The work does not represent FAA opinion or how the FAA interprets the current requirements and guidance material.

Naturally, any discussion of active flutter suppression technology cannot be disjoined from a discussion of the field of aeroservoelasticity as a whole. An effort is made here to cover the state of the art and key historical developments in aircraft aeroservoelasticity from the perspective of active flutter suppression in a detailed enough way and with a rich enough bibliography to serve the active flutter suppression technology overview needs. The bibliography, while substantial, is selective. The hope is that the references, through their own bibliographies and their discussions, would direct readers to most, if not all, key publications and works in this area to date.

2. A Survey of Aeroservoelasticity, Active Flutter Suppression, and Related Areas and the Structure of the Report.

In creating the bibliography presented here an effort was made to cover all aspects of aeroservoelasticity and active control of elastic aircraft and all major efforts in this area to date nationally and internationally. The bibliography is expected to expand over time when important publications that it should include and have been missed will be discovered and when new work will be reported.

The references gathered here include publications that describe work on real aircraft and realistic wind tunnel models, work with mathematical models that capture the full complexity of actual flight vehicles, and methods that can be used for the design, analysis, and certification of actual actively controlled aircraft. Publications on active flutter suppression using highly simplified mathematical models which neglect major elements of the physics of coupled real aeroservoelastic systems and publications describing work that is still in the very basic and fundamental stage are generally not included in this bibliography.

To make it user friendly, the bibliography is made of sections, each covering a topic. Because of the multidisciplinary nature of the technology addressed here, many papers may belong in a number of different categories. A detailed subject index, following the example of Ref. 7, precedes the bibliography. Each reference is included in the bibliography only once.

Subjects covered by major sections of the bibliography and the discussion include: flight stability and control of rigid and flexible aircraft (Refs. 13-29); the effect of aeroelastic behavior on flight stability and control via static aeroelastic stability derivatives corrections for six degrees of freedom simulations (Refs. 30-48), historic perspectives of the deformable airplane flight dynamics problem from the flight stability and control and aeroelasticity communities (Refs. 49-51); Aeroelastic tailoring and “Active Flexible Wing” or “Active Flexible Airframe” concepts (Refs. 52-72); Maneuver load control (Refs. 73-77); Aircraft morphing (Refs. 78-85); early work on the influence of servoactuators (Refs. 86-89); Gust Load Alleviation (Refs. 90-103); Ride Comfort and Handling Qualities (Refs. 104-114), Active Buffeting Alleviation (Refs. 115-116); A systems perspective of active controls (refs. 117-135); Aeroservoelasticity general progress reviews (Refs. 136-153); Reviews of aeroservoelastic experimental programs (Refs. 154-157); Linear aeroservoelastic solution methods (Refs. 158-169); The aeroservoelastic flight system equations of motion – equations of the aeroservoelastic “plant”, including a hierarchy of modeling levels of fidelity, reduced order modeling, actuation and sensing as well as propulsion integration (Refs. 170-346). Approaches to active flutter suppression control law generation are covered next (Refs. 347-423), including methods of classical control, modern control, adaptive control, and control of parameter varying systems. Discussion of topological aspects of the active control problem as well the control of nonlinear systems follows (Refs. 424-435) and the applied math work on what is known as the continuum approach to aeroelastic control (Ref. 436) is briefly mentioned to make the exposition of aeroelastic modeling and control law synthesis methods as complete as possible. Experimental system identification and test planning practices in aeroservoelastic flight and wind tunnel tests is covered in Refs. 437-475. The importance of efficient, reliable, and informative experiments cannot be overstated given their cost and schedule constraints and their link between mathematical models and "reality". Covered in what follows, case by case, are aeroservoelastic and active flutter suppression projects involving actual aircraft as well as wind tunnel tests over the years involving vehicles and models with complexity representative of actual flight vehicle systems (Refs. 476-610). The subject of aeroservoelastic uncertainty is presented next (refs. 611-646), followed by aeroservoelastic multidisciplinary design optimization (Refs. 647-660). References on targeted energy transfer (Refs. 661-666) conclude the technical part of the discussion and bibliography. The last section of the bibliography lists key sources that cover current aircraft certification requirements from the perspective of aeroelasticity, aeroservoelasticity, and active control (Refs. 667-684).

3. Active Flight Control of the "Rigid Body" Airplane

The idea that an active control system in which sensors of aircraft motions would feed some control law mechanisms (Electromechanical or electronic) that, in turn, would command control surfaces or other changes in airframe shape to achieve desired dynamic behavior was considered and discussed by pioneers of aviation from close to the early days of manned flight (Refs. 13-24). With the rapid development of classical control theory in the 1930s to 1960s, followed by Modern Control Theory, together with the development of powerful and reliable flight control hardware, computing power, and flight dynamic theory and simulation, flight control systems have been an integral part of practically every advanced airplane over the last fifty or sixty years. Numerous flight stability and control textbooks, going back to the early 1950s, cover automatic flight control thoroughly – Refs. 20-28, for example. The focus was on the rigid body motion of aircraft at first, in six degrees of freedom, and on aircraft trajectories and responses to disturbances. Stability augmentation progressed to stabilize airplanes that without active control were unstable in rigid body motion with the General Dynamics YF-16 and F-16 (Ref. 29). It is now widely used to obtain desirable handling qualities on both inherently stable and unstable aircraft.

4. Static Aeroelastic Corrections of the Six Degrees of Freedom Equations of Motion

The importance of Aeroelasticity from the perspective of flight stability and control was recognized long ago. For aircraft in which separation between rigid body motion frequencies and structural dynamic frequencies (as affected by the interaction with flow, including thermal effects) is large – aeroelastic effects, when six-degrees-of-freedom (6 dof) motion models are used, have been traditionally accounted for by static aeroelastic corrections of aerodynamic stability derivatives (Refs. 13, 16-17, 30-48). This includes fuselage flexibility effects on stability derivative contributions of the empennage or canards as well as lifting surface flexibility effects on leading edge (LE) and trailing edge (TE) control surface effectiveness, dihedral, and Neutral Point location. Control surface reversal is one example of the effect of static aeroelasticity on the aerodynamic stability derivatives of an airplane modeled as a rigid body moving in six degrees of freedom.

In earlier years static aeroelastic effects on a flight vehicle configuration had to be found component by component (wings, empennage, etc.). With the maturation of structural finite element and aerodynamic linear modeling capabilities, the static aeroelastic corrections of all stability derivatives of a maneuvering airplane could be obtained by analysis based on complete models of the vehicle (Refs. 39-43). A link between airplane stability and control engineers, working with 6dof mathematical models, and aeroelasticians, providing the static aeroelastic corrections of aerodynamic stability derivatives (aka "flex to rigid ratios"), was formed early in the history of aviation, even though simultaneously for many years the two communities used different mathematical models and different analysis and design approaches to the dynamics of the airplane (Ref. 49).

While static aeroelastic corrections of aerodynamic stability derivatives were based originally on coupled steady structural / aerodynamic solutions, developments in aeroelasticity in the area of unsteady linear aerodynamics, with potential-aerodynamic panel codes, began to contribute to 6dof simulation of aircraft by adding capability to calculate both static and dynamic stability derivatives (Ref. 13 pp. 276-283, Ref. 50 and 51) for complete configurations. Commercial unsteady aerodynamic codes such as Ref. 41 and Ref. 42 can now efficiently calculate aeroelastic-based stability derivatives for 6 dof simulations of full aircraft configurations.

Another aspect of the static aeroelastic problem and the way by which "flexiblized" aerodynamic stability derivatives are calculated is the detail in which structural stiffness (or flexibility) is used. The problem with a modal approach, in which a small set of natural modes or some carefully selected Ritz vectors is used via superposition to model the motions of the deformable airplane, is that with not enough modes (and even in the case of many modes, not enough of the right modes) the full flexibility of the structure and the aeroelastic consequences of that full flexibility are not captured. For quite some time, historically, static aeroelastic analysis was carried out with as detailed stiffness/flexibility of the structure as practical, while mode shapes were used as generalized coordinates for flutter analysis. But the growing power of digital computers, which began to make multi-degree-of-freedom linear static analysis practical, led to an emergence of modal based static aeroelastic analysis (Refs. 45-47), and this approach, with enough mode shapes that are carefully selected to converge quickly on static aeroelastic aerodynamic stability derivative flex-rigid ratios, is now widely used.

The importance of static aeroelastic effects extends beyond 6dof rigid body simulations to flexible-airframe aeroservoelastic simulation. While in essence there should be no separation between static and dynamic aeroelastic effects, both having to be well captured by one aeroelastic mathematical model of an airframe, the need for structural order reduction for control law design makes it necessary for aeroelasticity and flight controls engineers to have full awareness of static aeroelastic effects on dynamic aeroelastic behavior and requires that the reduced order structural dynamic models used would capture both static and dynamic aeroelastic behavior. Examples of what can go wrong when static aeroelastic effects are not captured accurately by a dynamic aeroelastic model are the case of the F18 leading edge flap modeling (Ref. 44) and the case of the YF16 aeroservoelastic instability (Ref. 510). Accurate accounting for static aeroelastic effects is a must in any aeroservoelastic modeling for active control system design.

5. Control of Static Aeroelastic Behavior

Lift / drag performance of the "rigid" airplane together with 6dof dynamic performance are shaped by the utilization of control surfaces to effectively change the aerodynamic shape of the vehicle (Ref. 52, for example). When static aeroelastic effects play a significant role, static aeroelastic behavior must be accounted for by analysis and tests and must be either constrained or harnessed in order to achieve desired behavior.

Static aeroelastic Constraints for desired flight performance have been for years and are still some of the key constraints affecting structural design in the multidisciplinary design optimization (MDO) of aircraft. The skin thickness and resulting weight of a wing or changes in wing cross sectional shape for sufficient torsional stiffness as well as the layout of internal structure (ribs and spars) are examples of the impact of such constraints (Refs. 53-54). More design-space freedom to optimize new configurations is now provided by composite structural tailoring technology (Ref. 55) and compliant structures (Refs. 56-57). But once designed and built, a structure cannot adjust its shape, unless some active control and some morphing are involved, to provide optimality at more than just a few design conditions.

In the Active Aeroelastic Wing (AAW) concept (Refs. 58-70) optimal scheduling of trailing edge and leading edge control surfaces on flexible wings can overcome trailing edge control surface reversal tendencies and attain required roll rates while keeping wing section loads within limits. The control laws that drive the scheduling of the multiple control surfaces on the configuration are quasi-steady and can be pre-programmed to cover the full range of flight conditions the vehicle has to perform at. Such control laws can also respond in real time to flight condition and flight performance information, working, through the scheduling of control surfaces, to achieve desired performance. The concept was developed in the 1980s, led to exploratory wind tunnel tests at the NASA Langley Transonic Dynamic Tunnel (TDT) under the name Active Flexible Wing (AFW), Refs. 60-65 and 553-562, where both control surface scheduling and Active Flutter Suppression (AFS) were studied. In a subsequent implementation on a full size vehicle an F18/A (later named the X-53) was modified by reducing the stiffness of its wing and adding / modifying sensors, actuation of leading edge and trailing edge surfaces, and control laws, and it was flight tested successfully (Refs. 65 and 542-543) . The X-53 was flutter free within its flight envelope, and so tests focused on the scheduling of multiple control surfaces to attain desired rolling performance.

At the early design stages of a flight vehicle AAW design philosophy (generalized, maybe, to include the complete airframe: AAA – Active Aeroelastic Airframe technology) coupled with multidisciplinary design optimization (MDO) has the potential to lead to substantial weight savings (Refs. 6, 66-70). Active Aeroelastic Airframe technology also has the potential to overcome static aeroelastic problems (especially, inadequate 6dof performance due to unacceptable stability derivative flex to rigid ratios) if such problems are discovered late in the development of a new airplane and if conventional passive design modifications are found to be too costly. It is interesting to mention in this context the case of the first swept-wing jet, the Boeing B47, where the destabilizing longitudinal effect of the flexible bent-up swept back wing was discovered late in the development program and led to great concern, until it was found, as a matter of coincidence, to be cancelled by the bending effect of the rear fuselage and the resulting horizontal tail increase in angle of attack (Refs. 71, 72). Automated elevator motion, following an AAA concept, tied to flight conditions, would have solved the problem if the fuselage had been too stiff and if, then, its “natural” compensation for the wing flex effect would not have been sufficient.

The movement of flight control surfaces to obtain desirable 6dof dynamic performance in the presence of static aeroelastic effects can be controlled by gains that are pre-selected by analysis and testing to yield the desired results (open loop) or by a feedback loop that adjusts control surface rotations to attain desired performance measures. In Maneuver Load Alleviation (or Maneuver Load Control) control surfaces move to distribute aerodynamic loads on a maneuvering airplane to keep its internal loads within limits, thus leading to structural weight savings (Refs. 73-77). Active Aeroelastic control technology, focused on the shaping of aircraft inflight to meet aerodynamic lift/drag performance as well as 6dof dynamic performance requirements, can involve conventional control surfaces, smoothly-morphing camber of lifting surfaces (Refs. 78-81) , or more major shape changes in flight (Refs. 82-85).

Care must be taken, however, if closed loop active static aeroelastic control is sought, to make sure that this form of “slow” vehicle shape control does not interact and interfere with dynamic aeroservoelastic behavior. In an interesting case of such interaction is described in Ref.135, where a Maneuver Load Control system on one of the Boeing 787 models in flight tests responded to the maneuver acceleration that drives it by getting the airplane into oscillation due to an interaction with one of the fuselage’s modes. The need of all active control systems on an airplane to work in harmony without interfering with each other’s functions and without leading to dangerous interactions must be met and demonstrated by design and tests. Moreover, any design of an active aeroelastic system, if flight critical, must be supported by comprehensive uncertainty and reliability analyses and tests to guarantee the safety of the system. Fig. 1 shows an X-53 (F18 AAW, Ref. 65) with a “stuck” leading edge flap. A number of stuck LE flap positions were tested in flight for the effect on performance and safety of the aircraft.

