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Future of Airplane Aeroelasticity

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Aeroelasticity is still dynamic, challenging, and a key part of cutting-edge airplane technology. Emerging trends, as well as challenges and needs in the field of airplane aeroelasticity, are surveyed and discussed. The paper complements other overview papers on various aspects of the fixed-wing aeroelastic problem, published recently for the centennial year of flight. It includes an extensive bibliography and emphasizes those aspects of aeroelastic technology development not covered thoroughly elsewhere.

Introduction

FROM the perspective of almost a hundred years of aeroelasticity[1–35] as we consider its future, a series of state-of-the-art review articles published in the 1970s stands out as particularly interesting.[1–8] Airplane aeroelasticity was already well established in the 1950s and 1960s, as reflected by successful high-speed airplanes designed in those years. Major aeroelastic phenomena were already quite well understood, as documented in classic textbooks[9–20] and many journal and conference publications.

What makes the 1970s special from the point of view of aeroelastic technology development is that they heralded a new era. The finite element method (FE) of structural dynamics, as well as lifting surface/panel aerodynamics on interfering wings, control surfaces, and bodies, made it possible to analyze general complex configurations that were intractable before. Composite materials led to aeroelastic tailoring. Active control technology added the "servo" to aeroelasticity, and analytic and computational methods were developed to tackle aeroservoelasticity. Structural synthesis in the 1970s was maturing to a level that allowed design optimization of general airframe structures subject to aeroelastic constraints. The 1970s also saw rapid developments in instrumentation, telemetry, and signal-processing techniques that led to significant improvements in aeroelastic wind-tunnel and flight-test methods and procedures. Most of these technologies that matured in the 1970s are still dominant in aeroelastic technology today.

When the scope and vision in these review papers from the 1970s and the complexity of flight vehicles designed and built using 1970s technology are grasped, one might reach the conclusion that no major developments in aeroelasticity have occurred ever since, and that except for incremental improvements aeroelasticity has become a mature and well-established field, where no new major breakthroughs are needed or can be expected.

This indeed was a common viewpoint in the 1980s and early 1990s in certain industry, government, and academic circles. Even though research and development in aeroelasticity and its foundation disciplines continued, it was not until the publication of Ref. 36 in 1999 that the perception of aeroelasticity as mature and somewhat stagnant was challenged head on.

As Ref. 36 had shown, aeroelasticity is still a dynamic field facing many challenges. These include modern aeroservoelasticity, computational aeroelasticity, nonlinear aeroelasticity, aerothermoelasticity, impact of new sensing and actuation technologies, and aeroelastic design optimization. Reference 36 also included an overview of developments and challenges in the area of rotary-wing aeroelasticity—an area more demanding and less developed than fixed-wing aeroelasticity—and concluded with predictions for the future. An overview of past and future of aeroservoelastric optimization was published at the same time.[37] Recently, to celebrate the centennial anniversary of the Wright brothers' first flight, a number of articles covering various aspects of aeroelasticity have been invited for a special issue of the *Journal of Aircraft*.[38–45] These papers include, in addition to descriptions of past achievements, also discussions of future needs and future developments in areas such as nonlinear aeroelasticity,[41] computational aeroelasticity,[44,45] aeroelastic wind-tunnel testing, and aeroelasticity of nonconventional configurations.[43]

The body of survey literature on aeroelasticity, including recent contributions, is considerable, and the areas these references cover are numerous. It is difficult, if not impossible, to do justice to all important aspects of this rich and complex multidisciplinary field within the confines of a single paper.

As we discuss the future of airplane aeroelasticity, an effort is made in the present paper to complement recent survey papers in this area with minimum overlap. For detailed discussion of nonlinear aeroelasticity, computational aeroelasticity, aeroelasticity of new configurations, and aeroservoelasticity, the reader is referred to Refs. 36–45. This will allow more detailed discussion here of aspects of the field not thoroughly covered by those recent survey papers or other areas this author considers to be of major importance.

The paper is entitled "The Future of Airplane Aeroelasticity," but no attempt is made here to foresee the future. Rather, the discussion focuses on challenges, needs, and emerging trends. The hope is that with its selection of topics and its supporting bibliography this paper will motivate research and development in aeroelasticity in the coming years and inspire both researchers and practitioners already

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working in this rich and important field as well as those who make their first steps.

Taxonomy: Contributing Disciplines

Examination of aeroelastic problems on emerging and future flight vehicles can start through the prism of the range of subdisciplines involved. Elasticity, aerodynamics, and dynamics are the fundamental building blocks of classic aeroelasticity. Static aeroelastic problems cover the interaction between the flexibility of a structure deforming under load and the aerodynamic loads determined by its deformed shape. They include both response problems, such as load redistribution, deformation in maneuvers, control-surface effectiveness, and flexibility corrections to flight mechanics stability and control derivatives (that is, effects of aeroelastic deformation on "slow" motions of the deformable airplane). Lifting-surface divergence—the quasi-steady exponential growth of deformation in an aeroelastic system, similar to buckling of structural systems—is the major static aeroelastic stability problem. With nonnegligible inertia effects the response and stability of aeroelastic systems become dynamic. The dynamic loss of stability via exponentially growing oscillation (flutter) and dynamic response problems, such as gust response, fatigue, ride comfort, and response to store ejection loads, form the domain of dynamic aeroelasticity. This can be in certain cases tightly integrated with flight mechanics of the complete deformable airplane.

When developments in active control technology led to tightening of the interactions between control systems (including their sensors, control computers, and actuators) and the deformable airplane, the field of aeroservoelasticity was born. Sensors, control laws, actuators, and control surfaces could now respond to elastic deformation of the vehicle, and if not properly designed they could react in a way that reduced stability and degraded overall dynamic behavior of the coupled system. As more advanced and powerful control systems continue to emerge and new sensing and actuation technologies evolve, and as airplanes become more dependent on active controls, aeroservoelasticity will continue to grow in importance.

In the presence of strong thermal effects, aerothermoelasticity addresses the stability and behavior of aeroelastic systems subject to heating of the structure, where material properties can change and induced thermal stresses can lead to reduced effective stiffness. Deformation of a hypersonic vehicle under aerodynamic loads can change aerodynamic load distribution and flowfield and thus affect aerodynamic heating and structural deformation. In preparation for the development of future hypersonic flight vehicles, significant advances in aerothermoelastic technology are expected in the coming years.

To this mix of disciplines external acoustics can be added, covering the effects of acoustic excitation on aeroelastic behavior of panels and lifting surfaces and the effects of aeroelastic deformations on noise signatures. It has also been known for quite awhile that acoustic excitation can in certain cases be used to affect flutter. Similarly, propulsion interactions can be considered, such as performance of deformable and controllable inlets and nozzles, interactions of vectored thrust with a flexible airframe, and, in the case of hypersonic airbreathing vehicles, effect of the shape of the front of the vehicle on flow conditions at the entry to engine inlets.

Complexity of Disciplinary Behavior

Aeroelastic phenomena can also be classified according to the complexity of phenomena involved in each of the contributing disciplines. Flight regimes classified by Mach number and Reynolds number determine the character of unsteady aerodynamic behavior. This covers subsonic, transonic, supersonic, and hypersonic Mach numbers as well as low- and high-Reynolds-number flows. The degree and extent of strong flow nonlinearities, such as separation, stall, and shock motion, are also determined by flight maneuvers and the resulting angle of attack, sideslip angle, and angular rates of the airplane relative to the flow. Similarly, in the structures area linearity and nonlinearity of the behavior are determined by the severity of loading and deformation, material characteristics, as it is in the case of actuators and complete control systems that can display nonlinear behavior caused by free-play, hysteresis, dry friction, and a host of other nonlinear phenomena.

