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Aircraft Active Flutter Suppression— State of the Art and Technology Maturation Needs

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16. Abstract

Active flutter suppression, a part of the group of flight vehicle technologies known as active controls, can be important contributor to the effective solution of aeroelastic instability problems when they appear late in the development of a new aircraft. If used from the start of the design process, it can be a key element in multidisciplinary design optimization that would lead to more efficient aircraft. This work presents a thorough overview of more than 50 years of research and development (R&D) in the active flutter suppression area. Key historical developments and the current state of the art in all supporting disciplines are surveyed along the way. Technology gaps and R&D needs are identified. Special attention is given to the vehicle-safety issue and to R&D in the active flutter suppression area that would complement ongoing R&D 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 will, hopefully, contribute to the preservation of the treasures of experience and knowledge in this area so that they will not be forgotten and lost, and will remain available to professionals working in this field.

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LIST OF ACRONYMS

AAW	Active aeroelastic wing
AFFDL	Air Force Flight Dynamics Laboratory
AFRL	Air Force Research Labs
AFS	Active flutter suppression
AFW	Active flexible wing
ARW	Aeroelastic research wing
AFWAL	Air Force Wright Aeronautical Laboratories
BACT	Benchmark Active Control Technology
BFF	Body Freedom flutter
CCV	Control configured vehicle
CFD	Computational fluid dynamics
CSD	Computational structural dynamics
DAST	Drones for Aerodynamic and Structural Testing
DOD	Department of Defense
DOF	Degrees of freedom
FCS	Flight control system(s)
FFT	Fast Fourier Transform
FMC	Flutter mode control
F0VMS	Flaps-up vertical modal suppression
FR	Fatigue reduction
GLA	Gust load alleviation
HALE	High-altitude long-endurance flight vehicles
ILAF	Identically located accelerometers and forces
LAMS	Load alleviation and structural mode stabilization
LCO	Limit cycle oscillation
LE	Leading edge
MDO	Multidisciplinary design optimization
MIMO	Multi-input multi-output
MLC	Maneuver load control
MUTT	Multi-Utility Technology Testbed
OAMS	Outboard Aileron Modal Suppression System
R&D	Research and development
RC	Ride control
RFA	Rational function approximations
SA	Stability augmentation
SAS	Stability augmentation system(s)
TDT	Transonic dynamic tunnel
TE	Trailing edge
UAV	Unmanned aerial vehicles

EXECUTIVE SUMMARY

Active flutter suppression (AFS), a part of the group of flight vehicle technologies known as active controls, can be an important contributor to the effective solution of aeroelastic instability problems when they appear late in the development of a new aircraft. If used from the start of the design process, it can be a key element in multidisciplinary design optimization that would lead to more efficient aircraft. This work presents a thorough overview of more than 50 years of research and development (R&D) in the AFS area. Key historical developments and the current state of the art in all supporting disciplines are surveyed along the way. Technology gaps and R&D needs are identified. Special attention is given to the vehicle safety issue and to R&D in the AFS area that would complement ongoing R&D in all areas of aeroelasticity, aeroservoelasticity, and active control. A thorough bibliography contains references that cover all building blocks of AFS technology. It will , hopefully, contribute to the preservation of the treasures of experience and knowledge in this area so that they will not be forgotten and lost, and will remain available to professionals working in this field.

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

1. 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 that they use and on which they rely.
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.
3. Comprehensive aeroelastic/aeroservoelastic reliability/uncertainty analysis capabilities that allow quantitative assessment of safety of actively controlled aircraft with interacting stability augmentation, gust alleviation, ride comfort, and AFS—uncertainty/reliability analysis capabilities for such systems should be developed. Although 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, 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.
4. Control law design and implementation methods for aeroservoelastic systems modeled by high-order multidegree 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. Although different control law design and architecture/hardware implementation strategies in the US can expectedly be proprietary and subject to ITAR and export control constraints, and although 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 R&D 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 (e.g., stability augmentation, gust alleviation, and flutter suppression); 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) validation, verification, and transparency of control laws and systems generated using competing approaches; and f) robustness to manufacturing variability and sensor error and noise.

5. Certification that involves technical analysis, design, and testing practices, and product safety-assurance regulations that reflect the cumulative experience in an engineering area from the safety perspective. It then integrates both into a coherent and thorough safety-verification and safety-demonstration process. AFS technology adds complexity to the certification process in all its aspects because of AFS' 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, therefore, would examine all aspects of the process, technical and regulatory—would further contribute to the identification of technical and regulatory needs in this area.

1. INTRODUCTION

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 (i.e., an oscillatory constant amplitude or divergent motion/deformation) and divergence (i.e., an exponential divergent motion/deformation), both with destructive potential and functions of flight conditions (e.g., altitude and Mach number, and in some cases, load factor and other maneuver parameters). Flutter may also be encountered because of 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 in which flutter oscillations occur. According to Frazer, Duncan, and Collar, “in the practical sense, ‘flutter’ means an oscillation that grows, and finally either breaks the structure or remains bounded at some amplitude whose value is dependent upon the departure from linear laws” [1].

Aeroelastic instabilities can be categorized into different types based on the way stability is lost with an 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 also 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 a gradual slide toward 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 significantly 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, often allowing test pilots to slow down back into the stable region of flight. A flutter mechanism of the hump-mode type will see gradual loss of damping toward 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 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 previously mentioned stability concepts are based on linear aeroelastic and aeroservoelastic theories.

When significant nonlinear effects (e.g., free play 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) become important, additional types of self-excited modes of behavior may occur, including limit cycle oscillations (LCOs)—sustained constant amplitude oscillations due to aeroelastic interactions. LCO may appear in an aeroelastic system well below the flight conditions that would lead to divergent destructive oscillation. As dynamic pressure and speed are increased, LCO amplitudes may become larger. However, an airframe may be able to tolerate LCO of limited amplitudes for quite some time well below the divergent oscillation flight conditions, affecting ride comfort but not compromising safety as long as fatigue problems do not arise. Like many other nonlinear dynamic problems, nonlinear aeroelastic and aeroservoelastic behavior can be complex and surprising in nature [2–4]. 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 [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 lives, when elimination of flutter through passive means (e.g., 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 [6].

AFS 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 systems (FCS), also known as stability augmentation systems (SAS), gust load alleviation (GLA) or dynamic loads alleviation, active ride comfort control, and maneuver load alleviation (MLA). The terms "stability augmentation" and 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. 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 FCS may also be 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 MLA (or maneuver load control [MLC]), GLA, FCS for desired and safe handling qualities, and active ride comfort systems. In addition to strict redundancy and reliability design requirements 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 AFS system 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. The failure to address uncertainties and 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 [7].

The willingness to accept any form of AFS may be linked to the type of flutter behavior involved. AFS 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, control system failure 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.

Depending on the type of flutter instabilities and subject to careful consideration, AFS may be acceptable when used for an airplane that is otherwise stable within its flight envelope (and up to the maximum speeds and dynamics pressures it would ever fly at) to provide stability up to the margins of safety required beyond the most severe flight conditions (in the region between design dive speed and 15% above that). AFS may also be used to augment stability within the flight envelope to bring insufficient damping in low-damped modes of motion to required levels.

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 the control laws of active-control systems used may make one flutter mechanism more critical than another. Single-degree-of-freedom flutter is also possible in certain cases. In general, mathematical models of the full aeroelastic behavior of an airplane that include many degrees of freedom must be used to capture all aeroelastic static and dynamic mechanisms accurately. Such mathematical models, which may consist of hundreds of equations of motion or more with a large variety of flight and loading conditions that need to be covered even after using model order reduction techniques, 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 established uncertainty and reliability estimation capabilities that cover hardware, operations, and maintenance aspects in addition to sources of uncertainty in all aspects of aeroelastic and aeroservoelastic simulation.

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

A flurry of AFS R&D activity in the 1970s and 1980s with major achievements [8–12] led to optimism regarding an expected imminent maturation and subsequent acceptance of the technology on manned flight vehicles at that time. However, although other active-control technologies, as listed above, have been accepted for certification and have seen widespread usage on aircraft by now, AFS is still viewed with reservation and caution. Except for very few special cases, AFS has not been allowed on commercial or even military aircraft.

The goals of the work presented here are to contribute to the development and maturation of AFS 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 AFS analysis, design, and certification problem, and b) discussing limitations and accomplishments to date and by identifying R&D needs and recommended research.

This work was initiated and supported by the U.S. 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 AFS technology. The work does not represent FAA opinion or how the FAA interprets the current requirements and guidance material.