6. Aeroelastic / Flight Control Systems Interactions and Active Flutter Suppression

Automatic controls have been part of airplane design since the introduction of the Sperry automatic pilot in 1912 (Refs. 13). But slow actuators and actuation mechanisms, serving as low-pass filters, prevented strong interaction of the control systems, designed to shape the rigid body dynamics of aircraft, with the higher frequency aeroelastic motions of the airframe. With the development of powerful fast actuators and actuation mechanisms, the capacity of onboard actuation to respond to and to affect aeroelastic motions in the frequencies above those of the rigid body motions became more significant (Refs. 86-89).

Active controls could now be developed to reduce dynamic loads due to gusts (Refs. 90-103), improve ride comfort and handling qualities (Refs. 104-114), and mitigate vibrations due to buffeting (Refs. 115-116. Together with stability augmentation and maneuver loads control, gust alleviation and ride comfort system needed to work in complete harmony (Refs. 117-135).

Figure 1: An Active Aeroelastic Wing X-53 with a stuck LE flap

Refs. 136-157 provide overviews of the field of Aeroservoelasticity, where the terms “Aeroservoelasticity” and “Active Controls” are commonly used to describe the field in general, while the terms for sub-fields consisting of “Gust Loads Alleviation”, “Maneuver Load Control”, “Ride Comfort”, “Stability Augmentation” and “Flexible Airplane Handling Qualities” are used to describe different aspects and uses of the technology. These references provide overview, vision, calls for R&D action, and useful bibliographies. Active flutter suppression is an additional important part of aeroservoelastic and active control technology.

Unlike flight control systems for stable aircraft (stability augmentation, handling qualities improvement, maneuver loads control, gust alleviation, ride comfort control) active flutter suppression means stabilizing an unstable system (in control systems jargon: an unstable plant). Allowing active controls to stabilize a statically unstable airplane, implemented in production first on the F16, took a long time and a major engineering effort to materialize. To bring the state of the art of active flutter suppression, where frequencies can be high and flutter mechanisms complex and multiple, and where analysis and testing techniques may still be subject to error and uncertainty, to a maturity level that would allow their wide-spread usage is much more challenging. The technology, for those reasons, has not seen yet wide application in the commercial airplane world, nor, actually, even in the military world. In the following, while surveying the state of the art in each of the disciplines that active flutter suppression depends on, this work will articulate the challenges and try to identify the needs.

7. The Aeroservoelastic Plant

In control system theory jargon the plant is the dynamic system to be controlled, providing outputs (through sensors) that a controller works with to produce inputs (via actuators) to the system that would affect its behavior. Any discussion or implementation of active flutter suppression, or any flight vehicle active control technology, must include a thorough understanding of the full aeroservoelastic system to be controlled, including the mathematical models used for control law synthesis – their accuracy, uncertainty, reliability, and practicality. To make the development of active flutter suppression systems practical, the plant mathematical models used must capture all important physics involved and must be of an order and computational cost that would be within the capability of mature control laws synthesis tools and uncertainty analysis tools.

7.1 Aeroservoelastic Modeling and Analysis for Control – the Linear Case

As has already been mentioned, the equations of motion of the deformable airplane used for flight control system development have converged from two historically different fields within aerospace engineering: The field of flight stability and control and the field of aeroelasticity. While there was awareness of the work in each of these fields by experts in the other field, mathematical models and analysis methods (Ref. 158-169) were quite different for many years: The American k-Method (aka the U-g method) and the British Method, followed by the p-k method and g-Method in aeroelasticity, and the methods of classical control theory followed by state-space modeling and solution methods in flight stability and control. Among the reasons for the developments of these two approaches to the dynamics of the airplane were the multi degree of freedom nature of aeroelastic problems (which, because of the large number of degrees of freedom required for aeroelastic analysis, presented a challenge to contemporary control systems modeling techniques) and the availability of unsteady aerodynamic loads models for simple harmonic motions only and not in the time domain or Laplace domain for general motions.

As the interaction between flexible airframes and active control systems became tighter, a major drive of aeroelastic research was initiated to harmonize aeroelastic modeling and general control systems modeling and analysis techniques (Refs. 158, 165-169). While frequency domain control system design and analysis techniques were used earlier for linear actively controlled aeroservoelastic systems, state space modeling and analysis methods in aeroservoelasticity have been adopted and have seen wide usage from the 1970s and on. A key element of casting aeroelastic plant equations in state space form is the approximation, via rational function approximations (RFAs), of the unsteady aerodynamic forces based on their values along the imaginary $j\omega$ Laplace domain axis. The required curve-fitting introduces an error into the state space aeroelastic equations on top of the inherent errors due to the limitations of the aerodynamic theory and numerical modeling used. Another source of potential problems in active control design based on state space aeroservoelastic models is the upper bound on the frequency range within which the models are valid since the curve fitting to produce unsteady aerodynamic RFAs is limited to the range of reduced frequencies $k = \frac{\omega b}{U_\infty}$ for which frequency-domain unsteady aerodynamic models are available. And yet another challenge is the potential significant increase in the number of aeroservoelastic states of the aeroservoelastoc plant model when rational function approximations are used for the state-space unsteady aerodynamic loads.

7.2 **Aeroservoelastic Models for Active Control at the Currently Highest Modeling Fidelity Level**

Instead of starting from the most practical and currently most widely used models, the discussion here begins with aeroservoelastic models of the highest levels of fidelity possible today: Models that in the structural / structural dynamic area are based on detailed non-linear large motion finite element and flexible multi-body dynamics models (aka Computational Structural Dynamics – CSD) and, in the unsteady aerodynamics area, on detailed Computational Fluid Dynamics (CFD) modeling, including compressibility and viscous effects. Development in CFD and CSD technologies in the last 20 years, plus development in the capabilities of computer systems hardware and parallel computing, have led to significant CFD/CSD aeroelastic and aeroservoelastic capabilities (Refs. 170-184) that allow for capturing the full dynamic / aerodynamic behavior of deformable flight vehicles in flight.

Remarkable achievements of current CFD/CSD simulation technology include the quite accurate capture by analysis of the aeroservoelastic behavior of fighter jets in flight executing maneuvers across their Mach range envelopes that could not be captured by earlier widely-used aeroservoelastic modeling techniques (Ref. 173, for example) . But still there are many challenges in the high-fidelity CFD/CSD modeling area. First, there are still physical phenomena that current CFD/CSD technology may not be able to capture in the reliable and accurate way that counting on it for active flutter suppression development would require. Unsteady aerodynamic loads in the presence of flow separation and boundary layer / shock wave interactions are still a major challenge. Structural nonlinear effects driven by localized distributed structural nonlinearities (such as regional buckling and post buckling) combined with uncertainty in material characteristics due to environmental effects may require extremely large mathematical model and substantial testing. Overall the resulting high-fidelity CFD/CSD models of whole aircraft are so large that even using massive parallel computation they take too long to run for an industry new flight vehicles development. In a design environment in which tens of thousands of simulations are required the usage of such high-fidelity models is still impractical. From the control law synthesis perspective, even though full aeroservoelastic high-fidelity simulations can be run today, including active control systems in the loop (Refs. 173, 180, 184), such math models present a significant challenge to the control system designer because of their large size.

7.3 **Reduced Order Models (ROMs) of High Fidelity Coupled CFD/CSD Mathematical Models**

Similar to the development of modal order reduction techniques in the structural dynamics area to capture structural dynamic behavior well enough for engineering purposes with models that are much smaller in size than the full finite element models of airframes, a major research and development effort over the last 25 years or so has been dedicated to the development of reduced order models for CFD-based unsteady aerodynamics and for coupled CFD/CSD aeroelastic models. Refs. 185-208 are selected publications on these important subjects, with Ref. 185 presenting a comprehensive survey. On top of the limitations on the capacity to capture complex unsteady aerodynamic flows accurately by analysis using the detailed high-fidelity models that ROMs approximate, additional challenges have to be faced: (a) The significant computational effort to create ROMs, (b) the large number of flight conditions that high-fidelity models and their ROMs must cover, and (c) the response fitting errors that are inherent to any surrogate modeling by computationally-fast low-order models of the information that high-fidelity models contain.

While major progress has been made in the area of high-fidelity CFD/CSD modeling of full flight vehicle configurations and the area of reduced order surrogate model approximation of such models, the technology, while capable of supporting limited design studies and providing validation in selected cases, is not ready yet for wide spread utilization by the aircraft industry for the purposes of developing active flutter suppression systems or active control systems in general.

7.4 Aeroservoelastic Models for Active Control based on Linear structural and Unsteady Aerodynamic Theories

The mathematical models for the flight dynamics of actively-controlled deformable aircraft which have served as the foundation of analysis and design of active controls for many years are based on linear finite element models and linear unsteady aerodynamics. In the unsteady aerodynamic area, Modified Strip modeling was used first (Ref. 209). With the development of aerodynamic panel modeling capabilities such as the Doublet Lattice method (DLM) for subsonic flows and the ZAERO as well as PAN-AIR codes for subsonic and supersonic flight, unsteady aerodynamic modeling for aeroservoelastic control application shifted from the 1970s and onward to aerodynamic panel models (Ref. 172). References 209-220 describe various simulation capabilities for integrated actively-controlled aeroelastic systems.

In the common approach to aeroservoelastic modeling of full flight vehicle configurations in flight, aerodynamic influence coefficients are generated by an unsteady aerodynamic code for a set of small panels covering the wet surfaces of the configuration and over a set of reduced-frequencies. A finite element structural dynamic model is used to generate mode shapes and natural frequencies. A reduced order structural model is generated using a subset of selected structural motion shapes, in the form of whole-vehicle mode shapes of the structure with selected mass and stiffness distributions, Ritz vectors, or mode shapes of components of the structure. Using interpolation between the structural finite element mesh and the aerodynamic panel grid, general unsteady aerodynamic forces are generated for the set of mode shapes used to describe the motion of the system. The generalized unsteady force matrices and vectors, corresponding to unsteady aerodynamic forces generated by the motion itself and generalized aerodynamic forces due to external excitation (such as by gusts) are transformed from the frequency axis (their Fourier transform) to the Laplace transform s-plane by analytic continuation. When rational function approximations (RFAs) in the reduced frequency k or Laplace transform variable s are used for terms of the unsteady aerodynamic forces, the coupled structural / aerodynamic model can be brought to a standard state-space form:

$$\begin{aligned} s\{x(s)\} &= [A]\{x(s)\} + [B]\{u(s)\} \\ \{y(s)\} &= [C]\{x(s)\} + [D]\{u(s)\} \end{aligned} \tag{1.1}$$

Where $\{x\},\{u\},\{y\}$ are the system's states, inputs, and outputs, respectively, and where $[A],[B],[C],[D]$ are the system matrices.

As a side note, depending on the order of numerators and denominators of the transfer functions of actuators, when the actuator state space models are part of the system state space model, and depending on the outputs of interest included in the $\{y\}$ vector, external inputs may not be passed directly to the outputs, and the $[D]$ matrix may be zero (Ref. 67).

The equations are usually refined to distinguish between control inputs (made by the pilot or an automatic control system) and inputs by atmospheric gusts or other inputs that can be viewed as external (the ejection of external stores, landing impact, etc.):

$$s\{x(s)\}=[A]\{x(s)\}+[B_c]\{u_c(s)\}+[B_G]\{u_G(s)\}$$
$$\{y(s)\}=[C]\{x(s)\} \quad (1.2)$$

With the c and G indices in the equation denoting control and gust inputs.

State-space models of the types (1.1) and (1.2) are in a form that lends itself to the implementation of both classical and modern linear control system design techniques. The motivation for developing them for aeroservoelastic systems in the 1970s was driven by the desire to bring aeroservoelastic models to forms to which the analysis and design techniques of modern control could be used.

But from active control technology perspective the linear state-space models of (1.1) and (1.2) suffer from a number of problems. First, in the conversion of unsteady aerodynamic force expressions from their Fourier transform to Laplace transform equivalents, using rational function approximations (RFAs) added aerodynamic states can lead to resulting large state-space models. In the case of the popular Roger approximation (Ref. 168):

$$[Q(jk)]\approx[P_0]+s[P_1]+s^2[P_2]+\frac{s}{s+\beta_1}[P_3]+\frac{s}{s+\beta_2}[P_4]+... \quad (1.3)$$

The frequency-dependent $[Q(jk)]$ is a generalized aerodynamic matrix for simple harmonic motions along the frequency axis of the Laplace domain, the matrices $[P_0],[P_1],[P_2]$ are aerodynamic real stiffness, damping, and inertia matrices, the variables β_i are aerodynamic lag roots, and the matrices $[P_3],[P_4],...$ are aerodynamic lag matrices.

Working with N modes as generalized coordinates that describe the motions of the vehicle, the resulting first order state space model corresponding to N_L lag terms is of the order $(2+N_L)\cdot N$. A larger number of lag terms, required, maybe, for obtaining a better match between the Roger RFA and the generalized aerodynamic matrices it approximate over the frequency range of interest, would increase the order of the resulting state-space model substantially. The Minimum-State Approach (Ref. 226, 227) leads to smaller-size state-space models but at the price of matching an RFA simulateneously to all terms of the $[Q(jk)]$ matrices (the Roger approximation is done term by term) with the resulting need to assign higher and lower weights to the approximation of different terms based on their potential contribution to aeroelastic instabilities. In all RFA cases, an error is introduced into the resulting aeroservoelastic model due to inaccuracies of the RFS / frequency-domain data fit. This adds to the uncertainty of the linear aerodynamic predictions themselves. Those cannot capture by the techniques and codes used any nonlinear unsteady aerodynamic effects. The leading unsteady panel aerodynamic codes cannot also capture reliable unsteady aerodynamic forces due to fore-aft motions of the vehicle or parts of the vehicle in flight.

The way the problems discussed above have been addressed in practice is by correction of aerodynamic influence coefficients and other elements of the state-space models based on wind tunnel or flight tests as well as high-fidelity CFD simulations. Structural dynamic models are fine-tuned based on static structural tests and modal tests. The correction factors have to be applied case by case, corresponding to different flight and loading conditions, and while they can improve the overall reliability of the resulting aeroservoelastic models they represent another source of uncertainty in the models with which the controls designer has to work.