Missions and Airplane Configurations

Different classes of airplane configurations, shaped by the missions for which they are designed, lead many times to particular aeroelastic problems and require particular developments in aeroelastric technology. Supersonic vehicles with their thin low-aspect-ratio (low-AR) wings and long slender fuselages can be aeroelastically quite different from high-aspect-ratio transonic airplanes with thick supercritical airfoils. Lifting-body type hypersonic vehicles can be aeroelastically different from conventional airplanes. High-altitude long-endurance airplanes with their slender high-AR wings and lightweight structures are aeroelastically different from fighter aircraft, which are geometrically more compact and structurally stiffer. An extensive discussion of the aeroelasticity of past nonconventional configurations is presented in Ref. 43. It shows how new configurations of the past drove aeroelastic technology and were affected by it. Examples include the swept-back jet transport with underwing engines; the T-tail airplanes; the low-aspect-ratio fighters, supersonic bombers and transports such as the B-70 and Concorde; variable geometry airplanes such as the F-14, F-111, and B-1; control configured vehicles such as the F-16; forward-swept wings; aeroelastically tailored vehicles; hypersonic airplanes such as the SR-71 and the X-15; and more.

A discussion of the future of airplane aeroelasticity must include (and Ref. 43 discusses) some examination of emerging and potential future airplane configurations and assessment of the aeroelastic challenges involved.

Analysis, Design, Computation, and Testing

Aeroelastic technology covers the analytical foundation of modeling the physical processes involved, numerical methods for simulation, test methods using scaled models, and finally, when a full-scale vehicle is cleared for flight, flight tests.

Developments in design and design-optimization methods have made it possible to include aeroelastic considerations in the design process—a marked departure from past practices, in which aeroelastic simulation and clearance were used only after a design was almost complete and only in a problem-fixing mode.

Current and potential future developments in aeroelastic analysis, simulation, design, and testing methods will be discussed in subsequent sections.

Science and Practice of Aeroelasticity

Aeroelastic "science," aimed at understanding basic mechanisms and fundamental phenomena, is different in nature from the practice of aeroelasticity in industry, where real, complex flight vehicles have to be designed, analyzed, and safely cleared for flight. Aeroelastic science will typically use simple models and small-scale problems in an effort to zoom in onto and thoroughly understand particular processes or to develop new analytical techniques and simulation tools for such processes.

For design and clearance of real vehicles, issues of vehicle complexity, high fidelity of modeling, reliability, speed, and cost become extremely important. It is one thing to properly simulate a basic phenomenon and capture it in a test using a simple model. It is completely different to design a full vehicle in a timely cost-effective manner, covering all flight conditions, loading conditions, shape variations, and all possible aeroelastic behavior modes. Although discussed in the past by industry aeroelasticians, the number of publications on the practice of aeroelasticity pales in comparison to the number of publications on its science. Improvements in the practice of aeroelasticity, however, are crucial to the vitality and competitiveness of the aircraft industry.

In the following sections selected aspects of the future of airplane aeroelasticity will be discussed, covering challenges created by new airplane configurations, mission expansion into new flight regimes, and the resulting complex processes involved, tighter interdisciplinary interactions, and developments in simulation, design, and testing technology. A special emphasis will be placed on the practice of aeroelasticity. Finally, a few comments will be made on that national and international body of knowledge, skill, and creative mastery shaped by extensive experience—the "art" of aeroelasticity—its state and its future.

Frontiers of Numerical Aeroelastic Modeling and Simulation

The development of structural finite element and three-dimensional aerodynamic panel/lifting surface methods in the 1970 to a level that made it possible to model real airplanes made an enormous impact on the field of aeroelasticity. New configurations that did not lend themselves to previous beam/modified strip modeling could now be design and analyzed. Examples include low-aspect-ratio wings of general structural layout, variable-sweep wings with possible tail/wing aerodynamic interference, T-tails, and various wing/control-surface combinations. Subsonic and supersonic flutter and gust response could be predicted quite reliably and at reasonable model preparation and computational costs.[44]

Linear aeroelasticity capabilities based on structural finite elements and lifting-surface theory are now available in general purpose commercial codes[24] as well as many computer codes developed in-house by airplane manufacturers. Improvements in linear unsteady aerodynamics continued in the 1980s with the development of panel codes capable of unsteady aerodynamic modeling of combinations of lifting surfaces and bodies, such as fuselages, nacelles, and external stores.[46–52]

These tools still serve as the backbone of aeroelastic analysis and design today and have proven reliable in the subsonic and supersonic regimes for high-speed flight at small angles of attack, where the flow is mostly attached and no shock-wave motion over lifting surfaces is present. The linear codes, however, cannot capture strong nonlinear aerodynamic behavior, and, thus, cannot model aeroelastic mechanisms involving shock waves, separation, and nonlinear vortex interactions.

A sustained drive in the area of computational fluid dynamics (CFD)-based aeroelasticity over the last 20–25 years progressed from transonic small disturbance (TSD) and full potential through Euler flow simulations and is now finally reaching a point where complex configurations of real vehicles can be modeled and analyzed using a variety of Navier–Stokes (N-S) solvers.

Any discussion of the future of aeroelasticity must recognize the growing power and growing importance of Navier–Stokes steady and unsteady flow solvers, aimed at capturing viscous and compressibility effects in general flows around complex configurations.

Aeroelastic CFD-based results on real configurations were first obtained for static aeroelastic cases. Dynamic aeroelasticity with N-S CFD solvers is now finally at a point where applications to real airplane can be carried out, compared, and evaluated. A number of representative review articles[53–57] provide excellent overviews of CFD-based aeroelasticity from the 1990s up to the present. The emerging picture of future aeroelastic modeling for airplanes is that of a three-level hierarchy of aerodynamic tools: Euler and Navier–Stokes solvers as high-fidelity tools, linearized panel codes for design, systematic evaluation of thousands of load cases and flight conditions, and for high-speed flight flutter clearance. In between these levels of fluid modeling fidelity are found codes based on integration of nonlinear full-potential aerodynamics with boundary-layer solvers to account for viscous effects. A tool such as the CAP-TSDv code (Refs. 53–55), which integrates the TSD equation with boundary-layer simulation, is proving to be very valuable. It has demonstrated capability to capture some important nonlinear aeroelastic phenomena, including cases involving shock-wave motion, such as in the case of the limit-cycle oscillation on the B-2 bomber.[58,59] Yet it is at least an order of magnitude less expensive numerically and requires much less effort to prepare the models of configurations analyzed.

To create the high-fidelity CFD-based aerodynamic tools the industry needs, development of Navier–Stokes solvers for aeroelastic simulation is expected to continue, and progress in numerical analysis techniques and computing power (including parallel computation) will allow more configurations and more cases to be analyzed with such tools. The goal of such development is to reduce design cycle cost and eliminate extensive physical testing of new vehicles.

Currently, model preparation and computational costs associated with N-S based aeroelasticity are still considerable. Existing important challenges include mesh generation and mesh deformation (generation of a mesh around a real vehicle that will capture local effects in areas of abrupt geometric changes, and the methodology of deforming the mesh during aeroelastic motion without unacceptable cell and mesh topology distortion); turbulence modeling and its effect on aerodynamic simulations (particularly in cases involving flow separation and vortex interactions); and structure/flow behavior matching at the structure/flow boundary. Algorithmic differences between various spatial and temporal discretization methods are still in need of assessment and better understanding. One example includes the effect of numerical damping on dynamic aeroelastic simulations. As Ref. 45 points out, certain aerodynamic CFD codes developed for static aeroelasticity might have too much numerical damping that can affect accuracy of dynamic aeroelastic frequency-response motion prediction.

CFD-based aerodynamic simulations can be coupled to structural FE models that are either full order or modally reduced. In the latter case a set of generalized coordinates, defined by mode shape, generalized mass, and generalized stiffness is used.[60–62] The structural models can be linear or nonlinear.