Any discussion of AFS 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 AFS in a detailed enough way and with a rich enough bibliography to serve the AFS technology overview needs. The bibliography, although 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, AFS, 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 should have been included 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 AFS using highly simplified mathematical models that 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 [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 [13–29]; the effect of aeroelastic behavior on flight stability and control via static aeroelastic stability derivatives corrections for six degrees of freedom (6 DOF) simulations [30–48]; historic perspectives of the deformable airplane flight dynamics problem from the flight stability and control and aeroelasticity communities [49–51]; aeroelastic tailoring and active flexible wing (AFW) or active flexible airframe concepts [52–72]; MLC [73–77]; aircraft morphing [78–85]; early work on the influence of servoactuators [86–89];

GLA [90–103]; ride comfort and handling qualities [104–114], active buffeting alleviation [115–116); a systems perspective of active controls [117–135]; aeroservoelasticity general progress reviews [136–153]; reviews of aeroservoelastic experimental programs [154–157]; linear aeroservoelastic solution methods [158–170]; 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, and propulsion integration [171–353]. Approaches to AFS control law generation are covered next [354–431], including methods of classical control, modern control, adaptive control, and control of parameter-varying systems. Discussion of topological aspects of the active-control problem and the control of nonlinear systems follows [432–443]. The applied math work on what is known as the continuum approach to aeroelastic control [444] 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 are covered in [445–483]. 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 AFS projects involving actual aircraft and wind tunnel tests over the years involving vehicles and models with complexity representative of actual flight vehicle systems [484–622]. The subject of aeroservoelastic uncertainty is presented in [623–660], followed by aeroservoelastic multidisciplinary design optimization (MDO) [661–674]. References on targeted energy transfer [675–680] 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 [681–702].

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 [13–24]. With the rapid development of classical control theory in the 1930s to 1960s, followed by state space multi-input multi-output (MIMO) technology, together with the development of powerful and reliable flight-control hardware, computing power, and flight dynamic theory and simulation, FCS have been an integral part of practically every advanced airplane during the last 50–60 years. Numerous flight stability and control textbooks, going back to the early 1950s, cover automatic flight control thoroughly [20–28]. The focus was on the rigid-body motion of aircraft at first, in 6 DOF, 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 [29]. It is now widely used to obtain desirable handling qualities on both inherently stable and unstable aircraft.

4. STATIC AEROELASTIC CORRECTIONS OF THE 6 DOF 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 6 DOF motion models are used, have been traditionally accounted for by static aeroelastic corrections of aerodynamic stability derivatives [13, 16–17, 30–48]. This includes fuselage flexibility effects on stability derivative contributions of the empennage or canards, and lifting surface flexibility effects on leading-edge and trailing-edge 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 6 DOF.

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 [39–43]. A link between airplane stability and control engineers, working with 6 DOF 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. Although, simultaneously, for many years, the two communities used different mathematical models and different analysis and design approaches to the dynamics of the airplane [49].

Whereas 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 6 DOF simulation of aircraft by adding capability to calculate both static and dynamic stability derivatives [13, 50–51] for complete configurations. Commercial unsteady aerodynamic codes [41–42] 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. In a modal approach, a small set of natural modes or some carefully selected Ritz vectors are used via superposition to model the motions of the deformable airplane. The problem with this approach 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. Historically, static aeroelastic analysis was carried out with as detailed stiffness/flexibility of the structure as practical, whereas mode shapes were used as generalized coordinates for flutter analysis. Conversely, the growing power of digital computers, which began to make multi-DOF linear static analysis practical, led to an emergence of modal-based static aeroelastic analysis [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 6 DOF rigid-body simulations to flexible-airframe aeroservoelastic simulation. Although in essence there should be no separation between static and dynamic aeroelastic effects, both being 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-control engineers to have full awareness of static aeroelastic effects on dynamic aeroelastic behavior. It also 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 LE flap modeling [44] and the case of the YF16 aeroservoelastic instability [519]. Accurate accounting for static aeroelastic effects is extremely important in any aeroservoelastic modeling for active-control system design.

5. CONTROL OF STATIC AEROELASTIC BEHAVIOR

Lift/drag performance of the rigid airplane and 6 DOF dynamic performance are shaped by the use of control surfaces to effectively change the aerodynamic shape of the vehicle [52]. When static aeroelastic effects play a significant role, static aeroelastic behavior must be accounted for by analyses and tests, and must be either constrained or harnessed to achieve the desired behavior.

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

In the Active Aeroelastic Wing (AAW) concept [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 preprogrammed to cover the full range of flight conditions in which the vehicle has to perform. Such control laws can also respond in real time to flight condition and flight performance information, working to achieve desired performance through the scheduling of control surfaces. The concept, 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), [60–65 and 565–574], for which both control surface scheduling and AFS were studied. In a subsequent implementation on a full-size vehicle, an F18/A (figure 1, 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. It was flight tested successfully [65 and 553–554]. The X-53 was flutter-free within its flight envelope, so tests focused on the scheduling of multiple control surfaces to attain the desired rolling performance.

Figure 1. An AAW X-53 with a stuck leading-edge flap (courtesy: NASA)

At the early design stages of a flight vehicle, AAW design philosophy (generalized to include the complete airframe: Active Aeroelastic Airframe [AAA] technology) coupled with MDO has the potential to lead to substantial weight savings [6, 66–70]. AAA technology also has the potential to overcome static aeroelastic problems (especially inadequate 6 DOF 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. Note the case of the first swept-wing jet, the Boeing B47, for which 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 coincidentally to be cancelled by the bending effect of the rear fuselage and the resulting horizontal tail increase in angle of attack [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 its natural compensation for the wing-flex effect would not have been sufficient.

The movement of flight-control surfaces to obtain desirable 6 DOF dynamic performance in the presence of static aeroelastic effects can be controlled by gains that are preselected 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 MLA (or MLC), control surfaces move to distribute aerodynamic loads on a maneuvering airplane to keep its internal loads within limits, therefore leading to structural weight savings [73–77]. Active aeroelastic control technology, focused on the shaping of aircraft inflight to meet aerodynamic lift/drag performance and 6 DOF dynamic performance requirements, can involve conventional control surfaces, smoothly morphing camber of lifting surfaces [78–81] or more major shape changes in flight [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. Such interaction is described in [135], where an MLC 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 because of 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. 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. Figure 1 shows an X-53 [65] with a stuck leading-edge flap. A number of stuck leading-edge flap positions were tested in flight for the effect on performance and safety of the aircraft.

6. AEROELASTIC/FCS INTERACTIONS AND AFS

Automatic controls have been part of airplane design since the introduction of the Sperry automatic pilot in 1912 [13]. Conversely, slow actuators and actuation mechanisms serving as low-pass filters prevented strong interaction of the control systems, which are 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 affect aeroelastic motions in the frequencies above those of the rigid-body motions became more significant [86–89].

Active controls could now be developed to reduce dynamic loads due to gusts [90–103], improve ride comfort and handling qualities [104–114], and mitigate vibrations due to buffeting [115–116]. Gust alleviation and ride-comfort systems needed to work in complete harmony with stability augmentation and to maneuver loads control [117–135].

Overviews of the field of aeroservoelasticity, in which the terms "aeroservoelasticity" and "active controls" are commonly used to describe the field in general, and the terms for subfields—such as "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 can be found in [136–157]. These references provide overview, vision, calls for R&D action, and useful bibliographies. AFS is an additional important part of aeroservoelastic and active-control technology.

Unlike FCS for stable aircraft (e.g., stability augmentation, handling-qualities improvement, MLC, gust alleviation, and ride-comfort control), AFS 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 was a major engineering effort to materialize. To bring the state of the art of AFS—in which frequencies can be high and flutter mechanisms complex and multiple, and analysis and testing techniques may still be subject to error and uncertainty—to a maturity level that would allow their widespread usage is much more challenging. The technology, for those reasons, has not yet seen wide application in the commercial airplane world or even in the military world. In section 7, while surveying the state of the art in each of the disciplines on which AFS depends, 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) with which a controller works to produce inputs (via actuators) to the system that would affect its behavior. Any discussion or implementation of AFS, 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—their accuracy, uncertainty, reliability, and practicality. To make the development of AFS 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 previously mentioned, the equations of motion of the deformable airplane used for FCS development have converged from two historically different fields within aerospace engineering: the field of flight stability and control and the field of aeroelasticity. Although there was awareness of the work in each of these fields by experts in the other field, mathematical models and analysis methods [158–170] 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 multidegree 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 [158, 166–170]. Although 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 onward. 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. Also, because the RFAs commonly used are based on tabulated data along the imaginary axis, the more distant aeroservoelastic poles are from the imaginary axis, the more inaccurate they can become [163] . 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 because 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. Another challenge is the potential significant increase in the number of aeroservoelastic states of the aeroservoelastic plant model when rational function approximations are used for the state-space unsteady aerodynamic loads.