Methods for reducing the order of linear aeroservoelastic state-space models have also been developed (Refs. 221-235), as well as methods for order reduction of aeroservoelastic models with linear aerodynamics but distributed nonlinear behavior (Refs. 236-240), and models based on linear unsteady aerodynamics and localized structural nonlinearities (Refs. 241-244).

In such cases the state-space models become nonlinear and can be presented in the form:

$$\{\dot{x}(t)\} = \left[A\left(\{x\},\{u\}\right)\right]\{x(t)\} + \left[B\left(\{x\},\{u\}\right)\right]\{u(t)\} \tag{1.4}$$

Or just:

$$\{\dot{x}(t)\} = \left\{f\left(\{x\},\{u\}\right)\right\} \tag{1.5}$$

It should be noted that there has been recently a drive to return to aeroservoelastic simulation and design methods based on frequency-axis (Fourier transformed) unsteady aerodynamic models without transforming them to the Laplace and time domains. Methods developed for control system analysis and design during the 1930s to the 1960s (the methods of Classical Control) can now be revisited, supported by the computational efficiency of Fast Fourier Transform (FFT) techniques (Refs. 158 and 245-248). Moreover, with the new development (Refs. 246-248) nonlinear aeroservoelastic problems can be tackled by separating their linear and nonlinear parts. The linear part, including Fourier transformed linear unsteady aerodynamics, is assembled to create a linear input-output subsystem for which Fourier transformed transfer functions are obtained. Using FFT / inverse-FFT techniques, impulse or step response time domain responses can now be generated for the outputs of the linear part. Those can be combined, via convolution integrals, with the time-domain marching forward simulation of the nonlinear part of the system. The result is a capability to efficiently simulate in the time domain aeroservoelastic systems which have nonlinear elements without the increase in order due to transforming unsteady aerodynamic force expressions via rational function approximations to the Laplace and time domains. Additional advantages include high computational efficiency and the resulting capability to check large numbers of cases for stability and dynamic response, including static and dynamic internal loads and including the effects of nonlinearities in the control system and in the airframe and its aerodynamics.

7.5 **The equations of motion**

Between the full high-fidelity models and the linear aeroservoelastic models (with nonlinear elements) discussed above, equations of motion have been developed over the years to meet the needs of flight vehicle active control design and simulation in cases involving various flight vehicle design concepts and flight maneuvers. There has been wide spread acceptance of the equations of motion of the maneuvering rigid airplane as developed by the flight control community and the equations of motion for small-perturbation aeroelastic analysis (quasi-static and dynamic) as developed by the aeroelasticity community. This, however, has not been the case for the maneuvering deformable airplane, with equations of motion that would capture elastic and rigid body motions with the associated unsteady aerodynamic force models that would be of the fidelity required for the design and simulation of real actively controlled airplanes.

Equations of motion for the elastic quasi-steady vehicle, maneuvering subject to linearized aerodynamic loads, are presented in Refs. 40, 41 and 249-251. Refs. 6, 42, 46, 47 and their bibliographies present modal approaches to the quasi-static aeroelastic equations of motion. Equations of motion that aim to harmonize rigid body stability and control equations (and their modeling of nonlinear and linearized rigid body rotations) with equations for the linearly deforming structure (subject to small shape perturbations) are presented in Refs. 27, 153, 250-269. The challenge with some of the derivations in these references is that while they are built on rigorous deformable-body dynamics foundations, the unsteady aerodynamic part included is not yet of the fidelity that would be adequate for the modeling of real aircraft for design and simulation purposes.

Motivated by the emergence of highly-flexible high aspect ratio configurations, equations of motion for the deformable airplane have been developed based on nonlinear beam theory coupled with linear strip theory unsteady aerodynamics that could account for aerodynamic forces and moments due to fore-aft motion of wing sections in addition to the effect on aerodynamic forces of out of plane motions of the lifting surfaces. Early efforts in this area are documented in Refs. 270-275, motivated by glider aeroelasticity and the aeroelasticity of human-powered vehicles. Later efforts, over the last 20 years or so were motivated by the interest in high-altitude long-endurance flight vehicles (HALE), and began as an extension of aeroelastic modeling techniques used for helicopter rotor blades (Refs. 276-281). Subsequent development added more advanced unsteady aerodynamic modeling in the form of three-dimensional unsteady vortex-lattice models (including the non-linearities due to wake deformation), and, more recently, coupling with high-fidelity CFD solvers.

Experimental validation of mathematical models for very-high deformation aeroelastic configurations has been scant. A highly flexible low-speed wind tunnel model of the Boeing Solar-Eagle configuration was tested in 2011 (Ref. 572), and was excited using an array of control surfaces at various dynamic pressure and deformation levels. The analysis / test correlation has not been completed and has not been reported. The capacity to capture by analysis the aeroelastic behavior of highly deformable flight vehicles and the development of active control methods for such configurations have not been validated sufficiently yet and are subject to considerable uncertainty.

Note, in addition, that all equations of motion formulations for such configurations involve large scale time-domain state space models. The development of flight control laws for these high-dimension nonlinear systems is still a challenge facing active control technology. Progress in this area for highly flexible configurations is especially important since active control must be integrated from the start into the design of these weight-critical configurations to ensure aeroelastic stability and to mitigate gust loads effects.

7.6 **Actuation and Sensing**

Closed loop active control depends on sensing of the behavior of the controlled “plant” – the aeroelastic system in our case - and on effective means of actuation. Common devices that have been used for aircraft active control are accelerometers and strain gages for sensing and electrohydraulic servoactuators for moving control surfaces that, via changes of the geometry of the flight vehicle, affect changes in unsteady aerodynamic loads. Unless actuators are so powerful, with natural frequencies that are so high above the range of frequencies of importance of the aeroelastic plant, dynamic models of the actuators have to be included in the aeroservoelastic model to be controlled. Dynamic models of sensors have to be included too if strong interaction with the aeroelastic plant over its range of frequencies cannot be neglected. References 282-323 describe the various sensing and actuation techniques used for the active control of aircraft, including the mathematical models of hardware dynamics, aspects of actuation and sensing hardware integration with the airframe, acoustic actuation (Refs. 290, 292, 299), strain actuation (Refs. 297, 298, 302, 303, 305, 310, 311, 312, 319), the impact of actuator model fidelity on resultant aeroservoelastic simulations (Ref. 295), distributed actuation using micro-flaps (Refs. 316-318), and emerging actuation and sensing techniques, including direct sensing of the unsteady flow at selected locations over the surfaces of the configuration (refs. 320-323), fiber-optic sensing (Ref. 310), and actuation by active flow control (Refs. 324-326).

The importance of identifying, modeling, and addressing nonlinearities in actuators is discussed in many of the references on actuation and sensing selected here. The designer of active control systems, and especially active flutter suppression systems, must make sure that actuator nonlinearities (including the important limit of actuator saturation) are modeled accurately and that the active control systems developed perform well in the presence of such nonlinearities as well as the possible changes in actuator linear and nonlinear behavior over time due to service wear and tear, operational heating, environmental effects, and actuator failure.

7.7 **Propulsion System Effects on Aeroservoelastic Behavior**

Except for affecting aeroservoelastic behavior by the effect of engine nacelle shapes on the unsteady aerodynamics of a configuration and by inertia effects, including gyroscopic effects, and by the stiffness, mass, and damping of pylons connecting engines to airframes (Refs. 327-333), propulsion systems interact with the aeroelastic dynamic of an airplane by thrust fluctuations in magnitude and direction due to inlet flow changes triggered by airframe deformation and due to possible interactions between engine control systems and the dynamics of the actively controlled aeroservoelastic plant (Refs. 334-340). Dynamic airframe / propulsion system interactions are extremely important on hypersonic vehicles of configurations where the shape of the airframe ahead and behind the engine affects flow into and out of the engine. Engine thrust variation effects (in magnitude and direction) can be present on conventional transport jets as well as the emerging configurations of supersonic jets (Refs. 341-342) or transonic jets where engine are integrated into the rear of the fuselage. Thrust vectoring (Ref. 527) may, of course, affect overall aeroservoelastic behavior via the dynamics of the thrust force itself and the dynamics of the nozzle actuation system that controls thrust direction.

Finally, the important dynamics that may lead to propeller whirl flutter must be included in any aeroservoelastic plant model of a flight vehicle powered by propeller thrust generating systems (Refs. 343-346).

An aeroservoelastic "plant" model used for active control and flutter suppression design and simulation must capture all dynamic mechanisms of systems and their interactions within the bandwidth of importance of the complete system. If propulsion system dynamics is important, it must be included in the state space or transfer functions models for which the controls are designed.

8. Active Flutter Suppression Control Laws

Extensive research and development efforts have been dedicated over the years to the challenge of active flutter suppression. The numerous references included in the bibliography of this work, in the sections dedicated to active flutter suppression control law development and in sections on aeroservoelasticity, testing, and the various flight and wind tunnel program dedicated to this effort, present a broad view of the many approaches and techniques used and the lessons learned. Almost all references on the development and implementation of active flutter suppression laws here focus on applications involving real aircraft, realistic wind tunnel models, or mathematical models of aeroservoelastic system that capture much of the full complexity of active control of real aircraft.

It is no coincidence that the first substantial contributions in this area track back to the mid-1960s. It was that time when classical control reached a certain level of maturity, modern control was rapidly evolving, and on the hardware side, actuation, sensing, and control hardware began to reach the level of power, weight, bandwidth, and reliability necessary for the fulfillment of the vision (Ref. 5) that "flutter performance" can be improved by "somehow installing in the structure a properly designed, rapidly responding automatic control system, actuated in closed-loop fashion by the motion to be stabilized".

The early years of active flutter suppression research saw two major lines of work. In one approach, which we should name here "the physics-based approach", control laws for flutter were based on searching in the physics or mathematical structure of the flutter problem to identify those mechanisms responsible for the flutter instability and finding ways to suppress them Refs. 347-362). The "aerodynamic energy" approach (Refs. 347-357) is one such approach. It is based on the insight that certain elements of the generalized aerodynamic matrix contribute to the flow of energy from the airstream to the structure over cycles of oscillations when flutter occurs and it seeks control laws that would counter this effect.

The method of Identically Located Accelerometers and Forces (ILAF, Refs. 360-362) seeks to position velocity feedback and actuation forces (in the generalized velocity and force sense for a set of modes) so as to create an effective viscous damping matrix for the multi-degree-of-freedom equations of the system that would stabilize it (See Ref. 363 for a similar approach to the active control of structures with guaranteed stability) . Similarly the method of "Fictitious Structural Modifications" (Ref. 359) seeks control laws that would effectively modify the net stiffness, mass distribution, or damping of a structure. In all "physics based" methods the aeroelastician, mastering the structural dynamics and full aeroservoelasticity of the problem, works hand in hand with the controls specialist who helps develop and implement the resulting control laws using control systems hardware.

While major accomplishments have been achieved with the "physics based" methods, they have been pushed aside over time by active flutter suppression control law synthesis methods based on developments general control systems theory. Refs. 365-392 present a variety of active flutter suppression control law synthesis approaches based on classical control: Nyquist, Bode, and Nichols compensation methods, LQR/LQG, pole placement, eigensystem synthesis, miu-analysis, and other methods based on mathematical programming, fuzzy logic, neural networks, and more. Control system robustness was addressed by the classical gain and phase margins, by constraints on matrix singular values, by miu-analysis, and more. Order reduction of flutter suppression control laws generated by modern control theory – an important element in creating a practical control laws for implementation on flight system computers – is discussed in Refs. 393-395 and in references describing research work on wind tunnel models and actively controlled flight vehicles.

The range of test cases used covers a number of flight test vehicles including the NASA DAST (Drones for Aeroelastic and Structural Testing), oblique-wing aircraft concepts, large transport airplane concept, and a number of actively controlled wind tunnel models. Additional information on the development and testing of active flutter suppression laws can be found in the section of the bibliography that gathers publications on different wind tunnel and flight test programs involving aeroservoelastic control and active flutter suppression over the years. This will be surveyed and discussed in a subsequent section.

In general an active flutter suppression system must stabilize an aeroelastic system that would otherwise be unstable over all flight and maneuver conditions of a flight vehicle covering all configuration and loading variations and all flutter mechanisms. It must perform well subject to all constraints on its range and power of operation. It must work in harmony with all other active control systems of the vehicle, including its stability augmentation system, gust alleviation system, maneuver load control system, and ride comfort system in all flight conditions. It must be robust and reliable, with protections against hardware failure, maintenance errors, airframe damage, and uncertainties in the mathematical models used to develop it.

Naturally, adaptive control is attractive in the case of flutter suppression because of the many variations in plant characteristics and uncertainties that need to be covered and the capability (if implemented with the power, reliability, and adaptation capacity required) to respond to damage scenarios. Gain scheduling, when control laws change in a pre-programmed way in response to changes in configuration and flight conditions is one way to tackle this challenge. Adaptive control systems with the capability to "learn and adjust" in real time, if proven to be adequately robust, have been of major interest in the Active Flutter Suppression area. Such systems have the potential to also identify system failures and to immediately correct for that. A sensor failure or an actuator failure, for example, occurring simultaneously with changes in flight conditions, would lead to immediate shift of sensing and actuation responsibility to other functioning elements together with the necessary change in control laws. The term "immediate" is used here to describe response that is fast enough to guarantee stability and proper operation of the suddenly different aeroservoelastic plant. A list of publications on adaptive control, in the context of flutter suppression, is contained in the bibliography in Refs. 396-416.

Other aspects of the flutter suppression law problem are discussed in Refs. 417-435: The effect of control system hardware delays – very important given the high frequencies at which some flutter mechanisms may occur and the high bandwidth that the flutter suppression system may need to cover (Refs. 417-418), special treatment, regarding active control, of parameter varying systems (Refs. 419-423), and the control of nonlinear aeroelastic systems (Refs. 424-431).