It is now well known[41,63–68] that nonlinear structural behavior in maneuvers can change static and dynamic aeroelastic response considerably. As CFD modeling of the nonlinear fluid behavior in CFD-based aeroelasticity becomes more available, renewed attention to structural modeling issues is expected to rise. Limitations in the structural simulation part in CAP-TSDv (Ref. 45), for example, prevented accurate modeling of free play in control surfaces, a feature of the structural behavior that had to be modeled, as described in Ref. 45, by artificially reducing the structural dynamic frequency of the control surface on its hinge. While modification of any modally based structural dynamic capability to account for nonlinearities such as nonlinear stiffness, free play, or hysteresis, or even sudden structural changes (due to store ejection, etc.) is not that difficult,[69] the problem of structural dynamic modeling for the case of large deformation and large rigid-body motions[70–73] is more demanding.

The simulation of large-motion maneuvers can, in theory, track the motion of FE computational structural mechanics (CSM) structural nodes and CFD grid points throughout the nonlinear simulation. This is not straightforward, however, because the fluid mesh, when very large motions of its grid points are involved, can become too distorted and ill conditioned. Also the numerical convergence problems that can arise in such simulations as a result of nonlinear structural behavior under loads that can lead to local and global buckling have not been studied thoroughly yet.

Development of coupled structure/fluid equations of motion and their discretizations in rotating frames of references[70–73] had been attempted in the past, but usually with structural models, and especially fluid models, that were simplified. Once such simulations are improved, however, effects of rapid angular motions or high g maneuvers on aeroelastic behavior (via changes in frequencies caused by effects of geometric stiffness) will become analyzable.

Application to real airplanes of the FE or modal formulations in rotating coordinates has been very limited to date. Although nonlinear structural behavior has been studied thoroughly in the case of helicopter aeroelasticity (taking into account large deformations of rotor blades as well as high angular rates and the associated effects of geometric stiffness) in the case of rapidly maneuvering airplanes, it is still not clear when such effects become important, if at all.

A growing need for introducing large-deformation structural simulation into the coupled aeroelastic equations of motion is caused by the emergence of new airplane configurations, such as the joined-wing, where geometric stiffness effects and possible buckling of major surfaces must be accounted for.[67,68]

Finally, although it is discussed in most publications on aeroelastic CFD/CSM integration, and thus can be found in many of the references on CFD-based aeroelasticity selected here, it is important for the completeness of the CFD/CSM discussion here to add a few additional references focusing directly on the "classic problem of aeroelasticity"[74]—the transformation of aerodynamic and structural information between aerodynamic and structural meshes. No universally accepted standard method is available today in an area that is at the heart of aeroelasticity. Issues of accuracy and consistency, adaptability to a variety of CFD/CSM discretization methods, the resulting size of the coupled structural/aerodynamic models, and costs of preparation and simulation all have to be considered and will continue to drive research and development.[75–89]

We can get a taste of things to come in the area of CFD-based aeroelasticity by examination of some representative recent results. A complete F-16 fighter airplane in flight was simulated at the Center for Aerospace Structures at the University of Colorado.[90–92] The method used is based on a three-field nonlinear aeroelastic simulation, in which a structural field, a fluid field, and a third fluid-mesh field track the motion of the vehicle together with the motion of the structural and fluid meshes. The structural finite element model (linear) of the F-16 contains 168,799 deg of freedom (Fig. 1). The fluid volume mesh has 403,919 points (for a small angle of attack Euler solution), 63,044 of which are on the surface of the airplane (Fig. 1). A large number of aeroelastic simulations were carried out including stabilized flight conditions at different altitudes and Mach numbers, accelerated flight conditions, and high-g flight conditions. Results of the CFD–FE aeroelastic simulations were correlated with measured results from flight tests carried out at the U.S. Air Force Test Pilot School. Frequency and damping correlations as a function of Mach number at 3000 m for the first torsional mode at 1 and 5 g are shown in Fig. 2. The results for the straight and level flight also include the case of accelerated flight.

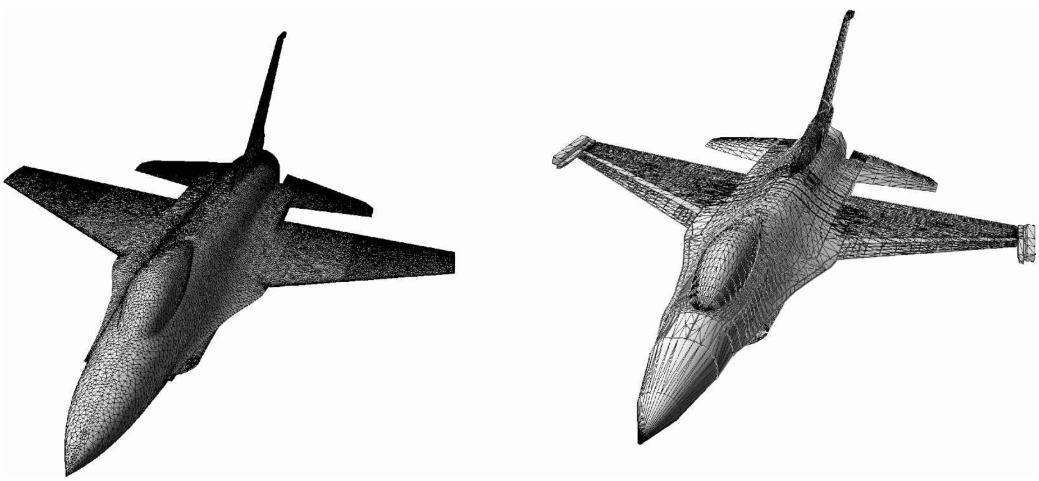

Fig. 1 CFD surface mesh and structural FE mesh for the F-16 (Courtesy of C. Farhat, University of Colorado, Boulder, CO; Ref. 92).