7.2 AEROSERVOELASTIC MODELS FOR ACTIVE CONTROL AT THE CURRENT 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 nonlinear large motion finite element and flexible multibody 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 (e.g., Euler, Euler with boundary-layer interaction, or Navier-Stokes solvers). Development in CFD and CSD technologies in the past 20 years, plus development in the capabilities of computer systems hardware and parallel computing, have led to significant CFD/CSD aeroelastic and aeroservoelastic capabilities [171–186], which allows 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, which could not be captured by earlier widely used aeroservoelastic modeling techniques [174]. Fuel sloshing effects, in fuel tanks, can now be captured by high-fidelity CSD/CFD math models [185]. But there are still 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 AFS development would require. Unsteady aerodynamic loads in the presence of flow separation and boundary-layer/shockwave interactions are still a major challenge. Structural nonlinear effects driven by localized distributed structural nonlinearities (e.g., regional buckling and post buckling) combined with uncertainty in material characteristics due to environmental effects may require extremely large mathematical models and substantial testing. Overall the resulting high-fidelity CFD/CSD models of whole aircraft are so large that, even when using massive parallel computation, they take too long to run for an industry-new flight vehicles development. For 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 carried out today, including active-control systems in the loop (with control laws that were usually synthesized using low-order math models [174, 181, 186]), such math models present a significant challenge to the control-system designer because of their large size.

7.2.1 Reduced-Order Models of High-Fidelity Coupled CFD/CSD Mathematical Models

Similar to the development of modal-order reduction techniques in the structural dynamics area to adequately capture structural dynamic behavior for engineering purposes with structural models that are much smaller in size than the full finite element models of airframes, a major R&D effort during the past 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. References 187–210 are selected publications on these important subjects, with [187] presenting a comprehensive survey. In addition to 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. The term "surrogate modeling" is used here to cover all model-order reduction methods, including basis function projection methods and sampling-based reduced-order models. In the technical literature, the term "surrogate models" is often used only to describe sampling-based reduced order models. Note the need to protect reduced-order model-based simulations from venturing into regions in parameter space beyond the limits within which the reduced-order models were created.

Although 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, although capable of supporting limited design studies and providing validation in selected cases, is not ready yet for widespread use by the aircraft industry for the purposes of developing AFS systems or active-control systems in general.

7.3 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 [211]. With the development of aerodynamic panel modeling capabilities, such as the doublet lattice method (DLM) for subsonic flows and the ZAERO and PANAIR codes for subsonic and supersonic flight, unsteady aerodynamic modeling for aeroservoelastic control application shifted from the 1970s and onward to aerodynamic panel models [173]. References 211–222 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 and Mach numbers. 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 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:

$$\begin{aligned} s\{x(s)\} &= [A]\{x(s)\} + [B]\{u(s)\} \\ \{y(s)\} &= [C]\{x(s)\} + [D]\{u(s)\} \end{aligned} \tag{1}$$

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

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

$$\begin{aligned} s\{x(s)\} &= [A]\{x(s)\} + [B_c]\{u_c(s)\} + [B_G]\{u_G(s)\} \\ \{y(s)\} &= [C]\{x(s)\} \end{aligned} \tag{2}$$

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

State-space models of the types shown in equations 1 and 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.

However, from an active-control technology perspective, the linear state-space models of equations 1 and 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 RFAs can lead to large state-space models. In the case of the popular Roger approximation [169]:

$$[Q(jk)] \approx [P_0] + s[P_1] + s^2[P_2] + \frac{s}{s+\beta_1}[P_3] + \frac{s}{s+\beta_2}[P_4] + \ldots \tag{3}$$

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 possibly required for obtaining a better match between the Roger RFAs and the generalized aerodynamic matrices they approximate over the frequency range of interest would increase the order of the resulting state-space model substantially. The minimum-state approach [228, 229] leads to smaller-size state-space models but at the price of matching an RFA simultaneously 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. As mentioned previously, in all RFA cases, an error is introduced into the resulting aeroservoelastic model because of inaccuracies of the RFA/frequency-domain data fit. Another error is introduced when RFA-based Laplace transform expressions for unsteady aerodynamic forces are used. Because, moving away from the imaginary axis in the Laplace domain (in the case of damped or unstable motions) may miss changes in the unsteady aerodynamic forces away from the imaginary axis (where the RFAs were created). This adds to the uncertainty of the linear aerodynamic predictions themselves. Linear or linearized-code-based RFAs cannot capture any major nonlinear unsteady aerodynamic effects. In addition, the need, when it arises, to accurately capture by analysis unsteady aerodynamic forces due to fore-aft motions of the vehicle or its parts may still present a challenge to both panel codes and CFD codes because of the difficulty of modeling unsteady viscous and form drag (See [274–288] for the way fore-aft motion unsteady aerodynamics is modeled in the case of very flexible wings with high aspect ratio).

The way the state-space modeling problems discussed above (especially transonic flow effects) 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 and high-fidelity CFD simulations [237, 658]. 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. Although these correction factors 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 [223–236], methods for order reduction of aeroservoelastic models with linear aerodynamics but distributed nonlinear behavior [238–242], and models based on linear unsteady aerodynamics and localized structural nonlinearities [243–246] have also been developed.

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

$$\{\dot{x}(t)\} = \left[A\left(\{x\},\{u\}\right)\right]\{x(t)\} + \left[B\left(\{x\},\{u\}\right)\right]\{u(t)\} \tag{4}$$

Or just:

$$\{\dot{x}(t)\} = \left\{ f\left(\{x\},\{u\}\right)\right\} \tag{5}$$

There has recently been 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 [158, 247–250]. With these new developments [247–249], 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 an efficient way to simulate aeroservoelastic systems with nonlinear element in the time-domain, where unsteady aerodynamic force expressions are transformed to the Laplace and time domains via rational function approximations without an increase in order. 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 the effects of nonlinearities in the control system and in the airframe and its aerodynamics.

7.4 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 widespread 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 (quasistatic and dynamic) as developed by the aeroelasticity community. The case of 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, has been more challenging.

Equations of motion for the elastic quasisteady vehicle, maneuvering the subject to linearized aerodynamic loads, are presented in [40–41, 251–253]. References 6, 42, 46, and 47 present modal approaches to the quasistatic 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 [27, 153, 254–273]. The challenge with some of the derivations in these references is that although they are built on rigorous deformable-body dynamics foundations, the unsteady aerodynamic part included may not yet be of the fidelity that would be adequate for the modeling of real aircraft for design and simulation purposes.

Major progress in this area has been made, however, [27, 272] and a case has been made recently that, despite earlier criticism, using a mean-axis formulation for the equations of motion of a deformable airplane is a useful natural extension of the rigid-body stability and control equations to the deformable aircraft flight dynamics domain. The formulation was used to develop simulations and control laws for the deformable University of Minnesota research Uninhabited Aerial Vehicles (UAVs) [542].

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 and unsteady aerodynamics that could account for aerodynamic forces and moments due to fore-aft motion of wing sections and the effect on aerodynamic forces of out-of-plane motions of the lifting surfaces. Early efforts in this area are documented in [274–279], motivated by glider aeroelasticity and the aeroelasticity of human-powered vehicles. Later efforts during the past 20 years were motivated by the interest in high-altitude long-endurance flight vehicles (HALE) (e.g., the Aerovironment Helios [283]) and began as an extension of aeroelastic modeling techniques used for helicopter rotor blades [280–288]. 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 [278, 281, 283]. Some studies of the accuracy of mathematical models based on measurements from the Helios flight vehicle and comparisons of various modeling techniques to test results were carried out during the investigation of the loss of Helios in flight [283]. A highly flexible low-speed wind tunnel model of the Boeing Solar-Eagle configuration was tested in 2011 [584] 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 yet been validated sufficiently and are subject to considerable uncertainty.

Note that most equations of motion formulations for such configurations involve large-scale time-domain state-space models (e.g., [184, 208] present a modal approach). 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 because active control must be integrated from the start into the design of these weight-critical configurations to ensure aeroelastic stability and to mitigate gust load effects.

7.5 ACTUATION AND SENSING

Closed-loop active control depends on sensing of the behavior of the controlled plant—the aeroelastic system—and on effective means of actuation. Common devices that have been used for aircraft active control are accelerometers and strain gauges 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 very powerful, with natural frequencies that are 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 also if strong interaction with the aeroelastic plant above its range of frequencies cannot be neglected. References 289–333 describe the various sensing and actuation techniques used for the active control of aircraft (e.g., the mathematical models of hardware dynamics aspects of actuation and sensing hardware integration with the airframe; acoustic actuation [299, 301, 306]; strain actuation [309–310, 312–313, 317–319, 326]; the impact of actuator model fidelity on resultant aeroservoelastic simulations [302]; distributed actuation using micro-flaps [323–325]; and emerging actuation and sensing techniques, including direct sensing of the unsteady flow at selected locations over the surfaces of the configuration [327–330], fiber-optic sensing [317], and actuation by active flow control [331–333]).

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 AFS systems, must make sure that actuator nonlinearities (including the important limit of actuator saturation and rate) are modeled accurately and that the active-control systems developed perform well in the presence of such nonlinearities and the possible changes in actuator linear and nonlinear behavior over time because of service wear and tear, operational heating, environmental effects, and actuator failure.

7.6 PROPULSION SYSTEM EFFECTS ON AEROSERVOELASTIC BEHAVIOR

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 [341–347]. Exceptions to this include affecting aeroservoelastic behavior by the effect of engine nacelle shapes on the unsteady aerodynamics of a configuration, inertia effects (e.g., gyroscopic effects), and the stiffness, mass, and damping of pylons connecting engines to airframes [334–340]. Dynamic airframe/propulsion system interactions are extremely important on hypersonic vehicles of configurations for which 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 and the emerging configurations of supersonic jets [348–349] or transonic jets, on which engines are integrated into the rear of the fuselage. Thrust vectoring [530] may 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 [350–353].