Topological issues of aeroelastic sensing and control are discussed in Refs. 432-435. The designer of control laws for the actively controlled airplane must work with aerodynamicist, structural, and configuration designers to identify the optimal locations of sensors and both location and size of control effectors that would make the aeroelastic plant most control-friendly regarding its controllability, observability, and the resulting weight and complexity that a control system working with such sensors and control effectors would have. Regarding the challenge and promise of distributed actuation, if different control surfaces (or other control effectors) are used for the different function of an active control system (such as flutter suppression, gust alleviation, etc.) an optimal selection has to be made regarding which control effector will be assigned to which function. If the same control effectors are to be used, in a shared way, for some of the control functions, then the level of authority of each control function over each control effector assigned to it must be carefully optimized. In either case it must be guaranteed that control effectors will not reach saturation and that different functions of the overall control system will not adversely affect one another. In the case of active flutter suppression, for example, activity of the control effectors due to gust excitation should be well within the limits of operation of the effectors and their actuators and should not adversely affect the loads on the wing. In the case of gust alleviation, gust alleviation control laws should not destabilize the flight vehicle or adversely affect its handling qualities. The example of Ref. 510 is another case of adverse effects of undesirable interactions between control laws and the hardware they use when such interactions are not addressed properly by the design.

To conclude this section about active flutter suppression control law synthesis, it is interesting to mention that work on the active aeroelastic control problem that has been pursued from the Applied Math perspective – known as the Continuum Approach to Aeroelasticity (ref. 436). Here careful mathematical analysis of the field equations of aeroelasticity is carried out before the equations are discretized for numerical solution. In addition to providing "mathematically correct" solutions that can be used for validation of numerical methods, the continuum approach has the potential to identify aspects of the behavior of aeroelastic systems that may be missed by the numerical methods commonly used. The solutions obtained so far by the continuum method are limited to very basic problems and are not, it seems, ready for utilization by industry for the aeroelastic analysis of full configurations.

9. Tests

The complexity of flight vehicle aeroservoelastic systems requires validation of the mathematical models used for designing and analyzing them, and, in most cases, fine-tuning of the mathematical models based on test results. In the structural dynamic area: static loads tests and modal tests (Ground Vibration Tests - GVT). In the control area: tests of actuators, sensors, and all other hardware elements of the control system loops. In the aerodynamic / unsteady-aerodynamics area: wind tunnel tests and flight tests. All tests of an aeroservoelastic system and its components are subject to test uncertainties due to the limitation of experimental techniques and the uncertainty in the test article, the environment in which it is tested, and even the makeup of the testing team itself.

The technical literature on structural, aerodynamic, and control system testing is vast. The focus of the present overview is on testing of complete aeroservoelastic systems. A few publications that can provide an introduction and guide for the interested reader to the key elements of ground vibration testing are Refs. 437-439 as well as Refs. 440-443 and the conference proceedings volumes that preceded them. Some representative earlier and more recent publications on unsteady aerodynamic wind tunnel tests and on effort to validate aerodynamic numerical prediction techniques using the results of such tests are presented in Refs. 157, 330, and 444-448. Actuator testing and math model validation is discussed in Refs. 282, 298, 307, 308, and other references discussing the integration of actuator models into the aeroservoelastic model.

In all the cases discussed above, tests can be used to validate and fine-tune mathematical models. The math models, however, based on the assumptions they are built on, may not be able to capture certain physics of the system, and the experimental results are subject to inaccuracy and uncertainty. Care must be taken to ensure that having to accept a certain level of uncertainty in the system's aeroservoelastic mathematical models after GVT, hardware dynamics, and wind tunnel aerodynamic test data that have been used to fine-tune them, the overall uncertainty level in the resulting aeroservoelastic models will be reduced compared to the level of uncertainty before the tests Refs. 623, 628, 640).

The final step in any aeroservoelastic development are the flight tests (Ref. 457). Aeroservoelastic flight testing has its roots in flight flutter testing (Refs. 449 and 456). A major element is the experimental identification of the mathematical models of the tested system, aimed at building confidence in the theory used to design the system and also at obtaining information during the tests that would allow prediction of the stability boundary. The identification by tests of aeroservoelastic stability boundaries is important for the protection of the tested vehicle and its crew, if it is a manned vehicle, from destructive instabilities in flight. It is also important for certification, since certification requirements generally require demonstration of safe operation, with enough margins of safety of one form or another, up to the boundaries of the flight capability of the flight vehicle.

The identification, in flight, of the aeroservoelastic characteristics of a flight vehicle is challenging. The operational environment and both inputs and outputs used for system identification may be noisy. Many degrees of freedom are involved, with some system aeroservoelastic poles very close and hard to separate using the distribution of actuators and sensors available. References 449-475 have been selected to cover the key elements of both aeroservoelastic flight testing and wind tunnel testing: Actuation, Sensing, instrumentation, data acquisition and system identification, test planning and execution procedures, and test/experiment uncertainty.

While wind tunnel model tests can provide very useful information on the core elements of aeroservoelastic behavior and control and the particular issues associated with different configurations, they suffer from certain limitations regarding the extrapolation to the kind of behavior that corresponding full-size flight vehicles of the same configuration would exhibit. Wind tunnel tests cannot fully duplicate the Mach number, Reynolds number, and reduced frequencies of full size tests. Wind tunnel walls and mounting equipment interference can be a problem. Free-free coupled aeroservoelastic behavior involving rigid and elastic motions (known as the Body Freedom Flutter problem – BFF) requires sophisticated model mounting systems. The wind tunnel flutter models, because of the scaling laws they need to be designed to, may not be strong enough to withstand high loading conditions in the tunnel, thus limiting the flight conditions at which tests can be carried out.

But wind tunnel tests offer significant advantages: the test environment can be carefully controlled, control laws can be quickly varied and tested, costs are lower, and risks in the case of manned flight vehicles is lower.

When the focus of wind tunnel tests is on concept demonstration, math model validation, and insight gains regarding the aeroservoelastic features of new configurations, they are an important element of aeroservoelastic flight vehicle development. Long before a new flight vehicle and its control system will be ready for flight, aeroservoelastic wind tunnel tests can provide information that would guide the design of the full vehicle and reduce risks in the program.

10. Active Flutter Suppression in Flight

The development of any new technology for flight vehicles cannot be complete without a substantial experimental effort involving ground tests, wind tunnel tests, and flight tests with systems that represent real aircraft in their full complexity and operational envelopes. In a very thorough review of active-control flight and wind tunnel experimental work, Ref. 154 covers almost all, if not practically all, major projects in this area in the U.S. from the late 1960s to the early 1980s.

From the perspective of active flutter suppression any experimental active control work with actual aircraft or with wind tunnel models that represent the complexity of real aircraft is important. Wind tunnel test and flight test results help validate aeroservoelastic mathematical models. They expose weakness in control laws and the capacity of an active control system (software and hardware) to meet design goals and provide required safety. The resulting lessons and insight guide follow-on development.

Out of the many experimental active-control programs to date the bibliography of this report focuses on those that capture in mathematical modeling and tests the full physics of deformable flight vehicles (or major components) including the structural dynamics of deformable airframes, unsteady aerodynamics, as well as sensor and actuator dynamics. An effort is made to expand the coverage of experimental programs to date to include developments in the U.S. after the early 1980s and major developments in other countries. Not every publication on work in this area has been included in this bibliography. The review papers and reports of Refs. 136-157 as well as Refs. 119-120 and

Refs. 131-132 would guide the reader to additional material on the experimental work with flight vehicle active controls to date.

Beginning the survey with flight tests, the most demanding experiments and most realistic, active flutter suppression of a modified Boeing B-52 was demonstrated in flight in the early 1970s (Refs. 480-485, Fig. 2). The B-52 program began with the Load Alleviation and Structural Mode Stabilization (LAMS) program and continued with the B-52 Control Configured Vehicle (CCV) program. For the CCV program control surfaces were added to the vehicle. External fuel tanks were mass balanced to reduce the flutter speed into the flight envelope of the B-52. The utilization of a destabilizing external store has the advantage of rapid stabilizing of the configuration by ejection of the store in case an instability is encountered in flight. Flight tests of the B-52CCV demonstrated successful active control action in five areas simultaneously: Flutter Mode Control (FMS), Maneuver Load Control (MLC), Ride Control (RC), Fatigue Reduction (FR), and Stability Augmentation (SA). Stability Augmentation was used to allow flight at cg location as far aft as the Neutral Point. Both Ride Comfort, as affected by accelerations along the fuselage, and Fatigue Alleviation , as affected by internal dynamic loads are aspects of Gust Alleviation.

It is important to note that by design the flutter instability of the B-52CCV was of the mild-moderate mechanism type. That is, a mechanism in which the decline in damping with increased speed (or dynamic pressure) is gradual and allows more accurate prediction by tests of the flutter speed by extrapolation. Flutter was predicted to be symmetric, at about 2.4 Hz, and a rate of damping los with increased speed of 0.01 g per 10 knots at 21,000 ft. Sensor locations and the control surfaces available for active controls on the B-52CCV are shown in Fig. 3. The important issue of which sensors and control surfaces to use for what function of the active control surface becomes immediately apparent. Certain sensors / control surface combinations would be more or less effective regarding observability and controllability of different dynamic responses. Any design must guarantee that control surfaces operate within their limits in their combined power and motion effort as they are used for the different functions of the control system.

The B-52 active control test program included wind tunnel tests at the Transonic Dynamic Tunnel (TDT) at NASA Langley (Refs. 283, 450, 483). Overall it was a pioneering effort in the development of active control technology for aircraft and wind tunnel model. It demonstrated that aeroservoelastic math modeling and control law synthesis methods of the time were adequate. It advanced wind tunnel and flight test techniques. The conclusions of Ref. 484 was that “whenever structural and aerodynamic theory are adequate to predict flutter, the controllability of flutter is also predictable. Whether FMC is applicable to more violent, higher frequency modes can then be decided analytically for each specific airplane”. Ref. 484 also notes, in its conclusions, that “parameter identification methods will need to be developed to support experimental control synthesis”. Considering the fact that the B-52 CCV program was completed more than 40 years ago, without the powerful, fast, equipment and computing power available today and before major developments in analysis and synthesis techniques of the last forty year, its achievements are remarkable.

B-52CCV (Note the canards and ventral vane)

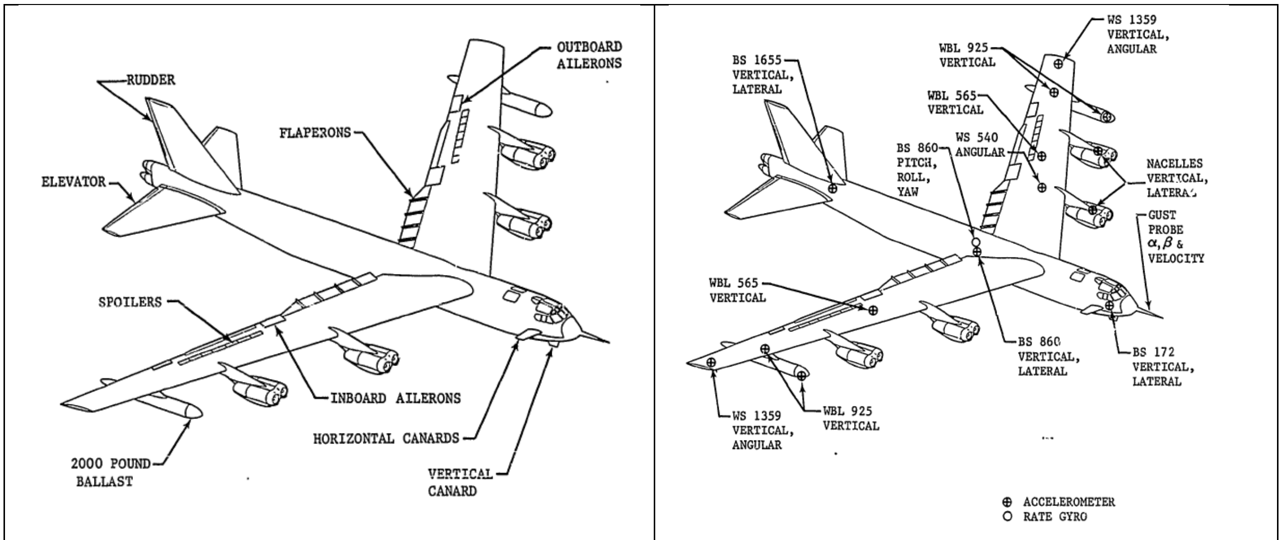
B-52 Active Controls Model at the NASA TDT

Figure 2: The B-52 active flutter suppression vehicle and wind tunnel model

A European active flutter suppression flight test program of the mid 1970s is described in Ref. 525. A FIAT G91/T3 was fitted with modified external fuel tanks which were ballasted to reduce flutter speed into the aircraft flight envelope. The tanks were equipped with aerodynamic vanes and flutter suppression systems. In addition to the study of using active flutter suppression for overcoming the quite common aircraft / stores flutter compatibility problem in fighter jets in certain external stores configurations, the tested system could be quickly stabilized by ejection of the external tanks if flutter was encountered. A German F-4F was used later to study active flutter suppression of wing / stores flutter. This time the aircraft's existing ailerons were used (Refs. 503-505) and control commands were generated by the existing flight control system hardware through a flutter suppression control box feed into the roll channel of the aircraft.

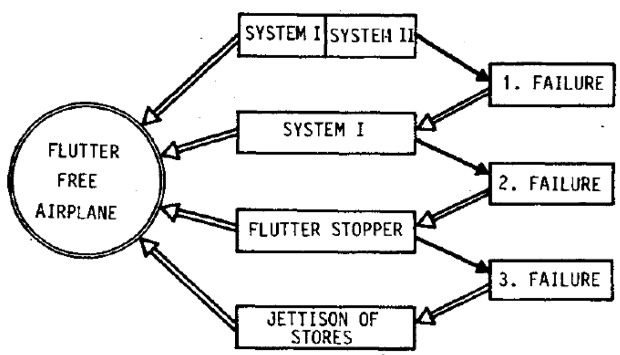
Key elements of importance in the evaluation of any active flutter suppression system were highlighted by the F-4F analysis and test program. First, nonlinearities in the structure (especially stores pylon structural nonlinearities) led to significant differences in modal frequencies at different oscillation amplitude levels. This affected the performance of the control laws. It also led to Limit Cycle Oscillations. And so a demonstration of stable flight using active control at flight conditions that without active control would be unstable became difficult. Another important aspect of the active flutter suppression design to make sure that there was no coupling between aileron and spoiler action. In the math models that were used to synthesize the flutter suppression control laws only two modes were taken into account (store pitch and first wing bending) with all other modes excluded by bandpass filtering or filtering by location. Such filtering makes it necessary to work with very accurate mathematical models of the flutter mechanism. It also makes it necessary to consider effects on other functions of the flight control system.