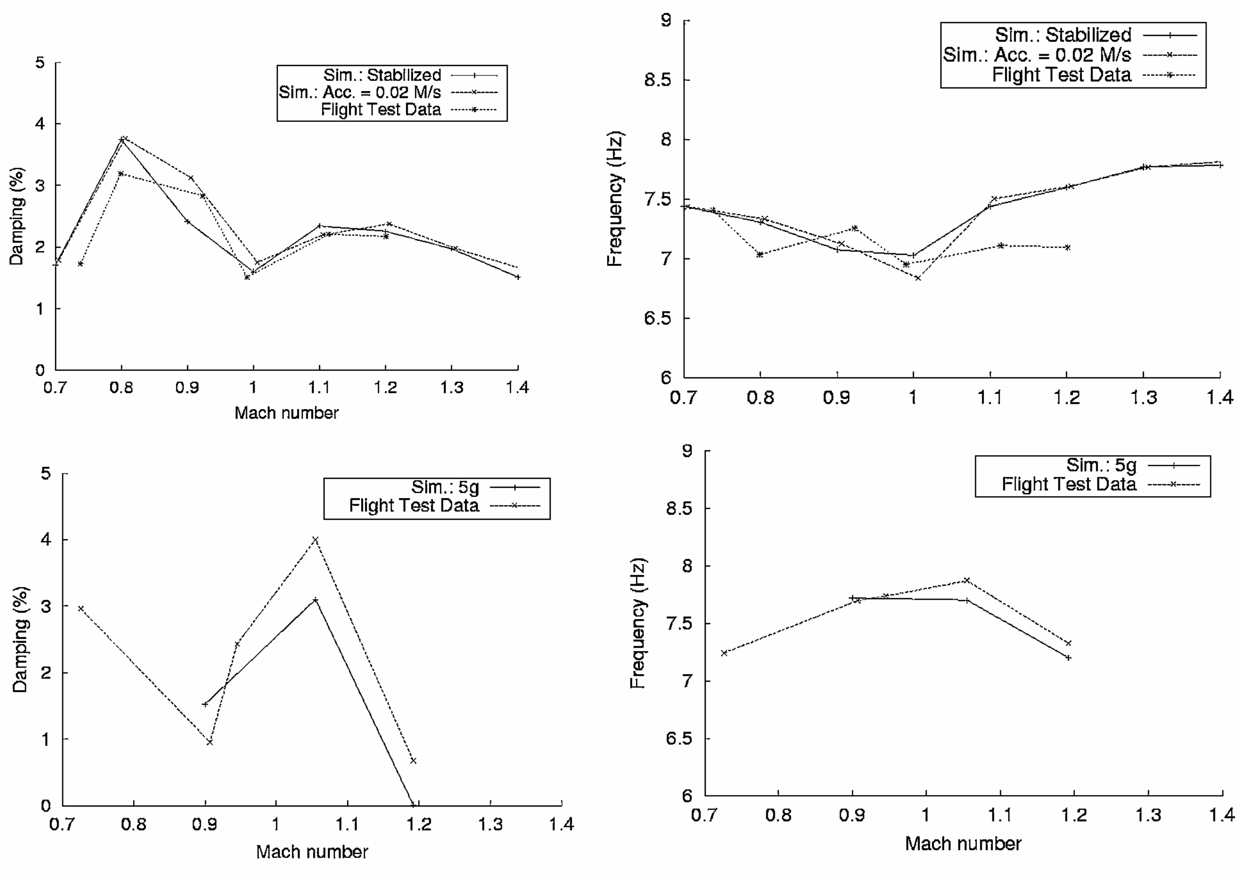

Fig. 2 Damping and frequency correlations for a torsion mode. F16 in flight. 1- and 5-g maneuvers, including accelerated flight (Courtesy of C. Farhat, University of Colorado; Ref. 92).

Computational costs of the numerical simulations (covering three cycles of oscillation at 134 points per cycle for the torsional mode) are also presented in Ref. 92. On a SGI Origin 32000 with R12000 400-MHz CPUs a typical simulation using six processors takes a total of 9.6 hours, 63.3% of that devoted to the fluids model, 35.4% to the mesh field, and 1.3% to the linear structural FE model. With 1,3,6,12, and 24 processors total CPU times were 52.3, 18.4, 9.6, 4.4, and 2.5 hours, respectively. By now, with improvements in hardware made since the original computations were carried out, computing times of half of those quoted are probably already attainable.

The capabilities described in Refs. 90–92 also allow N-S fluid simulation with a variety of turbulence models including k-e, Spallart–Almaras, and variational multiscale large-eddy simulation. Models for viscous flows have about three million grid points and are used when configurations with underwing stores are analyzed.

Another important example of CFD-based aeroelastic simulation of a realistic complex configuration is the Boeing effort to simulate the B-1 bomber limit-cycle oscillation (LCO) found in flight and also in the wind tunnel at specific flight conditions (Mach = 0.975, angle of attack = 7.38 deg, $Re_c = 5.9 \times 10^6$).[93–95]

The CFL3D N-S code was used for the simulations, with a modal representation of the structure, and a mesh perturbation method using master (solid surface)/slave (fluid field). A decaying function concept grid-deformation method was used in place of the common spring-analogy method for the fluid grid, thus reducing memory requirements.

The B-1 LCO problem is particularly challenging because it involves interactions of a leading-edge vortex with the elastic wing and includes flow separation over the outer wing. Comparisons of rigid and static aeroelastic results are shown in Fig. 3. Total damping results as a function of angle of attack are shown in Fig. 4. The dynamic simulations follow the measured trend in damping but do not capture the measured decrease to zero damping corresponding to the development of limit-cycle oscillations (even when additional 1.1% structural damping is added to the structural simulation model to account for the existing structural damping in the wind-tunnel model).

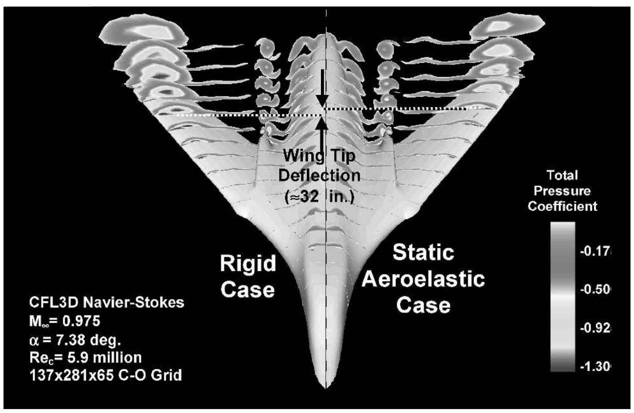

Fig. 3 B-1 LCO case (Courtesy of Boeing; Ref. 93).

More work is needed to understand the characteristics of current CFD-based aeroelastic simulation methods, improve them, and improve the practice of their application to real problems. In the case of the B-1, more accurate time stepping might improve correlation with test results (Ref. 95). A repetition of the simulations with alternative turbulence models better suited for modeling dynamic vortical flows will also lead to more insight and possible improvement. To move from the thin-layer N-S equations in CFL3D to a full N-S solution with a grid that can resolve viscous terms in all coordinate directions would require the fluid grid to grow by one or two orders of magnitude from the 2.5 million grid-point grid used. Such an increase in problem size, together with the associated turbulence modeling and grid-adaptation issues involved, makes the full N-S modeling a "formidable endeavor. . .in the foreseeable future" (Ref. 95).

Because of significant efforts currently underway, the capacity to model complex flows around complex configurations will improve, and flow phenomena associated with nonlinear mechanisms will be better captured with growing computational efficiency. Improvements in linear unsteady aerodynamic methods for complex configurations, however, are no less important. Methods such as the doublet-lattice method for subsonic flows, the harmonic gradient method for subsonic and supersonic flows (such as implemented in the ZAERO suit of codes[50–52]), and other equivalent methods capable of modeling combinations of wings, control surfaces, and bodies, will continue for the foreseeable future to be used for the bulk of static aeroelastic, flutter, aeroservoelastic, and gust-response analyses. The ease and speed of model generation combined with their low computational costs make the linear unsteady aerodynamic methods orders of magnitude more efficient and user friendly than any CFD-based approach (Fig. 5).

This becomes even more important when design optimization of airplane configurations is considered. Major progress has been achieved in sensitivity analysis and aerodynamic optimization with CFD-based codes, and aeroelastic optimization based on CFD modeling is now emerging. Still the need to repetitively analyze large numbers of configurations deforming (caused by variations in the structure being optimized) in a large number of ways presents such

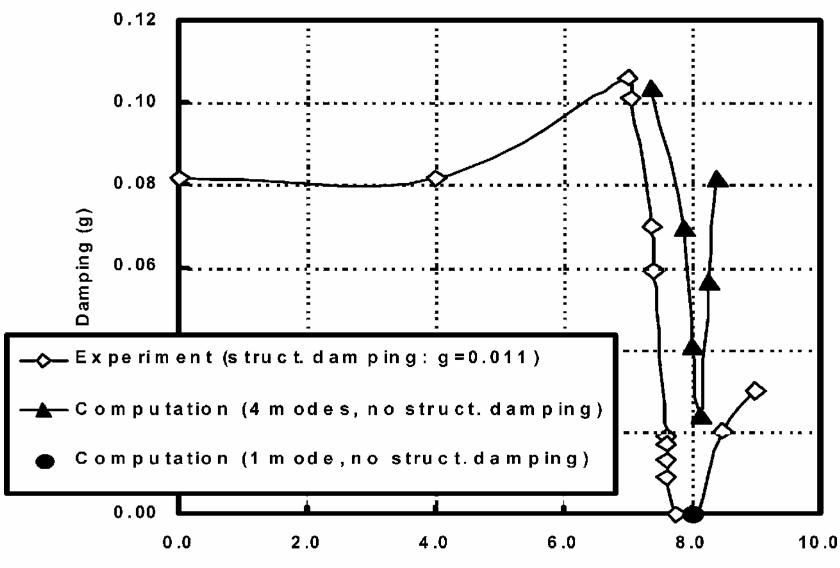

Fig. 4 B-1 LCO case: damping trends (Courtesy of Boeing; Ref. 93).