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 are important, they must be included in the state-space or transfer-functions models for which the controls are designed.

8. AFS CONTROL LAWS

Extensive R&D efforts have been dedicated over the years to the challenge of AFS. The numerous references included in the bibliography of this work; in the sections dedicated to AFS 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 AFS laws here focus on applications involving real aircraft, realistic wind-tunnel models, or mathematical models of aeroservoelastic systems 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, a time when classical control reached a certain level of maturity, and modern control was rapidly evolving. 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 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.*" [5]

The early years of AFS research saw two major lines of work. In the physics-based approach, control laws for flutter were based on searching the physics or mathematical structure of the flutter problem to identify those mechanisms responsible for the flutter instability and finding ways to suppress them [354–371]. The aerodynamic-energy approach [354–363] 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) [367–369] seeks to position velocity feedback and actuation forces (in the generalized velocity and force sense for a set of modes) to create an effective viscous damping matrix for the multidegree-of-freedom equations of the system that would stabilize it (see reference 370 for a similar approach to the active control of structures with guaranteed stability). Similarly, the method of fictitious structural modifications [366] 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. All these developments of aeroservoelastic systems and this tight link between the physics and mathematical aspects must be preserved.

Although major accomplishments have been achieved with the physics-based methods, they have been pushed aside over time by AFS control-law synthesis methods based on developments in general control systems theory. References 372–400 present a variety of AFS control-law synthesis approaches based on classical control: Nyquist, Bode, and Nichols compensation methods; linear–quadratic regulator/linear–quadratic–Gaussian control; pole placement; eigensystem synthesis; μ-analysis; and other methods based on mathematical programming, fuzzy logic, and neural networks. Control-system robustness was addressed by the classical gain and phase margins, by constraints on matrix singular values, and by miu-analysis. Order reduction of flutter-suppression control laws generated by modern control theory—an important element in creating practical control laws for implementation on flight system computers—is discussed in [401–403] 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 Drones for Aerodynamic and Structural Testing (DAST), oblique-wing aircraft concepts, large transport airplane concepts, and a number of actively controlled wind-tunnel models. Additional information on the development and testing of AFS 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 AFS over the years. This will be surveyed and discussed in sections 11 and 12.

In general, an AFS 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, MLC 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—in which 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 AFS area. Such systems also have the potential to identify and immediately correct system failures. A sensor failure or an actuator failure, for example, occurring simultaneously with changes in flight conditions, would lead to an 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 a 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 section [404–424].

Other aspects of the flutter-suppression-law problem discussed in [425–440] include: 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 [425–426]), special treatment (regarding active control) of parameter varying systems [427–431], and the control of nonlinear aeroelastic systems [432–439].

Topological issues of aeroelastic sensing and control are discussed in [440–443]. The designer of control laws for the actively controlled airplane must work with aerodynamic, structural, and configuration designers to identify the optimal locations of sensors and both the location and size of control effectors that would make the aeroelastic plant most control-friendly with respect to its controllability, its observability, and the resulting weight and complexity that a control system working with such sensors and control effectors would have. If different control surfaces (or other control effectors) are used for the different functions of an active-control system (e.g., flutter suppression and gust alleviation), 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 AFS, 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 [519] 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.

A few notes on MIMO control laws versus frequency domain classical control laws are warranted here. A significant amount of AFS control-law research has focused to date on MIMO techniques and the order reduction that is required to make the design laws and their implementation practical. Classical control law synthesis techniques can be as effective, however, in many cases, with the advantages of low-order from the start and a resulting control system that is transparent (i.e., where the flow of information and the functions of all elements of the control loop are well understood) [542]. More work is needed before final conclusions can be drawn regarding capabilities, advantages, and disadvantages of classical versus MIMO control law synthesis and implementation.

To conclude this section about AFS control law synthesis, note the work on the active aeroelastic control problem that has been pursued from the Applied Math perspective—known as the Continuum Approach to Aeroelasticity [444]. 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 ready for use 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 (i.e., 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 can provide an introduction and guide to the key elements of ground vibration testing [445–451] and the conference proceedings volumes that preceded them. Some representative earlier and more recent publications on unsteady aerodynamic wind-tunnel tests and on efforts to validate aerodynamic numerical-prediction techniques using the results of such tests are also available [157, 337, 452–456]. Actuator testing and math-model validation are discussed in [289, 305, 314–315].

In all the cases discussed above, tests can be used to validate and fine tune mathematical models. However, based on the assumptions they are built on and parameter uncertainties, the math models 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 accepting a certain level of uncertainty in the system's aeroservoelastic mathematical models after GVT, hardware dynamics, and wind-tunnel aerodynamic test data have been used to fine-tune them will reduce the overall uncertainty level in the resulting aeroservoelastic models compared with the level of uncertainty before the tests [640, 643, 658].

The final step in any aeroservoelastic development are the flight tests [464]. Aeroservoelastic flight testing has its roots in flight flutter testing [457, 465]. 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 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 because 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 457–483 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.

Although 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 simultaneously 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 [BFF] problem) requires sophisticated model-mounting systems. The wind-tunnel flutter models, because of the scaling laws to which they need to be designed, may not be strong enough to withstand high-loading conditions in the tunnel, therefore limiting the flight conditions at which tests can be carried out.

However, wind-tunnel tests offer some advantages: The test environment can be carefully controlled, control laws can be quickly varied and tested, costs are lower, and risks compared with the case of manned flight vehicles are 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. AFS FLIGHT TEST PROGRAMS

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, [154] covers almost all major projects in this area in the U.S. from the late 1960s to the early 1980s.

From the perspective of AFS, 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, and 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 [136–157] and [119–120, 131–132] would provide additional material on the experimental work with flight vehicle active controls to date.

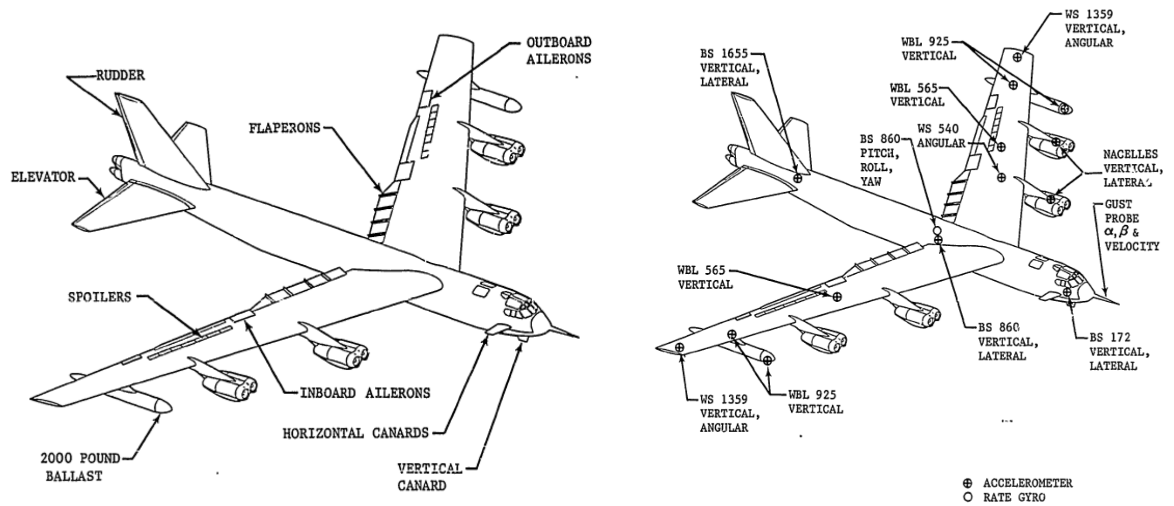
Beginning the survey with flight tests, the most demanding experiments and most realistic AFS of a modified Boeing B-52 was demonstrated in flight in the early 1970s [488–493] (see figure 2). The B-52 program began with the Load Alleviation and Structural Mode Stabilization (LAMS) program and continued 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 use 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-52 CCV demonstrated successful active-control action in five areas simultaneously: flutter mode control (FMC), MLC, ride control (RC), fatigue reduction (FR), and stability augmentation (SA). SA was used to allow flight at CG locations 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.

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

(b)
B-52 Active Controls Model at the NASA TDT (courtesy: NASA)

Figure 2. The B-52 AFS vehicle and wind-tunnel model

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 approximately 2.4 Hz and a rate of damping loss with increased speed of 0.01 equivalent structural damping, g, per 10 knots at 21,000 ft. Sensor locations and the control surfaces available for active controls on the B-52 CCV are shown in figure 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.