For safety, ballast masses were installed in the external stores to serve as flutter stoppers by, on command, moving and changing radii of inertia of the stores. Each store could suppress flutter on its own, by making the configuration a-symmetric, where in this particular case the flutter speeds of a-symmetric configurations was higher than the flutter speeds of the corresponding symmetric ones. Also, the stores could be ejected. The change of store radius of gyration could be made with 0.5 seconds. With flutter frequency close to 5 Hz, this meant less than three cycles of flutter oscillation. Safety, using such a test safety mechanism, can be provided if the amplitude growth during the transition from unstable to stable structural dynamics is not high enough to cause major damage. The overall safety approach adopted by the F-4F program is illustrated in Fig. 4. Note the redundancy in the flutter suppression system, with two systems working independently on each wing.

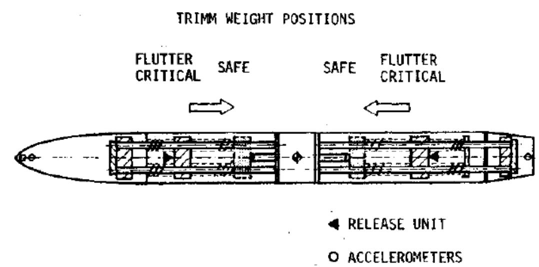


Control Surfaces | Sensors

Figure 3: Control Surfaces and sensors of the B-52CCV (Ref. 482)



F-4F Flutter Test Program Safety (Ref. 505)



F-4F Flutter Stopper (Ref. 505)

The capacity to protect the vehicle or a wind tunnel aeroelastic model from destruction, if an instability is encountered, is an important feature of any research flight or wind tunnel flutter test. In the B-52CCV, Fiat G91/T3, and F-4F modified aircraft were flown, on active control, into unstable flutter regions of the flight envelope equipped with mechanical means to change the configuration abruptly into a flutter stable one if problems appeared. An important question, regarding the certification of aircraft, is how to address the test safety issue when testing the actual vehicle and its systems is required.

The 1970s and early 1980s saw significant active flutter suppression development activity at NASA with the DAST UAV (Drones for Aerodynamic and Structural Testing, Refs. 493-497 and numerous references on the development of flutter suppression control laws, including Refs. 351, 373, 374). The wing of the DAST vehicle was designed to flutter within its flight envelope. It had a supercritical airfoil shape and an Aspect Ratio of 6.8. An ejectable ballast weight was placed aft of the rear spar of each wing to function as a “flutter stopper”. Four accelerometers and two control surfaces were used for flutter suppression. The accelerometers were placed on the wing and in the fuselage to allow separation of the measurements of rigid body and elastic motions. The control surfaces were used to suppress flutter and also to provide excitation to the wings for system identification during flight tests (Ref. 374). Ref. 154, in addition to the references already mentioned, gives an overview of the DAST program. The vehicle used a series of Aeroelastic Research Wings (ARW) attached to a modified Firebee II target drone. In a third flight after a flight in which valuable data was collected with good signal to noise ratio and error in the implementation of control gains in the active flutter suppression system led to explosive flutter and the loss of the vehicle (Fig. 5). The wing was rebuilt (as ARW-1R) and attached to another Firebree fuselage. It was destroyed when the drone recovery parachute deployed and was torn loose on separation of the drone from the B-52 carrier aircraft. A new research wing – ARW-2 – was developed in a design effort that involved integration of structures, aerodynamics, and control, accounting for multiple control systems operating simultaneously and capable to controlling the vehicle at multiple flight conditions. A variety of control law synthesis techniques was studied, addressing software and hardware issues, including the robustness of the control, order of control laws and the effects of control system hardware, control "spillage" (where control action in one range of frequencies affects the dynamics of the system negatively in other ranges of frequencies), etc.. Not surprisingly, nonlinear effects and the difficulty to design control laws that would function well at off-design conditions were encountered. Nonlinearities in the DAST ARW-2 case were due to nonlinear torsional stiffness of the fiberglass-skin wing and the nonlinear aerodynamics of supercritical airfoils on top of the nonlinearities of the actuators. As Ref. 495 describes, a correlation between angle of attack and aeroservoelastic poles' damping ratios was measured for the DAST ARW in flight. Between Mach numbers of 0.893 and 0.911 at 25,000 ft and active flutter suppression system off the critical damping ratio in anti-symmetric motion decreased from $\varsigma = 0.03$ to $\varsigma = 0.01$ as the angle of attack decreased by 0.3 degrees. Aeroelastic poles showed sensitivity to angle of attack at other transonic Mach numbers. Clearly the non-linear aerodynamics of transonic flight must be accounted for properly, and that includes, in the case of small perturbation disturbances, both the steady state static aeroelastic equilibrium flight and the unsteady motions about it. Note that the safety mechanisms built into the DAST design (the ejectable ballast masses and the parachute) failed to save it. The ARW-2 wing, while used for analytical and ground test studies, was not flown.

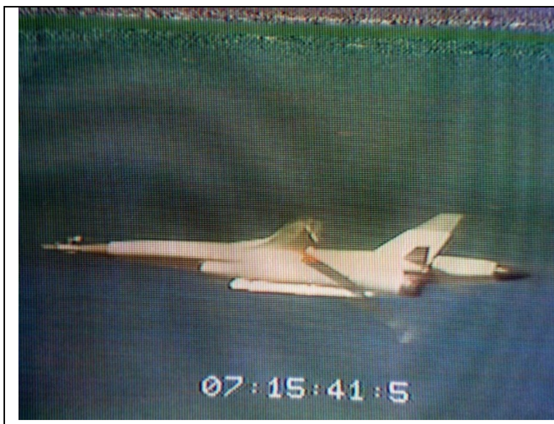


Figure 5: Flutter of the right wing in flight on the modified BQM-34 Firebee II Drone with Aeroelastic Research Wing ARW-1 (NASA Photo ECN-31306-fr41-5)

(NASA Photo ECN-31306-fr43-9

The first active flutter suppression system to fly on a production airplane was, probably, that of the F-18 (Ref. 520 and 523). At the time it was named "Active Aeroelastic Oscillation Control" because the problem it was tasked to solve was that of Limit Cycle Oscillations (LCO) in some external stores configurations of the F18. In the title of Ref. 523 it was named "Limit Cycle Oscillation Solution". Indeed, it is important to distinguish, when active controls are used to suppress aeroelastic instabilities, between cases in which the instability is of the divergent flutter kind, where crossing the flutter boundary would result in oscillations of increased magnitude that would damage the airframe and cause catastrophic failure and cases in which beyond certain flight envelope boundaries an airplane would develop LCO. Clearly, the failure of an active flutter suppression system in the LCO case would not be as catastrophic as in the divergent flutter case. In the LCO case, a failure of an active suppression system would lead to limit cycle oscillations that, as long as the amplitudes and accelerations involved are not too high, would pose no immediate danger to the airframe and allow corrective action.

There can, therefore, be an argument whether the shift of an aeroelastic system from well-damped behavior to limit cycle oscillation behavior constitutes loss of stability or not. If we adopt the definition of flutter in Ref. 1: “an oscillation which grows, and finally either breaks the structure or remains bounded at some amplitude whose value is dependent upon the departure from linear laws.”, then, whether suppressing LCO or divergent flutter, an active control system that suppresses self-sustained aeroelastic oscillations is an active flutter suppression system.

In the F-18 case the LCO, which was sensitive to Mach number and static aeroelastic shape of the airplane in flight, could be suppressed using the existing flight control system (Fig. 6). Anti-symmetric motions could be well-sensed by the rate gyros and accelerometers in the fuselage. Control laws, then, drove action by the ailerons.

Because of a lack of adequate mathematical models that would capture the behavior of the F18 in LCO in the original case, the control laws used to suppress the oscillation were developed iteratively by test pilots while flying the airplane. A control panel was added to the cockpit and allowed the pilot to adjust gain and phase of an aileron command signal relative to control system sensor signals. To quote from Ref. 523: “Once the appropriate gain and phase were obtained using this experimental hardware, the new feedback loop was coded into the F/A-18 existing fly-by-wire control system”. In the case of the F18 the active oscillation control system is activated as function of Mach number and Altitude in those areas of the flight envelope in which the LCO problem exists (Fig. 7).

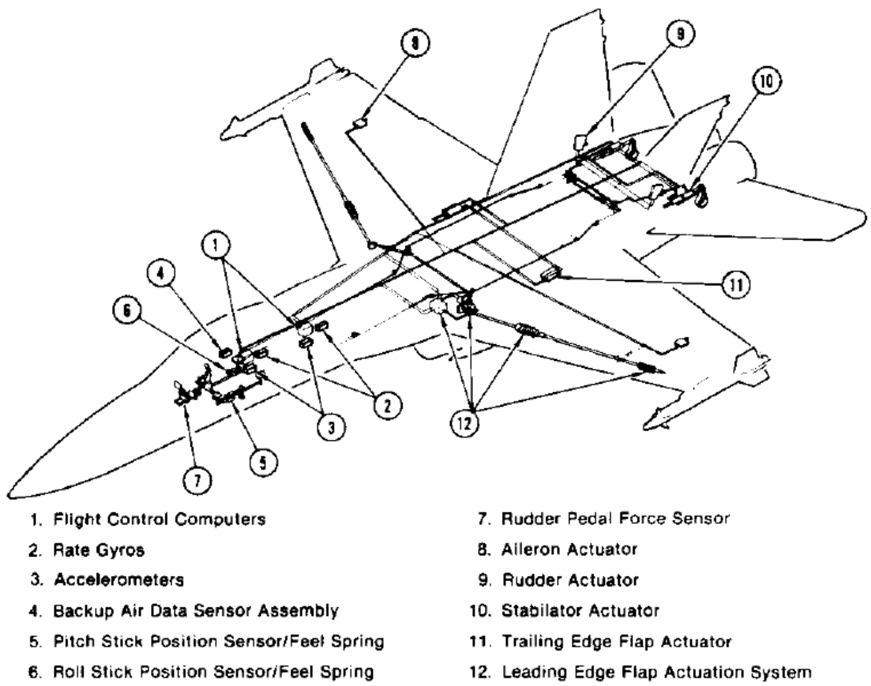


Figure 6: The F/A-18A Flight Control System (Ref. 520)

A recent case of adoption of active dynamic aeroelastic control on production aircraft is the case of the cargo and passenger derivatives of the new Boeing 747-8 (Ref. 490 and 685-687). Not enough technical information has been made available to the aeroelastic community. What can be learned from newspaper stories such as Ref. 490, and regulatory agency publications (such as Ref. 685) is that in certain flight conditions the airplane "exhibits an aeroelastic mode of oscillation that is self-excited and does not completely damp out after an external disturbance…The limit cycle flutter mode is primarily symmetric, manifesting itself as a 2.3 Hz sustained oscillation of the wings, engine pylons, and fuselage.".

Ref. 685 continues: "It has been established that compliance with CS 25.252 and CS 25.629 can not be shown with this amount of LCO present. Boeing is therefore adding an Outboard Aileron Modal Suppression System (OAMS) to the fly-by-wire roll flight control system to reduce the amplitude of the sustained oscillation and to control the aeroelastic instability.. This would be the first time the use of an active flight control system to control flutter is approved on a commercial transport aeroplane. The OAMS system is considered to be a novel and unusual design feature that the existing airworthiness requirements do not adequately address. Therefore Boeing is requested to show compliance with Special Condition C-18".

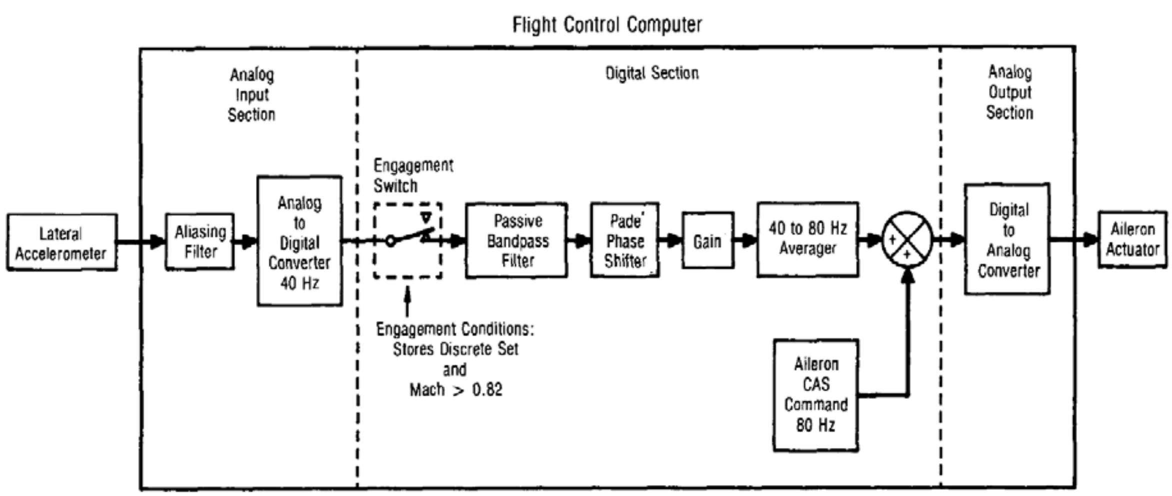


Figure 7: The F/A-18A Production Active Oscillation Suppression System (Ref. 520)

Note (Ref. 687) that "These special conditions require that the airplane meet the structural requirements of subparts C and D of 14 CFR part 25 when the airplane systems are fully operative. These special conditions also require that the airplane meet these requirements considering failure conditions. In some cases, reduced margins are allowed for failure conditions based on system reliability."