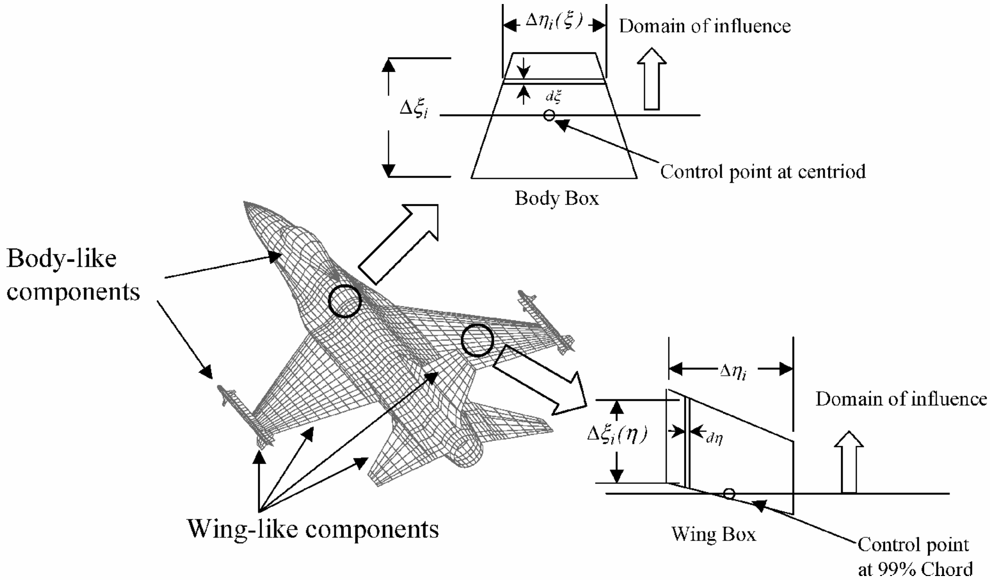

Fig. 5 Paneling for shape sensitivities of unsteady linear panel aerodynamics on a fighter airplane (Courtesy of ZONA Technologies).

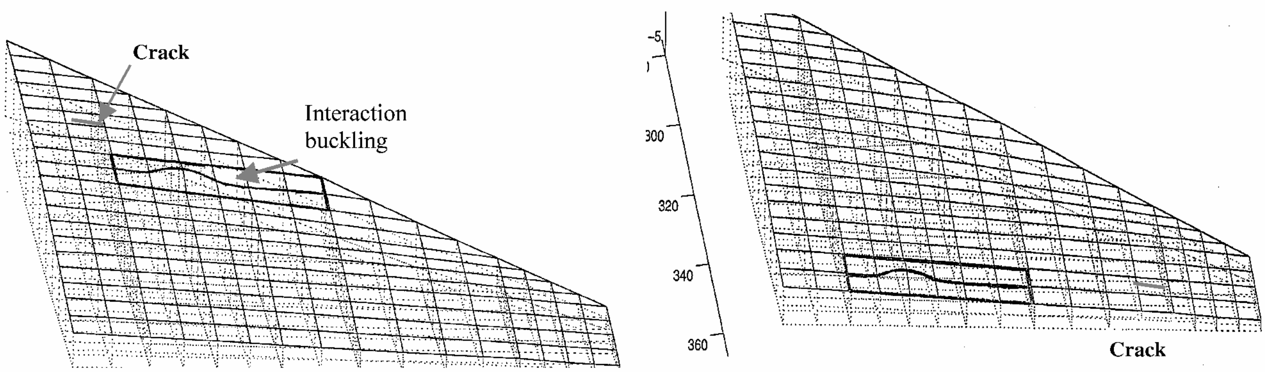

Fig. 6 Local buckling and damage tolerance failure mechanisms in a fighter aircraft wing (Ref. 99).

a computational challenge that it is going to be quite awhile before CFD-based aeroelasticity is expected to become an active part of the design optimization process in its early stages. Linear unsteady aerodynamic techniques, however, are already part of major aeroelastic optimization capabilities, and optimization of aeroelastic configurations covering structures, aerodynamics, and controls using these techniques has already been demonstrated.[37]

Capturing Global and Local Behavior

Most displacement-based structural finite element models of airplanes used for aeroelastic analysis and design focus on the global behavior of the structure. For a complete configuration such FE models can have tens to hundreds of thousands degrees of freedom, and these will often be reduced to the order of thousands of degrees of freedom when flutter and gust response are considered. Stress models capable of capturing local behavior, such as local stresses in areas of geometric discontinuity, joints, actuator attachments, etc., have to be much larger, with adaptive meshes,[96] which are refined to capture local behavior. If structural behavior of very localized nature has to be captured, structural models capable of capturing such behavior as well as global behavior of the complete vehicle become too large for today's structural modeling technology.

The common practice in structural modeling is to use a hierarchy of models with different levels of detail. A coarse-mesh global model of a complete configuration will be used for load transfer computation leading to internal loads on local parts and segments. These internal forces will, then, be used to load a fine-mesh model of the local component, where detailed geometry and possible imperfection and damage are taken into account. The global/local analyses have to be carried out in some coordinated way to account for local effects on global behavior, and, of course, global force distribution effects on local behavior. Examples include the possible local buckling or interaction buckling[97–100] (Fig. 6) of panels, or any subassemblies, including effect of support stiffness provided by the global structure, crack propagation, and residual strength where global stress distribution and effects of very localized nature are strongly coupled[101–105] (Fig. 6). The case of panel flutter[106–108] is also interesting. Usually focused on the behavior of single panels supported along their edges in some idealized way, an analysis capable of capturing local behavior can account for the behavior of panels and assemblies of panels supported by the actual internal structure of a wing or a fuselage and allowed to respond together to variation in flight conditions (stability) and to sound and boundary layer excitation.

The importance of local effects in predicting the global behavior of nonlinear flows has already been mentioned. Small differences in the radius of a leading edge[93–95] can determine when leading-edge (LE) vortices will develop and what areas of a configuration they will impact. In addition to the B-1 example, an interesting example is that of the horizontal stabilizer of the F-15 fighter (Fig. 7). It was found that a "snag" in the leading edge of the stabilizer led to an increase of flutter speed—an effect not predicted by linear flutter analysis.[109]

A slight inaccuracy in modeling the shape of a supercritical airfoil or the location and shape of a nacelle can have significant impact on the capacity to capture shock-wave motion and shock/boundary-layer interactions. The importance of turbulence modeling in unsteady aerodynamic simulations is well known and is still a subject of intense research and development.

Fig. 7 Dogtooth "snag" on the F-15's horizontal stabilizer. The effect on flutter is not captured by linear theories.

Similar considerations apply to aeroservoelastic analysis, where the level of detail in the modeling of control system components has to be carefully considered depending on the cases analyzed.[110,111] As Refs. 110 and 111 show, different-order state-space models of the same control actuators in a fighter airplane can lead to significant differences in modeled aeroservoelastic response of the complete vehicle. In aerothermoelasticity, where details of heat transfer in the structure, including local modeling of embedded active cooling systems, can affect the accuracy of the system level behavior,[112–114] careful consideration of interactions between local and global effects is also important.

Current numerical capabilities in the structures, aerodynamics, control, and heat-transfer areas and computing power are now at a point where complete vehicles can be modeled and a rich mix of physical mechanisms can be captured to a degree not possible 30 years ago. Yet, the challenge of capturing in a practical, efficient, and reliable analysis and design cycle both local and global behavior across the disciplines as just described is still not met and will continue to drive research and development in aeroelasticity for years to come.

Approximation and Model-Order Reduction

The essence of engineering has always been the capacity to do the best with the most advanced tools and resources available. In the face of the formidable computational challenge posed by state-of-the-art mathematical modeling techniques, aeroelasticity has progressed over the years as a result of the development of engineering approximations methods that made analysis and design practical. Beam models followed by finite element models and modal-order reduction for structural dynamics, strip and modified strip methods for unsteady aerodynamics, followed by correction factor techniques[115–118] for lifting surface aerodynamics all reflect a continuous effort to find the most practical way to advance airplane design, subject to given computation technology resources and theoretical state-of-the-art limitations.