(a) Control Surfaces (b) Sensors

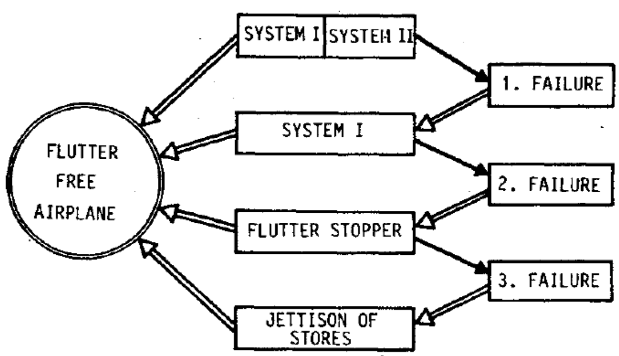
Figure 3. Control surfaces and sensors of the B-52 CCV [490]

The B-52 active-control test program included wind-tunnel tests at the TDT at NASA Langley [290, 458, 491]. Overall it was a pioneering effort in the development of active-control technology for aircraft and wind-tunnel models. 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 [492] were 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." Reference [492] also notes, in its conclusions, that "parameter identification methods will need to be developed to support experimental control synthesis." Considering that the program was completed more than 40 years ago, without the powerful and fast equipment and computing power available today, and before major developments in analysis and synthesis techniques of the past 40 years, the achievements of B-52 CCV are remarkable.

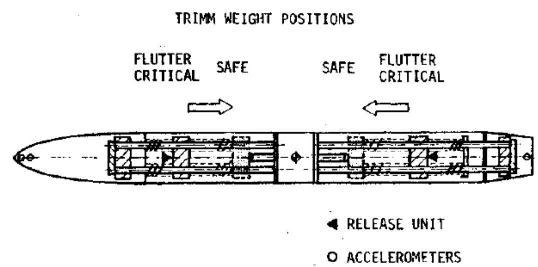
A European AFS flight-test program of the mid-1970s is described in [534]. A FIAT G91/T3 was fitted with modified external fuel tanks, which were ballasted to reduce flutter speed into the aircraft flight envelope. The tanks were equipped with aerodynamic vanes and flutter-suppression systems. In addition to studying the use of AFS for overcoming the 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 AFS of wing/stores flutter. This time the aircraft's existing ailerons were used [512–514], and control commands were generated by the existing FCS hardware through a flutter-suppression control box feed into the roll channel of the aircraft.

Key elements of importance in the evaluation of any AFS 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 LCOs, 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 AFS design was to make sure that there was no coupling between aileron and spoiler action. In the math models used to synthesize the flutter-suppression control laws, only two modes were taken into account (i.e., 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 FCS.

For safety, ballast masses were installed in the external stores to serve as flutter stoppers by, on command, moving and changing the radii of inertia of the stores. Each store could suppress flutter on its own, by making the configuration asymmetric, where, in this particular case, the flutter speeds of asymmetric configurations was higher than the flutter speeds of the corresponding symmetric ones. The stores could be also 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 shown in figure 4. Note the redundancy in the flutter-suppression system, with two systems working independently on each wing.



(a) F-4F Flutter Test Program Safety [514]



(b) F-4F Flutter Stopper [514]

Figure 4. The (a) F-4F AFS and (b) test safety systems

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-52 CCV, 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 AFS development activity at NASA with the DAST UAV [502–506] and numerous references on the development of flutter-suppression control laws, including [358, 380–381]. 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 [381]. Reference 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, following a flight in which valuable data were collected with a good signal-to-noise ratio, an error in the implementation of control gains in the AFS system led to explosive flutter and the loss of the vehicle (see figure 5). The wing was rebuilt (as ARW-1R) and attached to another Firebee 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 of 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 (for which 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 [504] 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 AFS 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 nonlinear 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, although used for analytical and ground test studies, was not flown.

(a) (NASA Photo ECN-31306-fr41-5)

(b) (NASA Photo ECN-31306-fr43-9)

Figure 5. Flutter of the right wing in flight on the modified BQM-34 Firebee II drone with ARW-1: (a) pre-failure and (b) just after failure

The first AFS system to fly on a production airplane was probably that of the F-18 [529, 532]. At the time it was named "Active Aeroelastic Oscillation Control" because the problem it was tasked to solve was that of LCOs in some external stores configurations of the F18. In the title of [532], it was named "LCO Solution." 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, for which 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 AFS 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 LCOs 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 LCO behavior constitutes loss of stability. If we adopt the definition of flutter in [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 AFS 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 FSC (see figure 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.

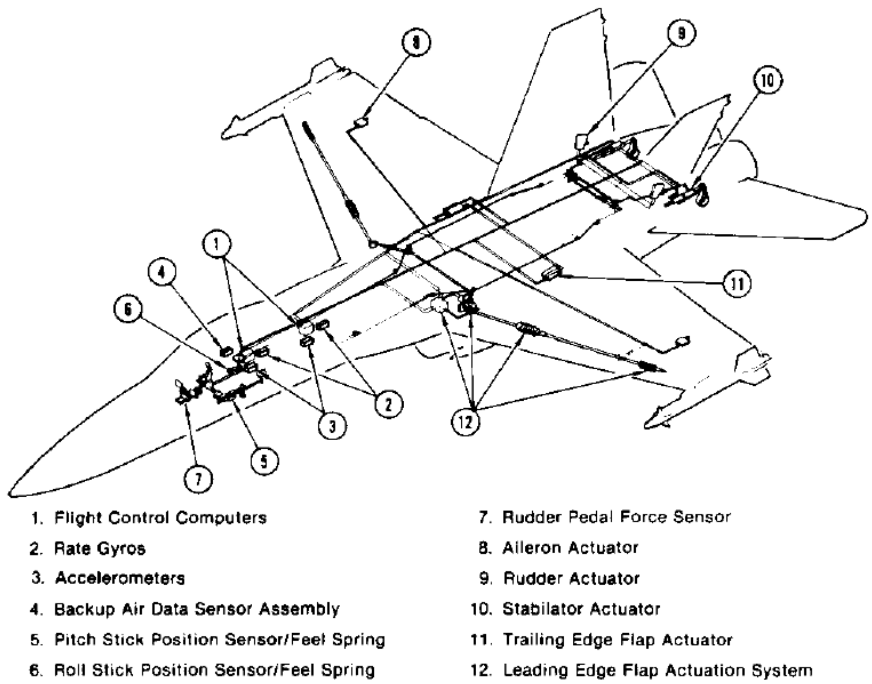


Figure 6. The F/A-18A flight-control system [529]

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. According to [532]: "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 a function of Mach number and altitude in the areas of the flight envelope in which the LCO problem exists (see figure 7).

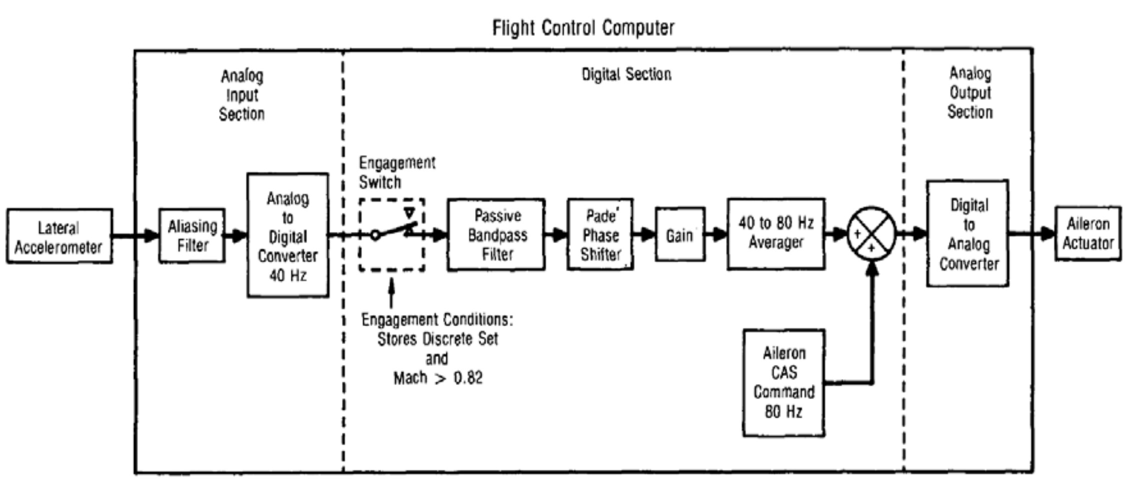


Figure 7. The F/A-18A Production active oscillation suppression system [529]

General Dynamics/Lockheed demonstrated an LCO suppression system on the F-16 in the late 1990s (information based on communication with David Boyce, Lockheed-Martin, Fort-Worth, TX).

> It used the production flight control actuators of the TE flaperons to generate the opposing forces, and used the production flight control sensors (accelerometers and gyros) to detect the oscillations. A dedicated test computer was used to generate the feedback commands, parallel to the production flight control computer actually "flying" the aircraft. The suppression computer had multiple adjustments to phasing and magnitude values of the various sensor inputs and control surface commands. The adjustments could be set in flight by the test pilot based on directions from the flutter engineers conducting real-time control room data processing and analysis. The approach was based on the results of the flutter-suppression wind tunnels tests conducted in the 1980s and 1990s [407]. Unfortunately, the system was not quite ready for operational use and a serious effort would have been needed to certify the Flutter, Flying Qualities, and Loads requirements if General Dynamics/LMT started adapting the control laws. The USAF was not interested in moving the project forward because of the scale of the effort.