The shift of the aircraft industry from willingness to share information, with the understanding that there are disadvantages but also significant gains for all, to an intellectual-property protection mode where very little or nothing is shared and published, has been evident in recent years, as even information that has safety implications, in an area such as flutter, that used to be shared in the past for the benefit of all, is now kept tightly protected.

To mature Active Flutter Suppression technology to where it can be widely accepted, not only as a fix for late-discovered problems but as a driver of the design of efficient new airplanes, requires an effort in which all major discoveries and experiences are shared. The X-56 MUTT (Multi Use Technology Testbed) flight research vehicle, developed by Lockheed-Martin Skunworks for the US AFRL with this vision, is a platform for elastic aircraft active control research (Refs. 544-547 and Fig. 8).

The X-56 follows a series of small UAVs for flutter suppression research built and tested by Lockheed Skunworks to develop active flutter suppression technology for flight vehicles displaying Body Freedom Flutter (BFF). The BFF instability is due to interaction between elastic motions of the airframe and its rigid body motions. Configurations with low overall pitch inertia (such as flying wings) and highly flexible wings may have high short period frequencies that would couple with low-frequency wing bending frequencies and the associated mode shapes to produce instabilities. Body Freedom Flutter can also be a critical instability mechanism on configurations with forward swept wings, where the aeroelastic divergence tendency of the wing (leading to reduction in frequencies with increased dynamic pressure) may couple with rigid body motion frequencies to create instabilities. The X-29 (Refs. 533-539) is an example of such a case. Rigid / Flex coupling was also found on the B-2 bomber, influenced by shock wave movement over the configuration, coupling wing bending and rigid body pitch (Refs. 478-479).

Figure 8: The X-56 (http://www.nasa.gov/centers/armstrong/research/X-56/index.html)

The X-56 is designed for a variety of configurations it would allow testing. Different wings and tails can be attached to the fuselage, including a Joined-Wing configuration. The main instrumentation and systems are housed in the fuselage which is equipped with a parachute recovery system. An open architecture flight control system, a modular data acquisition system, and ten control surfaces allow tests of alternative active control concepts and systems. Like the B-52CCV, the X-56 allows for the development of active control systems that serve many functions, including flutter suppression, gust alleviation, stability augmentation (and handling qualities), maneuver load control, and ride comfort. The challenge in the case of such a vehicle, where rigid body and elastic motion dynamics are tightly coupled and where active flutter suppression, gust alleviation, and stability augmentation have to work in harmony with the same frequency range, is significant. To challenge technology development in the active flutter suppression area, the flexible wings provided with the aircraft have three flutter mechanisms within the flight envelope, including a BFF mechanism. Note that the X-56 is not a transonic airplane. In the configurations developed for it so far it does not represent the aeroelastic mechanisms and behavior that passenger aircraft display. And yet, following the note in Ref. 484, confidence in analysis and synthesis methods validated by flight tests on the X-56 can guide and significantly reduce risks when such analysis and design methods are used for other aircraft, especially in the areas of sensing, actuation, control systems hardware integration with the airframe, and the seamless operation of a control system that satisfies demands and constraints of multiple types.

Two X-56 vehicles were built for the AFRL and flight tested. They were delivered to NASA Armstrong Flight Research Center for future tests. An X-56 carrying a flexible composite wing crashed on take-off in November 2015 and was lost. At the time of writing this report, a second X-56 was undergoing ground vibration tests at NASA Armstrong in preparation for subsequent flight tests with NASA generated flight control laws.

Influenced by the X-56 design, the University of Minnesota, in a NASA-supported active flutter suppression research program, developed its Mini-MUTT UAV (Refs. 230, 423, 531-532). The Mini-MUTT is based on the outer mold line of a donated Lockheed-Skunkworks BFF UAV (Ref. 423), but it follows a modular design philosophy similar to the X-56 MUTT aircraft. It also has a rigid center body capable of carrying interchangeable flexible wings and it also allows tests of a rich variety of flexible wing configurations at low cost. The Lockheed-Martin BFF UAV and its University of Minnesota derivative, the Mini-MUTT, are shown in Figure 9 (taken from Ref. 423).

Figure 9: The Lockheed-Martin BFF UAV (back) and the University of Minnesota Mini-MUTT (front), Ref. 423.

The aeroservoelastic literature is rich in reports, papers, and book chapters that describe active control flight tests on a rich blend of flight vehicles. While not being active flutter suppression tests in which a flight vehicle is flown using active control into a flight region in which it would flutter without active control, the experience gained in testing gust load alleviation systems, maneuver load control systems, or active ride comfort systems, as well as handling qualities and stability augmentation control is important. Mathematical models of the actively controlled deformable airplane and its sensors and actuators are validated, different control law synthesis techniques and the resulting control laws are evaluated, hardware implementation issues are analyzed and lessons regarding hardware implementation and integration are drawn, the important issue of safety measures and safety guarantees must be addressed, and finally, test procedures and system identification techniques can be evaluated in flight and improved.

Important flight test programs of aeroservoelastic actively controlled aircraft include ythe ride comfort system on the B-1 (Refs. 476-477), the B-2 (Refs. 478-479), the XB-70 (Refs. 486-489), the C-5A (Refs. 491-492), Eurofighter (Refs. 498-501), the Boeing E-6 aeroservoelastic instability case due to non-linear structural loss of stiffness under load (Ref. 502), the F-15 (Ref. 506), the F15 STOL Maneuver Technology Demonstrator (SMTD, Ref. 507-509), The F16, YF16, and F16XL (Refs. 510), the YF-17 (Ref. 515), the F18 thrust-vectored vehicle (Refs. 521-522), the F22 (Ref. 524), The SAAB Gripen (Ref. 526), the Gulfstream G550 (Ref. 527), the Lockheed L-1011 (Refs. 528-530), the X-29 (Refs. 533, 537-539), the Boeing X-32 (Ref. 540), the Boeing X45A (Ref. 541), The Boeing X53 F18 Active Aeroelastic Wing vehicle (Refs. 542-543), and the University of Michigan's X-HALE research UAV (Ref. 548).

References in the bibliography on the aeroservoelasticity and active control of real aircraft include research that did not lead to flight tests but was based on mathematical models of actual aircraft with all their complexity. Work on adaptive control with the F16 model, including a wind tunnel test at the TDT is described in Ref. 511. Development of flutter suppression for the YF-17 using, in addition to the full aircraft, a NASA TDT tested wind tunnel model, is described in Refs. 514-519. Similarly, active flutter suppression development for the X-29 and its NASA TDT model is described in Refs. 533-536.

While mathematical models and detailed test results were not available to the general aeroservoelasticity community, data for a few key configurations were made available to many researchers working in the flutter suppression area. This includes the mathematical models of the NASA DAST vehicle and the wind tunnel model of the YF-17 with external stores. Math models of the B-52CCV became available more recently. The mathematical aeroservoelastic models of the X29 and F18 have been available to researchers subject to export controls and ITAR restrictions.

11. Active Flutter Suppression in the Wind Tunnel

Wind tunnel tests are less expensive than flight tests and provide a controlled test environment and important sensing and actuation options that are difficult to implement on aircraft in the early stages of technology development. In the case of active flutter suppression, with the risks to the flight test vehicle and its crew, wind tunnel tests provide more safety. The advantages and disadvantages of active control wind tunnel tests have already been discussed above. The bibliography includes papers and reports on key wind tunnel tests in the active flutter suppression area in particular and aeroservoelasticity in general over the las 45 years or so. They provide insight, via analysis / test correlation regarding the accuracy of mathematical models of actively controlled deformable vehicles, on the effectiveness of different control laws, on different sensing and actuation methods, on the unsteady aerodynamics of actively control aircraft configurations and their control effectors, and more.

A wind tunnel test program of a US AFFDL forward-swept wing model is described in Refs. 549-550. The wing / store flutter problem is naturally of major interest to the Air Force. In the context of active flutter suppression, wind tunnel tests of aeroservoelastic models with different external stores configurations offer the opportunity to evaluate the effectiveness and robustness of different control laws and control system sensing, actuation, and topology. Robustness can be evaluated not only with respect to variations of structural dynamic properties of the system to be controlled but also of the unsteady aerodynamics of aircraft / stores combinations and the significant uncertainty in the mathematical modeling of aircraft / store combinations that current modeling technology still faces.

Wind tunnel tests of a US AFWAL wing/store model are described in Refs. 551-552. Tests by ONERA in France of a wind tunnel model of a wing/store configuration is described in Ref. 597. Wind tunnel tests of X29, YF17, and F16 aeroelastic models with external stores will be discussed later in this section.

The Active Flexible Wing (AFW) program is described in Refs. 553-562. It was a joint Air Force / Rockwell International / NASA program from the mid 1980s to the early 1990s.

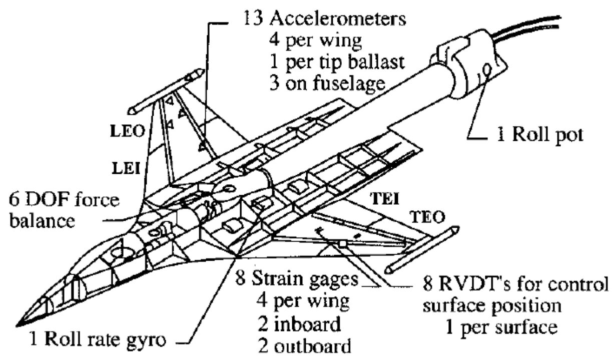
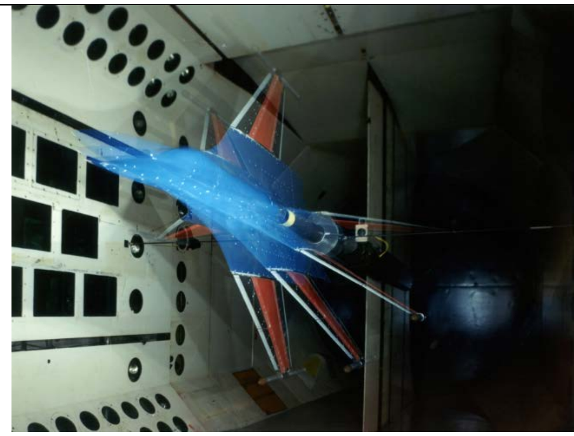


Figure 10: Schematic of the AFW model (Ref. 554)



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The AFW model, tested in the NASA TDT, was an aeroelastically scaled model of an advanced fighter jet with two leading-edge (LE) and two trailing-edge (TE) control surfaces per wing. The model was mounted on a sting mount which allowed it to roll and also pitch over a range of angles of attack. The model and its instrumentation are shown in Figure 10. Quoting from Ref. 554, "An important objective of the AFW program was to gain practical experience in designing, fabricating, and implementing a real-time multi-input/multi-output (MIMO) multiple function digital controller, and in developing the hardware interface between the controller and the wind tunnel model. Required features of the digital controller were that 1) it be representative of a digital controller on a full-scale airplane, 2) control laws could be easily modified and/or replaced, 3) it be capable of simultaneous execution of flutter suppression control laws and rolling maneuver control laws, and 4) it be capable of receiving and sending both analog and discrete signals." For safety the AFW model included a wing tip ballast store that was attached to the wing via a variable pitch stiffness mechanism. Release of an internal hydraulic brake that held the store in place led to a significant increase in the first torsion mode frequency and resultant increase in flutter speed. Bypass valves in the wind tunnel, upon activation and opening, could cause a rapid reduction in dynamic pressure which would quickly stabilize the model.

Numerous tests were carried out with the AFW model. The effect of nonlinear transonic aerodynamics was studied and the capacity of CFD codes of the time to capture it; different active flutter suppression laws, the performance of the control system in single function and multiple function operation. In the multiple function case: suppressing flutter while attaining commanded rolling. The program demonstrated the capacity of the AFW model, its control laws, sensors, and array of control surfaces to perform rolling maneuvers while suppressing flutter above the open-loop flutter boundary.

The NASA Benchmark Active Control Technology (BACT) program is described in Refs. 563-568. It was a collaboration of NASA with a number of universities and the industry, aimed at measuring and archiving unsteady aerodynamic data on an actively controlled model in the transonic regime, to study, record, and actively control transonic flutter instability phenomena. The data gathered have been enormously valuable for the validation of aeroservoelastic computational models and the evaluation of the performance of different control laws. The BACT model is not representative of the complexity of a full actively controlled flight vehicle. Yet, its importance and contribution to the state of the art in active flutter suppression have been significant.

Wind tunnel tests with an aeroelastic X-29 model in the TDT have already been mentioned (Ref. 536). An actively-controlled semi-span statically-unstable model with wing stores was used to achieve high relaxed static stability while providing adequate speed margins against body-freedom-flutter. Performance of candidate control laws was assessed based on the flutter speed margins and handling qualities they attained.

In the YF-17 case, a half model of the aircraft was tested at the NASA TDT (Fig. 11 and Refs. 397, 514-519). The model was designed to have violent flutter in a particular external stores configuration, and several control laws developed using different control law synthesis techniques were tested. To build confidence in the transition from analog control hardware (which was used in the early years of flutter suppression and active control development) to digital control, the model was tested with both analog and digital hardware. Leading edge and trailing edge control surfaces were used for flutter suppression including cases when only a LE device was used for flutter control. Moreover, in an effort to evaluate adaptive control, the model was tested with an adaptive control system, demonstrating the capacity to stabilize otherwise unstable conditions by quickly adapting to changes in the configuration (Refs. 396-398). Tests in which control laws were switched from one type to another at a condition in which the model was unstable without active controls were also carried out (at a 40% dynamic pressure higher than the no-control flutter dynamic pressure). "The ability to switch from a leading edge control law to a trailing edge control law, and vice versa, was also demonstrated" (Ref. 517). Capabilities like this are important for adaptive control and for fail-safe active flutter suppression control system design.

Adaptive active flutter suppression control was also tested on the F-16 flutter model at the NASA TDT (Ref. 399, and Fig. 12). In over 2 ½ weeks of tests of about 6-8 hours of testing per day and during long wind tunnel passes the active flutter suppression system stabilized the wind tunnel model (carrying external stores over varying flight conditions, including external store drops). The tested ended, however, with a failure of the control system, resulting in damage to the model. A significant amount of information was gathered regarding the varying aeroelastic characteristics of the model and aspects of adaptive control synthesis and performance.