Reduced-basis order-reduction methods, also known as modal methods, have been the key to the success of practical structural dynamic analysis for decades. Substructure synthesis methods[119–126] use mode shapes of modified small substructures of a large structural system to create a reduced-order model of the complete system. In such a method special attention has to be paid to the treatment of interface degrees of freedom, where information is transferred from one substructure to another by local action. In modal methods adapted to problems with concentrated external loads acting on a structure, special reduced bases are used, including Ritz vectors, fictitious mass mode shapes, and combinations of Ritz vectors and natural mode shapes.[127–143]

For flutter and gust-response analysis normal modes of a flying vehicle have been traditionally used. These lead to accurate reduced-order flutter and deformation prediction caused by the distributed nature of aerodynamic loads.

When local stresses are sought, or when concentrated loads are applied, or when local changes are made in the structure in the course of design optimization,[132,133] all modally based reduced-order structural modeling methods are challenged. If a reduced basis is sought that will be capable of capturing local effects in areas of concentrated loads, stress evaluation, and element changes, the need to add base vectors to account for all local effects required leads quickly to reduced-order models that can be quite large. This is a severe problem especially in the case of active control of aeroelastic systems because modern control synthesis techniques are still very limited in the size of the system models they can handle. Such a challenge arises in the case of what is commonly referred to as "smart" structures, where an array of small actuators are either embedded in a structure's skins, spars, and ribs or distributed to act point to point at many locations throughout the structure. Reduced-order bases capable of capturing all important local effects and allowing accurate stress prediction throughout the structure are still the subject of ongoing research.[144,145] As efficient simulation of structural dynamic behavior in large-scale CSM models is sought, improvements in structural order-reduction methods for nonlinear structural systems will continue to be pursued.[146–149]

With the growing power (and model size) of CFD-based aerodynamic models, an extensive research effort was launched in search of practical reduced-order aerodynamic models for static and dynamic aeroelastic analysis and design.[150–186] A number of approaches have been under investigation for more than 10 years now. Inspired by modal order reduction commonly used in structural dynamics, one method seeks to use aerodynamic mode shapes of some linearized CFD solution as a set of base vectors for order reduction. Other methods apply various system identification methods adopted from systems theory to identify a low-order model of the CFD-based aerodynamic system: Volterra series theory and Volterra kernels identified using impulse or step inputs to the fluid system, Kahrunen–Loeve modes (proper orthogonal realization) extracted from the dynamic response of the full-order fluid system when excited by proper inputs, balanced realizations of control systems state-space theory, and other system identification methods based on input–output relations for the system.

Reduced-order model creation in all of these methods is computationally intensive, even in cases involving only a small number of full-order fluid response analyses to a small number of well-designed inputs. Yet, once such reduced-order models are created for a given configuration dynamic simulation of many cases (corresponding to many inputs, dynamic pressures, and initial conditions) is fast and cheap computationally. It is expected that reduced-order aerodynamic methods will see increasing use in industry[58,59,95] as part of the effort to create systems capable of analyzing large numbers of load cases and flight conditions using CFD-based aerodynamics. Issues that will continue to drive research and development include order reduction of highly nonlinear fluid dynamic models, cost of reduced-order model generation, utilization of reduced-order aerodynamic methods in design[187] (where major changes in configurations still take place), reduced-order models for cases involving strong local effects, and the accuracy and reliability of reduced-order models.

An example from a recent study of CFD-based aeroelastic analysis and associated aeroelastic model-order reduction[182] involves an artificially flexiblized mathematical model of a HSCT wind-tunnel model configuration (Fig. 8) tested at the NASA Langley Transonic Dynamic Tunnel. CFL3D and an eigensystem realization algorithm (ERA) are used to create a reduced-order state-space model of the coupled fluid/structure system using a set of impulse responses to individual mode excitation. The resulting model is further reduced using a set of inputs to excite the state-space ERA system and a Kahrunen–Loeve technique to cover the frequency range of interest. Comparisons of coupled full-order simulations at three dynamic pressures (each taking approximately 108 CPU hours on an Origin-3000 computer) to reduced-order simulations are shown in Fig. 9. Generation of the reduced-order model based on four full-order coupled impulse response simulations costs about 1250 CPU hours (312 hours per mode), but that can be done in parallel: one response

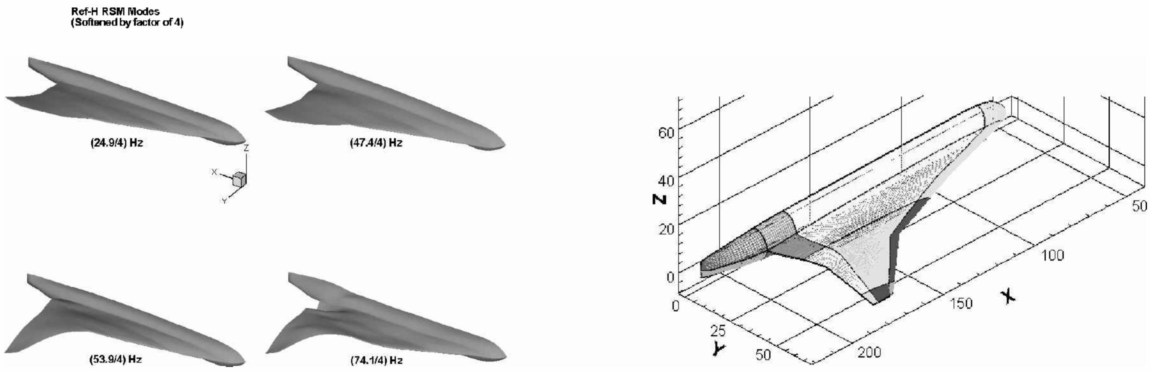

Fig. 8 Structural modes and CFD grid zoning for the HSCT aerodynamics wind.