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 [498, 699–701]. Not enough technical information has been made available to the aeroelastic community. What can be learned from newspaper stories such as [498] and regulatory agency publications [699–701], is that under 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.".

Reference [699] continues:

> It has been established that compliance with CS 25.252 and CS 25.629 cannot 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 FCS 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 FCS 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.

According to [700–701]:

> 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.

Another very recent case is the Boeing 787-10 model [499, 702], for which there was a need to add a flaps-up vertical modal suppression (F0VMS) system to the normal mode of the primary FCS. The F0VMS system is needed to provide additional damping to an already stable but low-damped 3Hz symmetric wing/nacelle/fuselage aeroelastic mode of the airplane. The system uses the elevators, oscillated symmetrically. Flaperons are applied to augment or supplant elevator control as needed. According to [499, 702], “Because Boeing's flutter analysis shows that the 3Hz mode is stable and does not flutter, the F0VMS system is not an active flutter-suppression system but, rather, a damping-augmentation system. At this time, the FAA is not prepared to accept an active flutter-suppression system that suppresses a divergent flutter mode in the operational or design envelope of the airplane.”

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 for which very little or nothing is shared and published has been evident in recent years; 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 AFS 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 Multi Utility Technology Testbed (MUTT) flight-research vehicle, developed by Lockheed Martin Skunk Works® for the US AFRL with this vision, is a platform for elastic aircraft active-control research [555–558] (see figure 8).

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

The X-56 follows a series of small unmanned aerial vehicles (UAVs) for flutter-suppression research built and tested by Lockheed Skunk Works to develop AFS technology for flight vehicles displaying BFF [540–541]. The BFF instability is due to interaction between the 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. BFF can also be a critical instability mechanism on configurations with forward-swept wings, for which 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 [544–550] is an example of such a case. Rigid/flex coupling was also found on the B-2 bomber, influenced by shockwave movement over the configuration, coupling wing bending and rigid-body pitch [104, 486–487]. In addition, BFF can be present on long slender configurations such as the SR-71 (outside its flight envelope) and the supersonic transport configurations of the 1960s and 1970s because of coupling between rigid-body pitch and fuselage vertical bending (with wing camber deformation participating) degrees of freedom.

The X-56 is designed to allow testing of a variety of configurations. 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 equipped with a parachute recovery system. An open-architecture FCS, a modular data-acquisition system, and ten control surfaces allow tests of alternative active-control concepts and systems. Like the B-52 CCV, 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), MLC, and ride comfort. The challenge in the case of such a vehicle, for which rigid-body and elastic-motion dynamics are tightly coupled and AFS, gust alleviation, and stability augmentation have to work in harmony with the same frequency range, is significant. To challenge technology development in the AFS 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 current transport aircraft display. However, following the note in [492], 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 were 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 this work, 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 AFS research program, developed its Mini-Multi-Utility Technology Testbed (MUTT) UAV [230, 431, 542–543]. The Mini-MUTT is based on the outer mold line of a donated Lockheed Skunk Works BFF UAV [431], 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 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 [431].

Figure 9. The Lockheed-Martin BFF UAV (back) and the University of Minnesota Mini-MUTT (front) [431]

The aeroservoelastic literature is rich in reports, papers, and book chapters that describe active-control flight tests on a rich blend of flight vehicles. Although not full AFS 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 GLA systems, MLC 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 issues of safety measures and safety guarantees must be addressed, and test procedures and system-identification techniques can be evaluated in flight and improved.

Important flight-test programs of aeroservoelastic actively controlled aircraft include the ride comfort system on the B-1 [484–485]; the B-2 [486–487]; the XB-70 [494–497]; the C-5A [500–501]; the Eurofighter [507–510]; the Boeing E-6 aeroservoelastic instability case (because of nonlinear structural loss of stiffness under load [511]); the F-15 [515]; the F15 STOL Maneuver Technology Demonstrator (SMTD) [516–518]; the F16, YF16, and F16XL [519–522]; the YF-17 [523–528]; the F18 thrust-vectored vehicle [530–531]; the F22 [533]; the SAAB Gripen [535]; the Gulfstream G550 [536]; the Lockheed L-1011 [537–539]; the X-29 [544–550]; the Boeing X-32 [551]; the Boeing X45A [552]; the Boeing X53 F18 AAW vehicle [553–554]; and the University of Michigan's X-HALE research UAV [559–560].

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 [407]. Development of flutter suppression for the YF-17, using a NASA TDT-tested wind-tunnel model, in addition to the full aircraft, is described in [523–528]. Similarly, AFS development for the X-29 and its NASA TDT model is described in [544–550].

Although mathematical models and detailed test results were not available to the general aeroservoelasticity community, information for a few key configurations was 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. AFS WIND-TUNNEL TEST PROGRAMS

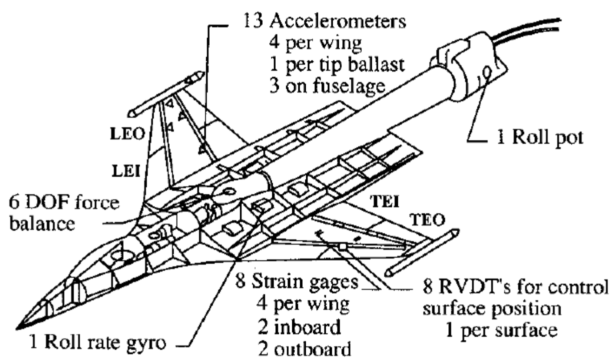
Wind-tunnel tests are often less expensive than flight tests, and they provide a controlled test environment and important sensing and actuation options that are difficult to implement on aircraft in the early stages of technology development. In the case of AFS, with the risks to the flight-test vehicle and its crew, wind-tunnel tests provide more safety. The advantages and disadvantages of active-control wind-tunnel tests have already been previously discussed. The bibliography includes papers and reports on key wind-tunnel tests in the AFS area in particular and aeroservoelasticity in general during the past 45 years. 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, different sensing and actuation methods, and the unsteady aerodynamics of actively controlled aircraft configurations and their control effectors.

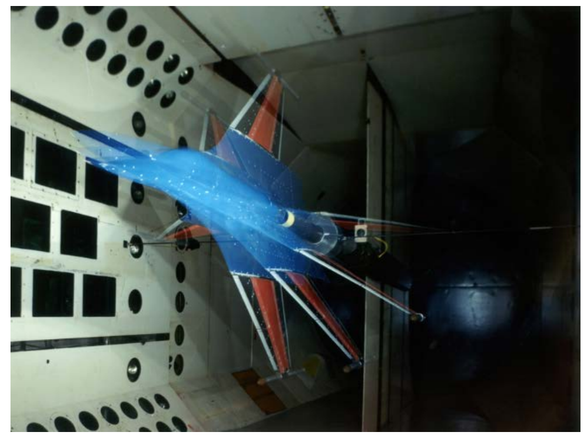
A wind-tunnel test program of a US Air Force Flight Dynamics Laboratory (AFFDL) forward-swept wing model is described in [563–564]. The wing/store flutter problem is naturally of major interest to the Air Force. In the context of AFS, wind-tunnel tests of aeroservoelastic models with different external 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 Air Force Wright Aeronautical Laboratories (AFWAL) wing/store model are described in [551–552]. Tests by ONERA in France of a wind tunnel model of a wing/store configuration is described in [609]. Wind tunnel tests of X29, YF17, and F16 aeroelastic models with external stores will be discussed later in this section.

The AFW program is described in [565–574]. It was a joint Air Force/Rockwell International/NASA program from the mid-1980s to the early 1990s.

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 pitch over a range of angles of attack. The model and its instrumentation are shown in figure 10. According to [566], "an important objective of the AFW program was to gain practical experience in designing, fabricating, and implementing a real-time MIMO multiple function digital controller, and in developing the hardware interface between the controller and the wind tunnel model."