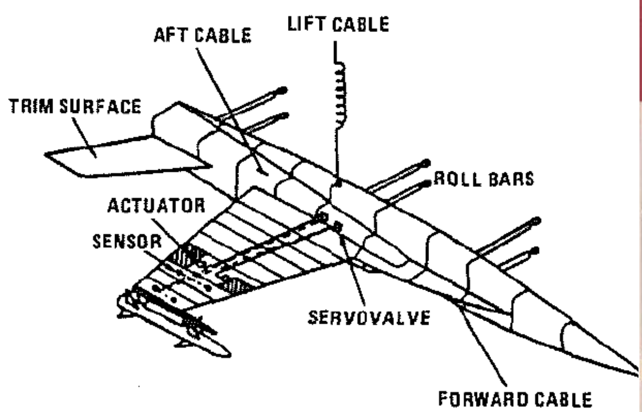
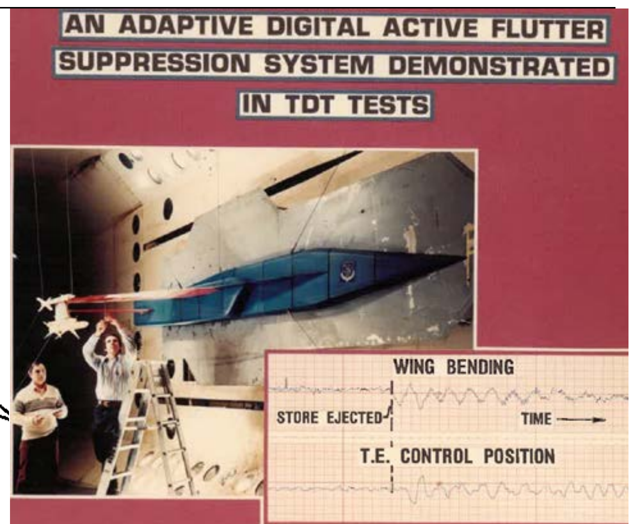


Figure 11: The YF-17 Wind Tunnel Model with External Stores (Ref. 397)



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Tests in Germany using a Tornado flutter model with different external stores configurations were reported in Ref. 141. More recent wind tunnel tests on active aeroelastic control tests include the Flexible Semispan Model (Refs. 573-574), The High Lift over Drag (HILDA) and Aerodynamic Efficiency Improvements (AEI) tests at the NASA TDT, Sensorcraft tests at the TDT (Refs. 601-607), The S4T tests (Refs. 609-610). More recent tests included the Strut-Braced Wing half-span aircraft model (Ref. 608) at the TDT and the Boeing Solar Eagle (Vulture) wing tests at the University of Washington's Kirsten Wind Tunnel (Ref. 572) aimed at gathering data on the aeroelastic behavior of structurally nonlinear non-conventional aircraft configurations. The Vulture wing was open-loop excited

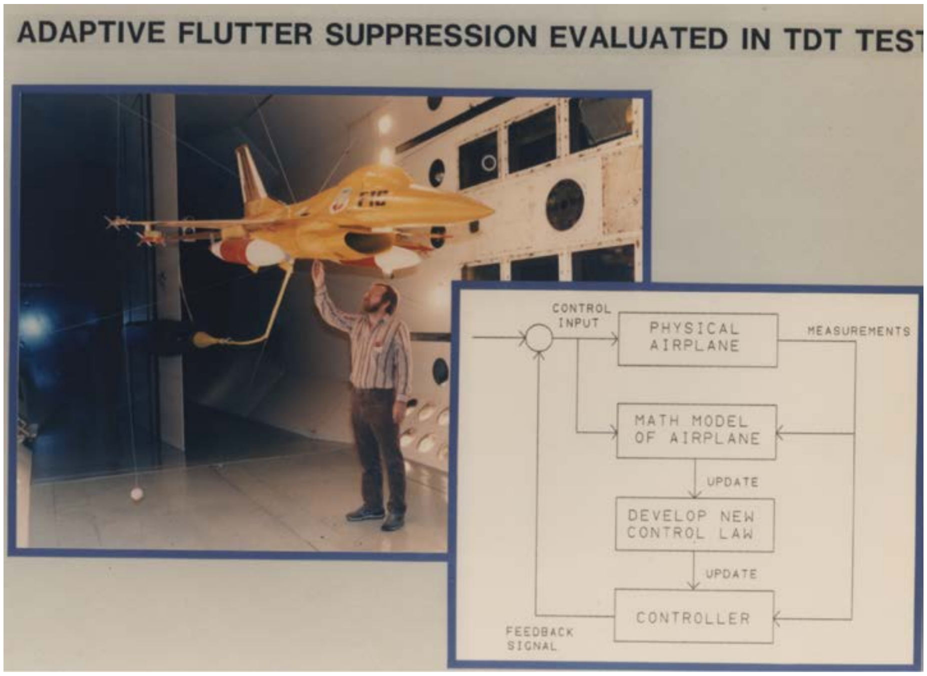

Figure 12: Adaptive F16 flutter suppression tests at the NASA TDT, NASA Photo L-86-8599

by controls for frequency response measurements at various flight conditions. In the strut braced wing case (SBW) both open-loop and closed loop tests were carried out, demonstrating active flutter suppression and gust alleviation. Figure 13 shows time histories of acceleration and aileron positions when the control system is switched from closed-loop to open-loop and back to close-loop at a flight condition of instability in the open-loop mode.

Active modal control tests on a 3D aeroelastic wind tunnel model of an innovative canard/wing/T-tail configuration were carried out in the Polytechnic of Milan, Italy, in the mid 2000s (Ref. 589-592, Fig. 14).

An adaptive flutter control scheme based on Recurrent Neural Networks (RNN) was used to provide stability against flutter and to improve gust response. The controller showed good robustness in the presence of significant measurement noise.

While it has been customary to use accelerometers and electrohydraulic or electric actuators in flight and wind tunnel tests of active control technology, continued interest in new sensor and actuator technologies has driven tests to evaluate such technologies. Noteworthy, in terms of model complexity, was the MIT “Smart Wing” wind tunnel model (Refs. 593-594) which used distributed piezo-electric actuation and was tested in the TDT.

Active control wind tunnel tests, including active flutter suppression, in other countries are described in Refs. 571, 583-592, and 595-598. The papers and reports describing the models used, the aeroservoelastic analysis and controls synthesis method used, system ID techniques, test procedures, test experiences and insights, test uncertainties, and test/analysis correlation including the performance of various control laws present a treasure of information and important lessons.

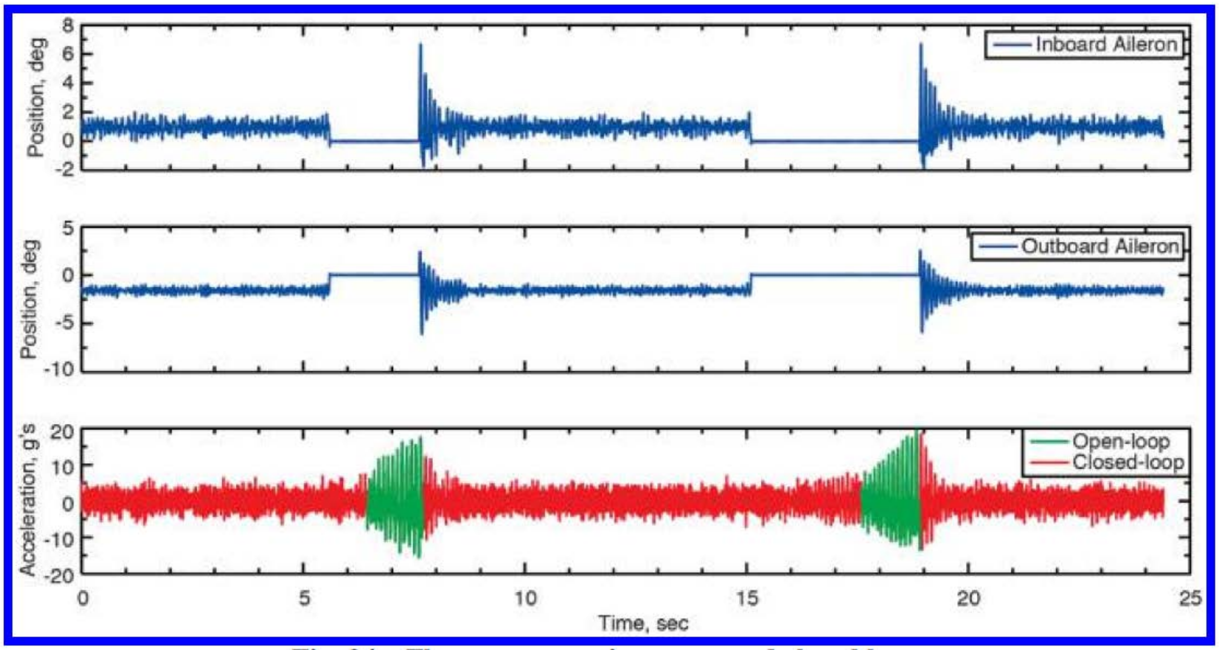

Figure 13: The performance of the Strut Braced Wing flutter suppression system when switched from closed-loop to open-loop and back to closed loop at an unstable open-loop flight condition (Ref. 608).

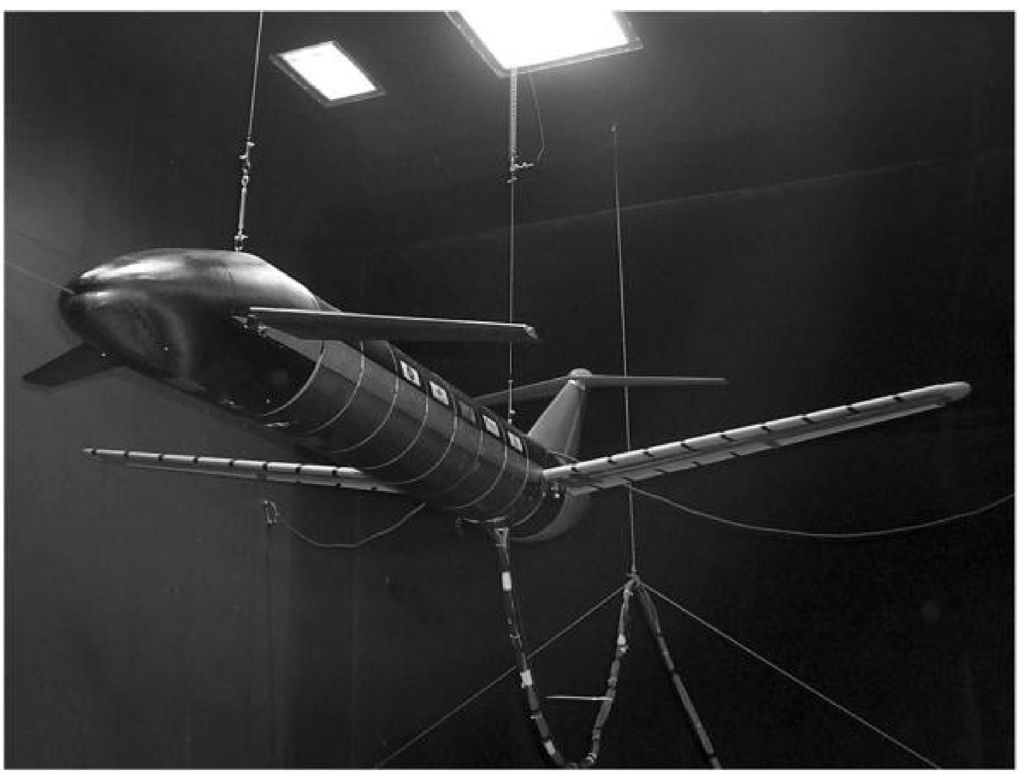

Figure 14: The Milan Polytechnic X-DIA model (Ref. 590).

12. Uncertainty

Most aspects of the aeroservoelastic uncertainty quantification and mitigation problems have been already discussed in the sections above. Refs. 611-646 together with Ref. 194 and Ref. 657 offer a rich selection of publications on the subject. Ref. 619 is an excellent overview of the work on aeroelastic uncertainty prior to 2004. Ref. 641 is a very recent overview of the field. Ref. 640 studies the effects of structural, aerodynamic, and control system hardware uncertainties on the overall safety of actively controlled flight vehicles.

The technical literature on the theory and practice of uncertainty, reliability, and safety engineering of complex systems, including flight vehicle systems, is vast and would serve as the foundation of any progress towards attaining the safety levels required for AFS implementation to be acceptable.

From the AFS safety evaluation perspective the following issues need to be considered: The uncertainty in mathematical models of all elements and disciplines involved as they impact the predicted behavior of the system; the uncertainty in information provided by tests, ground tests and flight tests, due to limited test article sample selection possibilities, the planning and execution of tests, data acquisition and data analysis uncertainties, etc. (Refs. 615, 617, 618, 631, 636); variability of flight vehicles as they come off the production line and as they age; variability of flight operations per flight vehicle; the effect of damage and hardware failure, and of maintenance practices (Refs. 623, 628);

While active control technology may be perceived as adding complexity and, hence, additional failure possibilities to an aeroservoelastic system that is complex to begin with, it can, actually, add safety if, with adequate redundancy of its hardware and software elements, it would be able to adapt itself, stabilize, and favorably shape the dynamic behavior of the aeroservoelastic system for all configurations, flight operations, and failures caused by internal loss of function or externally inflicted damage.

The challenge of “robust” design has been a major driver in the development of modern control technology and quite a number of methods of robust control system synthesis have been developed over the years, with most, if not all, applied to the active flutter suppression problem in research studies. Aeroservoelastic robust control was briefly discussed in Section 8 of this report and is covered by selected publications in the bibliography. From the safety perspective it is important, when an active control system is synthesized, to work with clear quantitative robustness requirements that would guarantee a required level of safety.