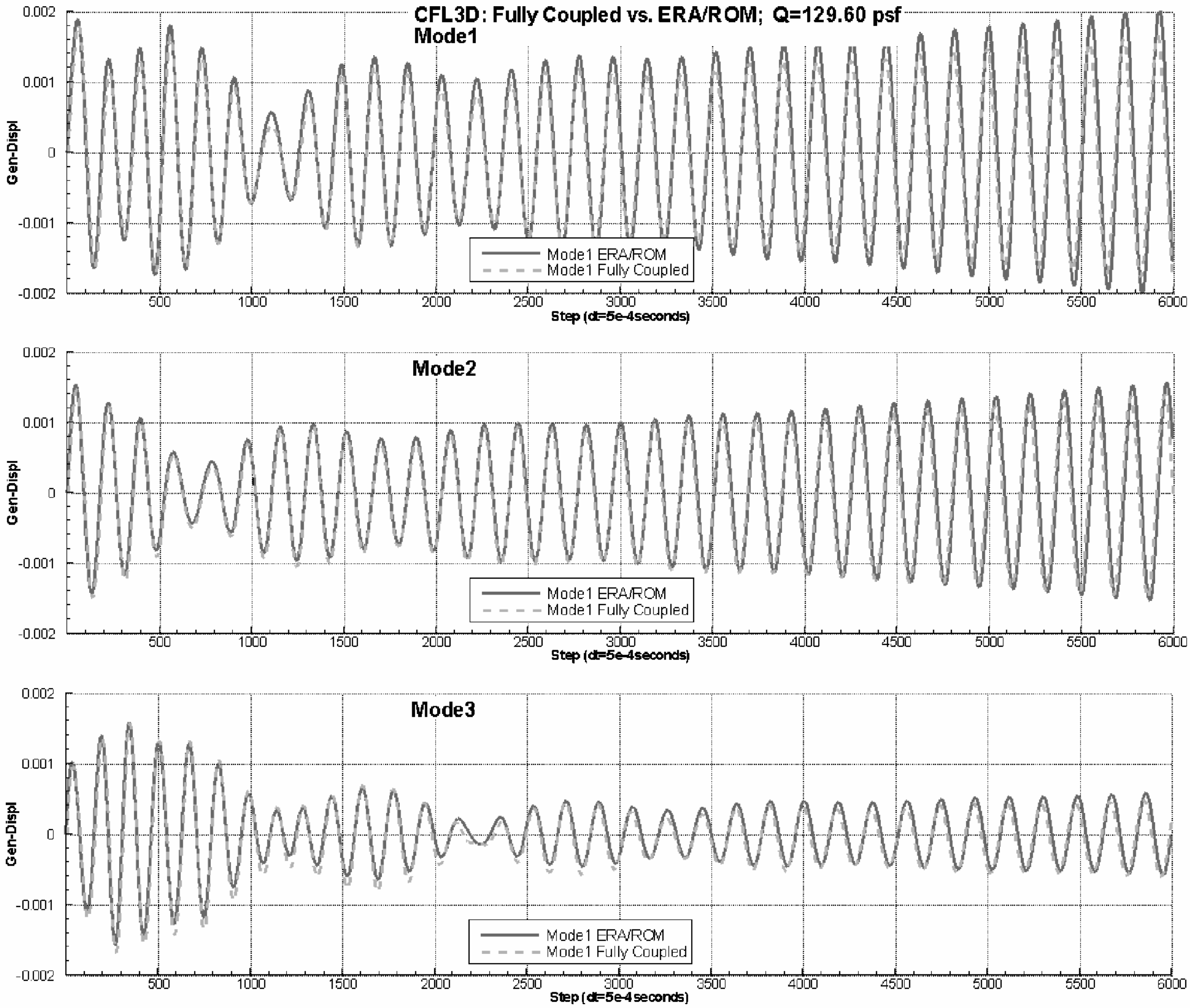

Fig. 9 Comparison of full-order fully coupled simulations with reduced-order simulations for the flexiblized HSCT wing model (Courtesy of Boeing; Ref. 182).

per mode run on a separate processor or set of processors. Once the reduced-order model is ready, a complete root-locus plot generation (that is, running numerous stability analyses for the same Mach number at many dynamic pressure conditions) takes less than 5 min in the case of four modes. When more modes are included in the dynamic model system, matrices become larger, and reduced-order model net preparation time increases. Parallel computation for extracting impulse responses to different modal excitation can reduce the elapsed time considerably. A case involving 20 modes was reduced (using Kahrunen-Loeve proper orthogonal realization after the ERA step) to a state-space model of the order of 80. With that model, generation of root-locus curves (corresponding to increased dynamic pressures) takes less than 20 min. As this case demonstrates, the generation of reduced-order aeroelastic models for CFD-based aeroelastic systems can still be very time consuming. More research in the near future will be directed at finding ways to reduce this cost by improving the system identification process. More efficient system input methods that excite all important dynamics with a few inputs or a single input, more efficient time stepping for the coupled CFD–CSD simulations, and massive use of parallel computation will be some of the areas explored. In the case of methods based on aerodynamic modes, more efficient methods for extracting modes of large-scale systems are needed, and alternative reduced base selection, similar, maybe to structural dynamics methods in which some modes of a related structure are used, needs to be examined. Note that in the case of reduced-order models for nonlinear aerodynamic response extraction of the reduced-order models is much more expensive compared to the linear case. More research is required in the area of nonlinear reduced-order aeroelastic modeling. The payoff, once efficient ROM are developed, is significant.

Aeroelastic Sensitivity and Optimization Using CFD–CSD Models

Aerodynamic configuration optimization has always been the key to successful airplane design. It was only natural that once modern CFD techniques became established a drive to develop CFD-based aerodynamic sensitivities would start and be immediately combined with gradient-based optimization techniques for the design optimization of airplane configurations.

Design-oriented lifting-surface analysis and techniques for gradient-based aerodynamic optimization followed a similar path years earlier. Theoretical results for optimal aerodynamic wing loading and wing design led in the past to the well-known subsonic elliptic wings and their derivatives or to the supersonic oblique wing.[188] It is interesting to note, however, that general numerical lifting surface based aerodynamic optimization, that could be integrated with general structural optimization, focused historically on the easier problem of optimal twist and camber distribution for wings of *given* planforms.[189]

The general planform shape sensitivity problem, where derivatives of aerodynamic pressures and loads with respect to planform changes such as leading-edge sweep,[190] span, taper ration, location and size of control surfaces, etc. are sought, is more difficult because variations in planform shape occur usually in areas of strong pressure gradients (leading edges, hinge lines, etc.) and because aerodynamic mesh motion is involved. Proper meshing of a configuration for planform shape sensitivity studies, mesh deformation, and proper accounting for pressure singularities are then required.

Planform shape sensitivities for general cases involving general three-dimensional lifting-surface configurations are still at the research and development stage with linear lifting-surface theory[191–194] and are extremely important in any development of future aircraft design optimization technologies because of the key role of unsteady aerodynamic linear modeling in aeroelastic and aeroservoelastic analysis and synthesis of practically every airplane—an importance only expected to grow as more comprehensive integrated multidisciplinary design optimization tools (MDO) are developed.[37]

For CFD aerodynamics covering its different levels of fidelity (from full potential, to Euler, to Navier–Stokes), development of aerodynamic sensitivities with respect to configuration shape have been an active area of research for more than 20 years now, and a variety of methods have been used, such as automatic differentiation, analytic differentiation, complex variable methods, direct and adjoint methods, etc. (Refs. 195–218). Similar to previous developments in shape sensitivity of structural systems,[219–224] CFD-based shape optimization has been tackled by differentiation of discretized CFD models (first discretize, then differentiate) or by discretization of differentiated equations of the flow (first differentiate, then discretize).[225–231]

The challenges faced by CFD-based aerodynamic optimization are closely related to the difficulties with CFD-based aeroelasticity. In both cases CFD meshes have to move and deform, and the flow simulation must not deteriorate in accuracy in the face of significant geometric changes of a configuration. Additional issues, such as the computing speed and memory requirements of repetitive analyses and the existence (and "smoothness") of derivatives, are also common. CFD-based sensitivity analysis and shape optimization does not completely avoid the problems encountered in lifting-surface theory along edges of pressure singularity. In such regions, CFD models too require fine meshing and special attention to local details.

From CFD-based aerodynamic shape sensitivities we can now move on to coupled CFD/CSM sensitivities. Coupled structural/aerodynamic sensitivity analysis for static aeroelastic systems and associated static aeroelastic optimization are now progressing from relying on linear vortex-lattice and panel-type aerodynamic methods to the more rigorous, and more computationally demanding, CFD-based methods. The technology will continue to progress from sizing-type optimization, where planform shape is predetermined and only changes in the thicknesses and cross-sectional areas of structural members are allowed, and where the CFD contribution to the aeroelastic analysis and sensitivity is through response to aeroelastic deformation of the configuration. An effort to develop the more demanding shape optimization technology with configuration shape variation (both planform and deformation) and structural shape variation (both sizes and locations of structural members) is currently underway (Fig. 10). Although structural finite element codes with state-of-the-art shape sensitivity and shape optimization capabilities have been widely available for quite awhile, the integration of any aerodynamic, but especially CFD-based aerodynamics, and structural shape optimization capabilities into an aeroelastic shape capability is still a challenging task.