NASA Photo L-89-12446

Figure 10. Schematic of the AFW model [566]

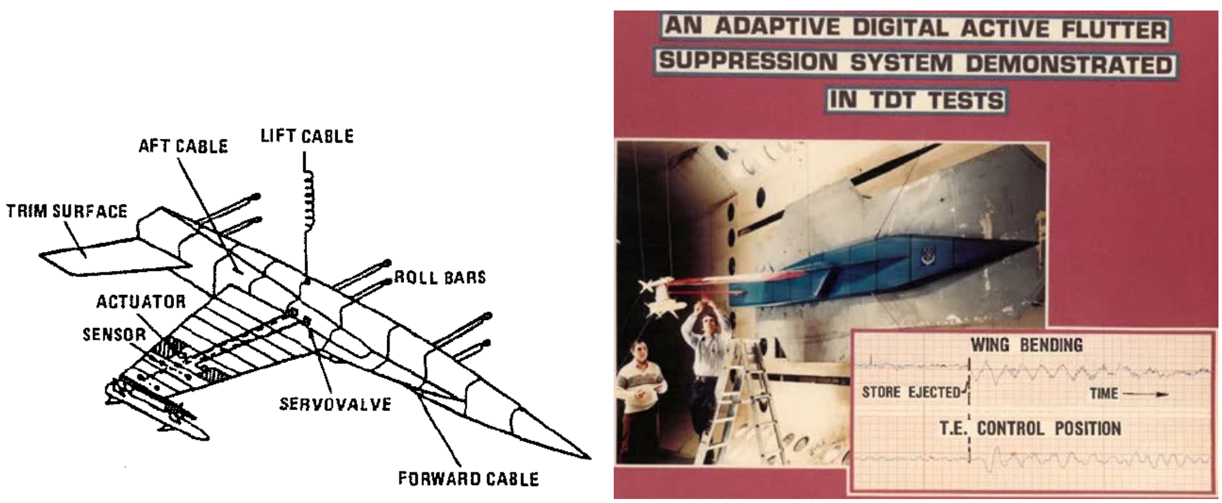
Required features of the digital controller were: 1) it be representative of a digital controller on a full-scale airplane; 2) control laws could be easily modified/replaced; 3) it be capable of simultaneous execution of flutter-suppression and rolling-maneuver control laws; and 4) it be capable of receiving and sending 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 and the capacity of CFD codes of the time to capture it were both studied. different AFS laws and the performance of the control system in single-function and multiple-function operation were also considered. In the multiple-function case, flutter was suppressed while attaining commanded rolling. The program demonstrated the capacity of the AFW model and 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 [575–582]. 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. However, its importance and contribution to the state of the art in AFS have been significant.

Wind-tunnel tests with an aeroelastic X-29 model in the TDT have already been mentioned [546]. 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 BFF. 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 (see figure 11) [404–406, 523–528]. 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. LE and TE control surfaces were used for flutter suppression, including cases when only an LE device was used for flutter control. 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 [404–406]. 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 an LE control law to a TE control law, and vice versa, was also demonstrated” [528]. Capabilities like this are important for adaptive control and for fail-safe AFS control-system design.



NASA Photo L-82-4.734

Figure 11. The YF-17 wind-tunnel model with external stores [405]

Adaptive AFS control was also tested on the F-16 flutter model at the NASA TDT [407] (see figure 12). In more than 2 ½ weeks of tests of approximately 6–8 hours of testing per day and during long wind-tunnel passes, the AFS system stabilized the wind-tunnel model (carrying external stores over varying flight conditions, including external store drops). The testing 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.

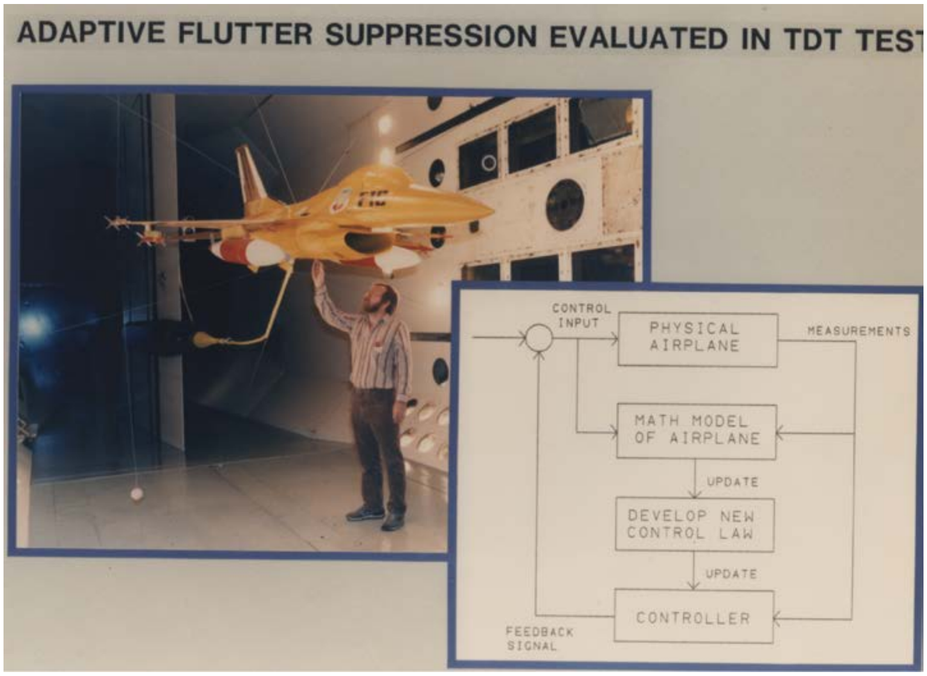


Figure 12. Adaptive F16 flutter-suppression tests at the NASA TDT, NASA photo L-86-8599

Tests in Germany using a Tornado flutter model with different external stores configurations were reported in [141]. More recent wind-tunnel tests on active aeroelastic control tests include the Flexible Semispan Model [585–586], The High Lift over Drag and Aerodynamic Efficiency Improvements tests at the NASA TDT, SensorCraft tests at the TDT [587–594, 613–619], and the S4T tests [621–622]. More recent tests included the truss-braced wing half-span aircraft model [620] at the TDT and the Boeing SolarEagle (Vulture) wing tests at the University of Washington's Kirsten Wind Tunnel [584], aimed at gathering data on the aeroelastic behavior of structurally nonlinear nonconventional aircraft configurations.

The Vulture wing was open-loop excited by controls for frequency response measurements at various flight conditions. In the truss-braced wing case, both open-loop and closed-loop tests were carried out, demonstrating AFS 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 closed loop at a flight condition of instability in the open-loop mode.

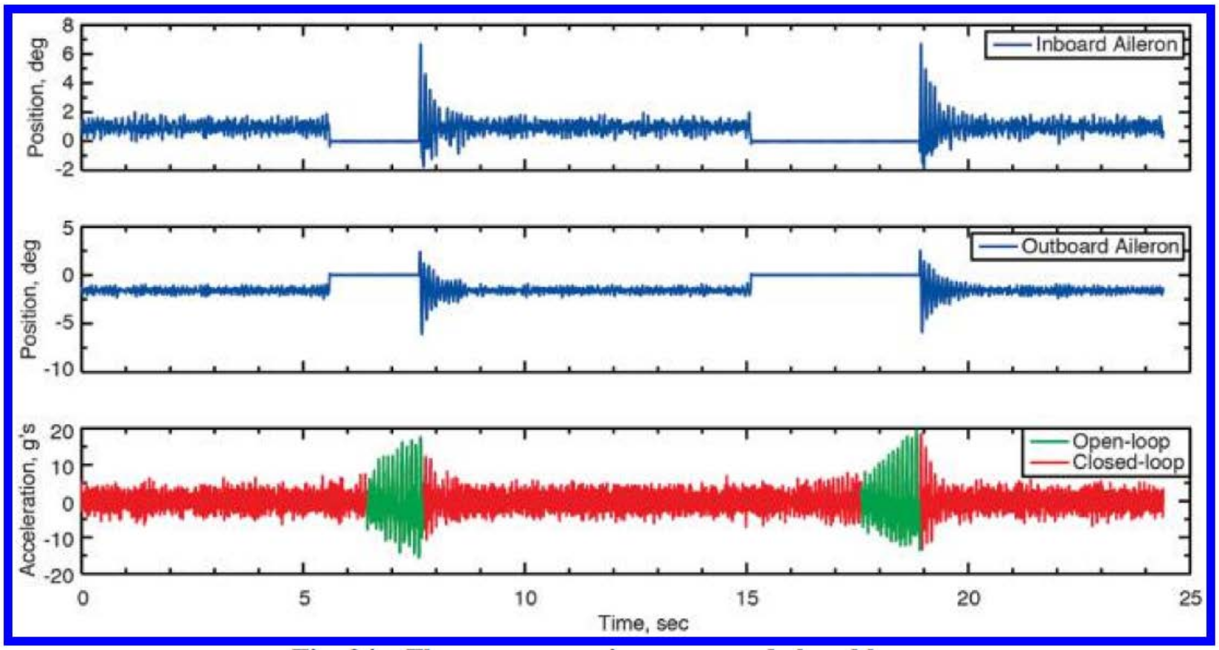


Figure 13. The performance of the truss-braced wing flutter-suppression system when switched from closed loop to open loop and back to closed loop at an unstable open-loop flight condition [620]

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 [602–604] (see figure 14).