13. Integrated aeroservoelastic optimization

Active control technology, in addition to the airframe weight savings it can lead to using gust alleviation, maneuver loads control, and aeroelastic adaptive wing (AAW) technology, can lead to major weight savings with the additional element of active flutter suppression. As a matter of fact, as Refs. 650 shows, active flutter suppression can remove all the airframe structural weight that would without it be required to provide enough stiffness that would eliminate flutter in the flight envelope of a flight vehicle. Integrated into a multidisciplinary design optimization process which allows the integrated optimization of airplanes from early in the design process by simultaneously searching for optimal design variables that cover all disciplines subject to constraints that represent all disciplines, active flutter suppression, as part of the complete flight control system to be optimized together with the structural, aerodynamic, and propulsion systems, has the potential to lead to major improvements in resulting vehicle efficiencies. When adequate redundancy and adaptability are included in the control systems model optimized with the rest of the vehicle’s systems, active flutter suppression may contribute to improved safety by being able to adapt itself to unanticipated operation, malfunction, and damage scenarios.

A thorough survey of the state of the art in integrated aeroservoelastic optimization in the years leading to the late 1990s, can be found in Ref. 6. A few additional contributions in the area are Refs. 647-651 with more discussion in

Ref. 149. Refs. 652-660 present work on integrated aeroservoelastic optimization, where aeroservoelasticity and control are coupled during the design optimization process, with Refs. 652 and 657 integrating into the multidisciplinary design process piezoelectric actuation. The development presented in Ref. 657 also includes "slow" actuation by shape memory alloys.

It has become quite clear in recent years, in the context of the development of new innovative configurations such as the truss braced wing (TBW, Ref. 608), the variable camber continuous trailing edge flap (VCCTEF) wing (Ref. 83), natural laminar flow (NLF) wings (Ref. 658), or high aspect ratio composite wings using advanced composite layout and construction technologies (Refs. 659-660), that active control is essential to allowing such configurations to fully benefit from the new technologies they introduce. Still, the integrated aeroservoelastic MDO technology available currently has not matured yet to its full potential. Questions regarding the performance of different control law techniques and strategies in the context of flight vehicle aeroservoelastic MDO, or the accounting in the optimization problem formulation of the penalty in weight and cost of the control system hardware required still need substantial research as do questions regarding the potential benefits from an MDO perspective of new sensing and actuation technologies.

From the certification perspective, the safety of an optimally designed aeroservoelastic system where design variables are optimized simultaneously subject to constraints representing all disciplines and all consideration must be demonstrated, of course, by analysis and tests of the resulting flight vehicle. An integrated multidisciplinary design optimization process that would account for uncertainty and reliability of actively controlled flight vehicles with active flutter suppression from the start is still in need of development.

14. Certification

References 667-684 present key aspects of aeroservoelastic system certification, including flight vehicle active controls, from both the Federal Aviation Administration and Department of Defense (DOD) perspectives. To reiterate: for any flight vehicle technology to be accepted as safe it must be deeply understood in all its aspects and be supported by reliable analysis tools, thorough testing, confidence in the correlation between analysis predictions and the real world, and by established uncertainty & reliability estimation capabilities that cover, in addition to sources of uncertainty in all aspects of aeroelastic and aeroservoelastic simulation, also hardware, operations, and maintenance aspects. Such technology, in its implementation, must be guaranteed to operate in harmony with all other systems on a flight vehicle and must not adversely affect their safety levels as required by certification requirements.

Refs. 669 and 670 present the federal regulations that cover aircraft safety based on aircraft categories and intended use. Ref. 671 and 672 add guidance regarding aeroelastic stability. Ref. 673 addresses the safety of aircraft with active controls. Refs 674-677 deal with the safety of safety-critical software and hardware on aircraft. Flying qualities criteria for aircraft are discussed in Refs. 678. General flight control systems design, installation, and test specifications are presented in Refs. 679-680. Ref. 679 provides "a comprehensive definition of the general performance, design, test, development, and quality assurance requirements for military aircraft flight control systems. Specific focus areas are flight safety and integration of the flight control system with other aircraft systems and subsystems, such as the electrical and hydraulic systems". Ref. 680 "establishes recommended practices for the specification of general performance, design, test, development, and quality assurance requirements for the flight control related functions of the Vehicle Management Systems (VMS) of military Unmanned Aircraft (UA), the airborne element of Unmanned Aircraft Systems (UAS), as defined by ASTM F 2395-07. The document is written for military unmanned aircraft intended for use primarily in military operational areas. The document also provides a foundation for considerations applicable to safe flight in all classes of airspace." Note that in addition to elements that are common to manned and unmanned aircraft regarding the active control, requirements in this document may apply to any unmanned flight vehicle used for AFS research. Software development, documentation, and the processes that cover the life cycle of software systems are discussed in Refs. 682-683. Additional information from

DOD perspective regarding airworthiness certification criteria is provided in Refs. 681 and 684. Information regarding the special conditions used by the FAA and EASA (the European Aviation Safety Agency) to certify the active flutter suppression systems on models of the Boeing 747-8 is given in Refs. 685-687. While details have not been shared with the aeroelasticity / aeroservoelasticity communities, as mentioned earlier in this work, some important insights into the problem and its solution are offered by Refs. 685-687 in addition to the general considerations by the regulatory and certification agencies that led to the certification of the aircraft.

A key element in this case, based on what is available in the public domain, could be the nature of the instability being a limit cycle oscillation (LCO) with amplitudes that do not endanger the aircraft in the absence of active control. Another important element may be that there would be no unacceptable adverse effects due to the flutter suppression system on all other functions of the flight control system. The key question for the certification of active flutter suppression systems in cases of divergent flutter instabilities is how to meet required safety levels in such cases subject to the considerations discussed in Section 12 above.

It is important to note here that even in cases of using modal suppression to add damping to already stable flutter modes, this technology is considered by the FAA to be new and novel with the required case by case caution used to evaluate it. The full picture regarding the LCO problem of the 747-8 and the way it is suppressed by active controls is not available to the public and so the discussion here does not reflect actual Boeing or FAA positions and philosophy in this matter. The overview here is aimed at motivating discussion, given what more than 50 years of active control and active flutter suppression technology have taught us, that would provide guidance regarding the integrated design of future actively controlled aircraft and the methods and steps required to certify them.

15. Recommendations

R&D work focused on the improvement of aeroelastic and aeroservoelastic analysis, simulation, and test is still pursued in the U.S. and worldwide, funded by government agencies and industry and carried out by industry, university researchers, and government research laboratories. Research challenges in aeroelasticity and aeroservoelasticity still include the integration of advanced computational fluid dynamics / computational structural dynamics (CFD/CSD) for fluid / structure interaction (FSI) analysis on the deformable, actively-controlled flight vehicle in flight, accounting for structural behavior from the small deformation linear range to nonlinearities due to very large deformation, as well as aerodynamic nonlinearities such as shock motions, shock/boundary layer interactions, and flow separation. Other areas of relevant active research are: multidisciplinary design optimization (MDO) of flight vehicles, covering structural, aerodynamic, and control considerations, as well as propulsion integration and interactions; System Identification of complex aeroservoelastic systems for implementation in wind tunnel and flight tests; Nonlinear dynamics of nonlinear aeroelastic and aeroservoelastic systems; advanced sensing and actuation for active control; and control law synthesis for nonlinear, uncertain, multi-input multi-output aeroservoelastic systems.

From the perspective of safety and certification needs, a few areas of importance to the development of acceptable Active Flutter Suppression technology and the determination of its limitations and certification requirements, complementing the R&D work in the areas listed above, are:

1. The creation of reference benchmark test cases that would allow researchers, the flight vehicle industry, developers of simulation codes, and government agencies, to build confidence in the analysis and design capabilities they use and rely on.

Some wind tunnel model and test information was made available to researchers in the past: The DAST wing, the YF-17 wind tunnel model, the S4T model, and for researchers in the US, subject to significant limitations, the X29 and F18 thrust vectoring flight vehicles. But full information for those wind tunnel models and flight vehicles is not available. And since industry is reluctant to share the models and test results of the aircraft it develops, there has been for a long time no realistic detailed model of an actively controlled flight vehicle that the aeroelastic / aeroservoelastic / flight mechanics / flight control community would be able to benefit from while developing required analysis and design methods.

Such a test-case vehicle must have considerable aeroelastic interactions as well as active control capabilities that can be used to implement all flight control options, including AFS. Its complete geometry, structural, inertial, actuation, and control characteristics should be made available (subject, if originating in the US, to ITAR and any export control limitations) alongside the results of ground and flight tests.

The US Air Force Research Labs (AFRL) organization funded the development, by the Lockheed-Martin Skunkworks division, of the X-56 research airplane for active controls research, including AFS (Refs. 544-547). The X-56, is now operated by NASA's Armstrong Flight Research Center. While it was created to serve industry and research organizations develop active controls technology, full information for the X-56 and its ground and flight test results has not been made widely available yet. In long term planning the X-56 may be configured for tests that would build confidence in active flutter suppression from both civil and military certification perspectives, followed by carefully planned tests and by test information that would be shared with the aeroservoelastic community.

Despite the fact that it is not a transonic vehicle, the X-56's complex aeroelastic behavior, the capability to fit it with different wings that would display different complex aeroelastic interactions, and the possibility to assess active control technology in flight for the free-free maneuverable and deformable airplane would allow Active Flutter Suppression related analysis, design, and flight testing with the X-56 to contribute significantly to the state of the art in this area. Finding a flight vehicle and modifying it for active flutter suppression research that would include transonic and maybe supersonic flight conditions and with information that would be widely available for validating computer modeling and control law development is desirable but will continue to be a challenge.

2. Development of consistent widely accepted formulations of the aeroservoelastic equations of motion of maneuvering deformable airplanes for active control applications, including rigid body / elastic motion coupling, nonlinear effects, flight control actuation, and readiness for control law design and the implementation.

Desirably, equations of motion formulations for the actively controlled deformable airplane should be further developed that would allow extension of conventional well known methods currently used in industry to enable modeling of nonlinear CFD-based aerodynamic and nonlinear structural effects. The formulations sought should be general, capable of working with widely used industry modeling tools, and allow rapid data turn-around for industry. Additionally, in this area, an effort should be made to asses and improve equations of motion of the actively controlled deformable airplane for usage in real-time man-in-the-loop and hardware-in-the loop flight simulators. Such formulations should have both required accuracy and high speed of computer execution.

3. Comprehensive aeroelastic / aeroservoelastic reliability / uncertainty analysis capabilities.

To allow quantitative assessment of safety of actively controlled aircraft with interacting Stability Augmentation, Gust Alleviation, Ride Comfort, and Active Flutter Suppression - uncertainty / reliability analysis capabilities for such systems should be developed. While modern control law design methods account for uncertainties in various ways, it is important to assess the reliability of such systems as actually implemented, accounting for parameter uncertainty and modeling errors and performance limitations in all areas; the effects of damage, repair, and maintenance; failure of subsystems; and the uncertainty in flight conditions and external excitations.

Such comprehensive reliability / uncertainty assessment methodology would provide insights into the performance of the highly complex and inter-connected actively-controlled aeroelastic system, as well as guidance for designers and for planners of ground and flight tests. They would also allow a rational evaluation of the effects on overall safety of any changes in required safety margins in particular cases.

4. Control law design and implementation methods for aeroservoelastic systems modeled by high order multi degree of freedom mathematical models, accounting for all aeroservoelastic phenomena, including handling qualities, stability, gust and other dynamic loads and load distributions, ride comfort, and maneuver loads.

While different control law design and architecture / hardware implementation strategies can be expected to be, in the US, proprietary as well as subject to ITAR and export control constraints, and while R&D efforts to develop and test such control systems are still underway, funded by government agencies and in-house by companies as part of various research and development programs, it would still be an important contribution to the state of the art from the certification needs perspective to invest in the development and testing of such methods and architectures, with emphasis on (a) flight vehicles and problems representative of the various types of aircraft of importance in which AFS technology may be used, (b) the harmonious safe operation of all active control functions (Stability Augmentation, Gust Alleviation, Flutter Suppression, etc.), (c) the capacity to control aeroservoelastic systems with multiple flutter mechanisms of different types and represented by large-scale multi-degree-of-freedom state space models, (d) robustness of minimal order controllers, (e) robustness to manufacturing variability and sensor error and noise.

5. Certification.

Certification involves technical analysis, design, and testing practices on one side, and product safety-assurance regulations that reflect the cumulative experience in an engineering area from the safety perspective on the other side. It then integrates both into a coherent and thorough safety verification and safety demonstration process. Active Flutter Suppression (AFS) technology adds complexity to the certification process in all its aspects, because of AFS's multidisciplinary nature and required uncompromising reliability.

An exercise that would follow a simulated AFS certification process of a representative advanced, optimized, and actively-controlled flight vehicle and, thus, examine all aspects of the process, technical and regulatory, would further contribute to the identification of technical and regulatory needs in this area.

16. Conclusion

Active flutter suppression (AFS) technology, when harnessed early in the design process of new flight vehicles when they are optimized across all the key disciplines and constraints that affect their design, has the potential to lead to significant weight savings and performance gains. When used to correct aeroservoelastic stability problems discovered late in the development of an aircraft, AFS solutions can save weight, schedule, and cost. They can provide solutions in cases when passive aeroelastic solutions (based on stiffness or mass distribution and aerodynamic modification) may prove impractical.

A significant body of engineering knowledge has been built in this area in the last fifty to sixty years, based on numerous research efforts covering analysis, computation, ground tests (including wind tunnel tests), and flight tests. The current work presents an overview of the field, evaluates the strength of the technology in its current state of the art, identifies technology gaps and needs, and makes recommendations regarding research and development in those areas that, complementing other research and development work in aeroservoelasticity and active control, would advance the technology towards implementation and acceptance, subject to strict safety requirements.

The drive towards more optimized, innovative, highly flexible, actively-controlled, aircraft, with their complex aeroservoelastic interactions, makes AFS extremely important. This work would, hopefully, contribute to the discussion and the required developments that would make this technology fully fulfil its potential.

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18. Index - A List of Key Topics Covered by References in the Bibliography

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