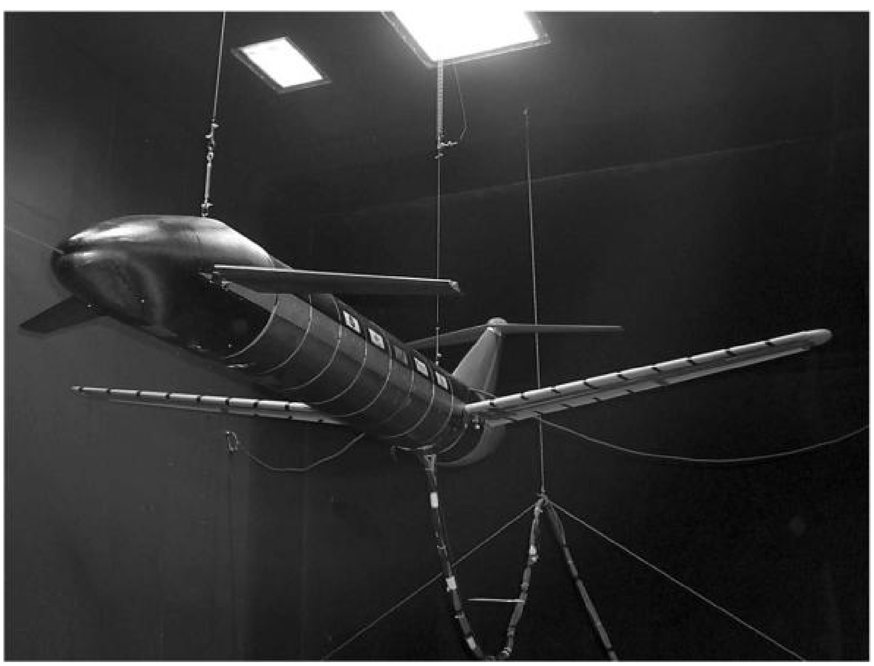


Figure 14. The Milan polytechnic X-DIA model [602]

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.

Although 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 [605–606], which used distributed piezo-electric actuation and was tested in the TDT.

Active-control wind-tunnel tests, including AFS, in other countries are described in [583, 595–598, 607-608]. 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.

12. UNCERTAINTY

Most aspects of the aeroservoelastic uncertainty quantification and mitigation problems have been already discussed in the sections above. References 623–660 together with [195] and [670] offer a rich selection of publications on the subject. Reference 631 is an excellent overview of the work on aeroelastic uncertainty prior to 2004. Reference 653 is a very recent overview of the field. Reference 652 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 toward 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 ground tests and flight tests because of limited test article sample selection possibilities, the planning and execution of tests, data acquisition and data analysis uncertainties, etc. [627, 629, 631, 643, 648]
- The variability of flight vehicles as they come off the production line and as they age
- The variability of flight operations per flight vehicle
- The effect of damage and hardware failure, and of maintenance practices [623, 628]

Some of these issues are already addressed in other disciplines in the context of current development techniques and processes used to establish protection against failure. Some, especially uncertainties in those discipline areas and multidisciplinary interaction areas to which aeroelastic stability is most sensitive, require more study.

Although active-control technology may be perceived as adding complexity and, therefore, 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 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 a number of methods of robust control system synthesis have been developed over the years, with most, if not all, applied to the AFS problem in research studies. Aeroservoelastic robust control was briefly discussed in section 8 and is covered by selected publications in the bibliography. From the safety perspective, it is important to work with clear quantitative robustness requirements that would guarantee a required level of safety when an active-control system is synthesized.

The translation of uncertainty analysis and test-technology experience into practical design and certification guidelines in the case of tightly integrated complex systems is highly desirable but is still a significant challenge. Section 15 is dedicated to the certification aspects of AFS. Considering AFS and its certification requirements from the beginning of the design process of a new airplane requires a definition of reliability/safety constraints or an equivalent set of safety margins that would be part of the set of constraints subject to which the vehicle will be optimized. This leads naturally to a discussion of AFS' place and role in the integrated MDO of flight vehicles.

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 AAW technology, can lead to major weight savings with the additional element of AFS. Reference 664 shows that AFS 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. AFS, as part of the complete FCS to be optimized together with the structural, aerodynamic, and propulsion systems, has the potential to lead to major improvements in resulting vehicle efficiencies when it is integrated into a MDO process that 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. When adequate redundancy and adaptability are included in the control-systems model optimized with the rest of the vehicle's systems, AFS 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 [6]. A few additional contributions in the area are [661–665], with more discussion in [149]. References 666–674 present work on integrated aeroservoelastic optimization for which aeroservoelasticity and control are coupled during the design optimization process, with [666, 671] integrating into the multidisciplinary design process piezoelectric actuation. The development presented in [671] 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 [620], the variable camber continuous trailing-edge flap wing [83], natural laminar flow wings [672], or high-aspect-ratio composite wings using advanced composite layout and construction technologies [673–674]—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 yet matured to its full potential. Questions regarding the performance of different control-law techniques and strategies in the context of flight vehicle aeroservoelastic MDO (e.g., what control methods would lead to better system designs) 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 in which design variables are optimized simultaneously subject to constraints representing all disciplines and all consideration must be demonstrated by analysis and tests of the resulting flight vehicle. An integrated MDO process that would account for uncertainty and reliability of actively controlled flight vehicles with AFS from the start is still in need of development.

14. CERTIFICATION

References 681–702 present key aspects of aeroservoelastic system certification, including flight-vehicle active controls, from both the FAA 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 and reliability estimation capabilities that also cover hardware, operations, and maintenance aspects in addition to sources of uncertainty in all aspects of aeroelastic and aeroservoelastic simulation. 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.

References 683–684 present the federal regulations that cover aircraft safety based on aircraft categories and intended use. References 685–686 add guidance regarding aeroelastic stability. Reference 687 addresses the safety of aircraft with active controls. References 688–691 deal with the safety of safety-critical software and hardware on aircraft. Flying qualities criteria for aircraft are discussed in [692]. General FCS design, installation, and test specifications are presented in [693–694]. Reference 693 provides:

> …a comprehensive definition of the general performance, design, test, development, and quality assurance requirements for military aircraft FCS. Specific focus areas are flight safety and integration of the FCS with other aircraft systems and subsystems, such as the electrical and hydraulic systems.

Reference 694:

> …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 of military unmanned aircraft,

> the airborne element of unmanned aircraft systems, 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 [696–697]. Additional information from DOD perspective regarding airworthiness certification criteria is provided in [695, 698]. Information regarding the special conditions used by the FAA and EASA to certify the AFS systems on models of the Boeing 747-8 is given in [699–701]. Although details have not been shared with the aeroelasticity/aeroservoelasticity communities, some important insights into the problem and its solution are offered in [699–701], 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 an 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 FCS. The key question for the certification of AFS 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.

Of note, 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 (see the Boeing 787-10 case) [702]. The full picture regarding the LCO problem of the 747-8 and the way it is suppressed by active controls, or the damping augmentation in the case of the 787-10, is not available to the public, 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, based on what more than 50 years of active-control and AFS 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 CFD/CSD for fluid/structure interaction analysis on the deformable, actively controlled flight vehicle in flight, accounting for structural behavior from the small deformation linear range to nonlinearities because of very large deformation and aerodynamic nonlinearities such as shock motions, shock/boundary-layer interactions, and flow separation. Other areas of relevant active research are MDO of flight vehicles, covering structural, aerodynamic, and control considerations; and 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, MIMO aeroservoelastic systems.

From the perspective of safety and certification needs, a few areas of importance to the development of acceptable AFS 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 on which they rely

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 and subject to significant limitations—the X29 and F18 thrust vectoring flight vehicles. However, full information for those wind-tunnel models and flight vehicles is not available. Because 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 from which the aeroelastic/aeroservoelastic/flight mechanics/flight control community would be able to benefit while developing required analysis and design methods.

Such a test-case vehicle must have considerable aeroelastic interactions and active-control capabilities that can be used to implement all flight-control options, including AFS. Its complete geometry and 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 Skunk Works division, of the X-56 research airplane for active controls research, including AFS (Refs. 555-558). The X-56, is now operated by NASA's Armstrong Flight Research Center. Although 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 yet been made widely available. In long-term planning, the X-56 may be configured for tests that would build confidence in AFS 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 AFS 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 AFS research that would include transonic and possibly 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 its 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 turnaround 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 AFS, uncertainty/reliability analysis capabilities for such systems should be developed. Although 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, modeling errors, and performance limitations in all areas; the effects of damage, repair, and maintenance; the 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 interconnected 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

Although different control-law design and architecture-/hardware-implementation strategies in the US can be expected to be proprietary and subject to ITAR and export-control constraints, and although R&D efforts to develop and test such control systems are still underway and funded by government agencies and in-house by companies as part of various R&D 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:

- Flight vehicles and problems representative of the various types of aircraft of importance in which AFS technology may be used.
- The harmonious safe operation of all active-control functions (e.g., stability augmentation, gust alleviation, and flutter suppression).

- 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.
- Robustness of minimal order controllers.
- Validation and verification as well as transparency of control laws and systems generated using competing approaches.
- 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. AFS technology adds complexity to the certification process in all its aspects because of AFS' 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, therefore, 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 for cases in which 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 past 50–60 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 R&D in those areas that, complementing other R&D 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 fulfill its potential.

17. INDEX - A LIST OF KEY TOPICS COVERED BY REFERENCES IN THE BIBLIOGRAPHY

18. BIBLIOGRAPHY

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