The discussion of progress in aeroelastic CFD–CSM sensitivity and optimization has focused so far on the static aeroelastic problem. The dynamic aeroelastic optimization problem, with sensitivities of nonlinear flutter and aeroservoelastic response to changes in structural and aerodynamic configuration shape design variables, is still in its very early stages of methods development. To carry out coupled dynamic structural/aerodynamic design sensitivity analysis and optimization using detailed nonlinear dynamic structural and fluid models is a formidable problem. The computational resources required for even one dynamic coupled CSM/CFD analysis are significant. Establishing stability boundaries and tracking behavior histories, and then calculating sensitivities of those repetitively, cannot yet be carried out efficiently and is not expected to be practical in the near future. This problem presents a significant challenge to the modern order-reduction techniques already discussed. In most of those order-reduction techniques, a reduced-order model is constructed based on the input–output behavior of a given configuration. For such a reduced-order model to perform well when this configuration gets significantly modified (say, by airfoil profile, sweep, and wing area changes) is still a major research challenge.[187]

Finally, for aerodynamic and structural sensitivity and optimization with shape design variables some parametrization of the shape is necessary. The issue of consistent shape parametrization in the context of multidisciplinary design optimization and the role of CAD-based shape definition is discussed in Refs. 232–234. Future airplane analysis and design system will integrate CAD with FE and CFD modeling and with shape optimization in a seamless way.

"Servo" in Aeroservoelasticity: Active Controls

Discussion in the preceding sections focused on the integration of the classic building blocks of aeroelasticity—the disciplines of dynamics, structures, and aerodynamics. Developments in modern control systems technology have been no less impressive than in the structures and aerodynamics technologies surveyed so far, and, indeed, the field of aeroservoelasticity has been in a state of rapid development in the last 30 years and is expected to progress at a rapid pace. It is now widely accepted that aeroservoelasticity and flight mechanics are tightly connected and that past separation in airplane companies between aeroelasticity and flight stability and control departments cannot be justified any more.[235]

A thorough review of aeroservoelasticity and aeroservoelastic design optimization is presented in Ref. 37 including a substantial bibliography, which will not be repeated here. Aeroservoelastic issues of past nonconventional airplane configurations and potential future vehicles are described in Ref. 43.

The controls discipline covers the technologies of sensing, control law synthesis/implementation, and actuation. The important area of system identification—the extraction of mathematical models of dynamic systems based on controlled actuation and the processing of sensor signals—can be categorized as a separate subdiscipline, or included in the controls synthesis and implementation subdiscipline, as, for example, in the case of adaptive control.

As in the case of classical aeroelasticity, attitudes toward aeroservoelasticity shifted over the years. Beginning with a focus on

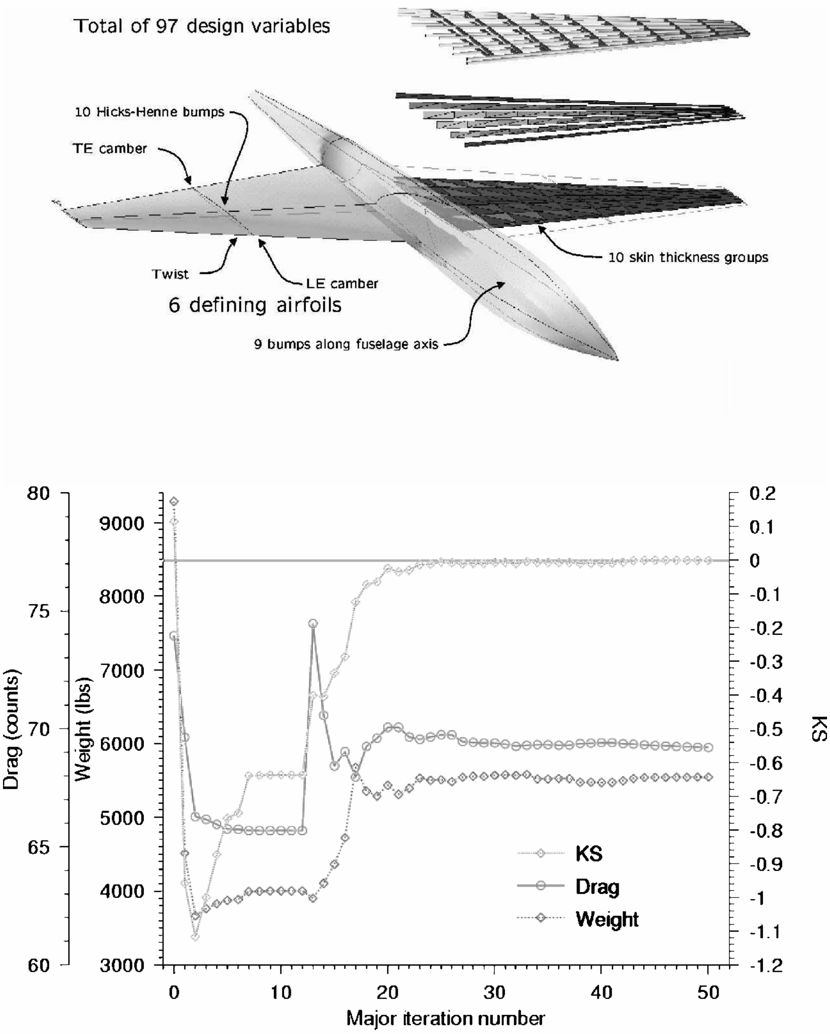

Fig. 10 Coupled shape/sizing optimization with CFD/FE models (Courtesy of J. J. Alonso, Stanford University).

aeroservoelasticity as a penalty—the elimination of undesirable interaction problems by the filtering out using notch filters of control system signals that might interact with structural dynamic/aeroelastic modes, or determining sensor locations on the structure to achieve the same effect—it has now been widely recognized that aeroservoelasticity, if included in the design of a modern airplane from the start, can offer major benefits (Fig. 11). Active control technology can be used to stabilize flight mechanics behavior and reduce, or even eliminate, conventional tail surfaces. Load redistribution and gust alleviation help reduce wing structural weight and improve ride comfort. Flutter suppression can be used to eliminate the structural weight required to prevent flutter, or, when flutter becomes a problem on an existing airplane because of some new external stores configuration, to stabilize the configuration actively.

Although great progress has been made over the years in the capability to analytically/numerically simulate aeroservoelastic behavior on active wind-tunnel models and complete vehicles, it is still a challenge to obtain early in the design process modeling accuracy suitable for controller synthesis. And even when ground-vibration test results for a vehicle are already available, nonlinearities in structures and actuators and inaccuracies in calculated steady and unsteady aerodynamic loads, especially in the transonic flight regime or at high angles of attack, lead to errors in overall damping, frequency, and dynamic response predictions. The problem becomes more severe in the case of airplanes with tightly spaced frequencies: very flexible vehicles where wing frequencies overlap short period or other flight mechanics frequencies, as well as airplanes with external stores or wing supported engine nacelles. In quite a number of recent flight/ride comfort controller syntheses for recent aircraft, final controller design had to be based on an aeroservoelastic model of the aircraft identified by flight tests.

Current challenges in aeroservoelastic controller design and implementation include the need to develop control synthesis techniques for systems with large numbers of inputs and outputs (multi-input/multi-output, MIMO) and with large-order plant models; reliable dynamic modeling of emerging new actuation devices; control strategies for systems that can change dynamic behavior significantly (covering flight at different maneuvers and flight regimes as well as changes in internal and external stores loading); integrated control of "slow" and "fast" behavior (configuration variation for performance improvement purposes as well as flight mechanics, gust response, and flutter control); and, finally, control of nonlinear systems. Integrated control for vehicles where aeroelastic/propulsive interactions might occur, such as thrust-vectored airplanes or hypersonic airbreathing vehicles with underbody engine inlets, is also a considerable challenge. Control of the propulsion system, the inlet, and the engine must now be integrated with the aeroelastic control of the vehicle, both statically and dynamically.

Given the variety of flight conditions and flight configurations as well as uncertainties in the aeroservoelastic modeling of complex actively controlled airplane, adaptive control has a special appeal as a way of building "intelligence" and adaptability into aeroservoelastic control systems that will allow addressing this variability of system characteristics and excitations by a single coherent strategy. Adaptive control was recognized as a promising control technology for aeroelastic application almost 30 years ago. Still, compared to the vast body of literature on theory and applications of general adaptive control, the number of publications discussing aeroservoelasticity is surprisingly small.[236–252] One reason might be the reluctance to accept active flutter suppression as safe enough for implementation

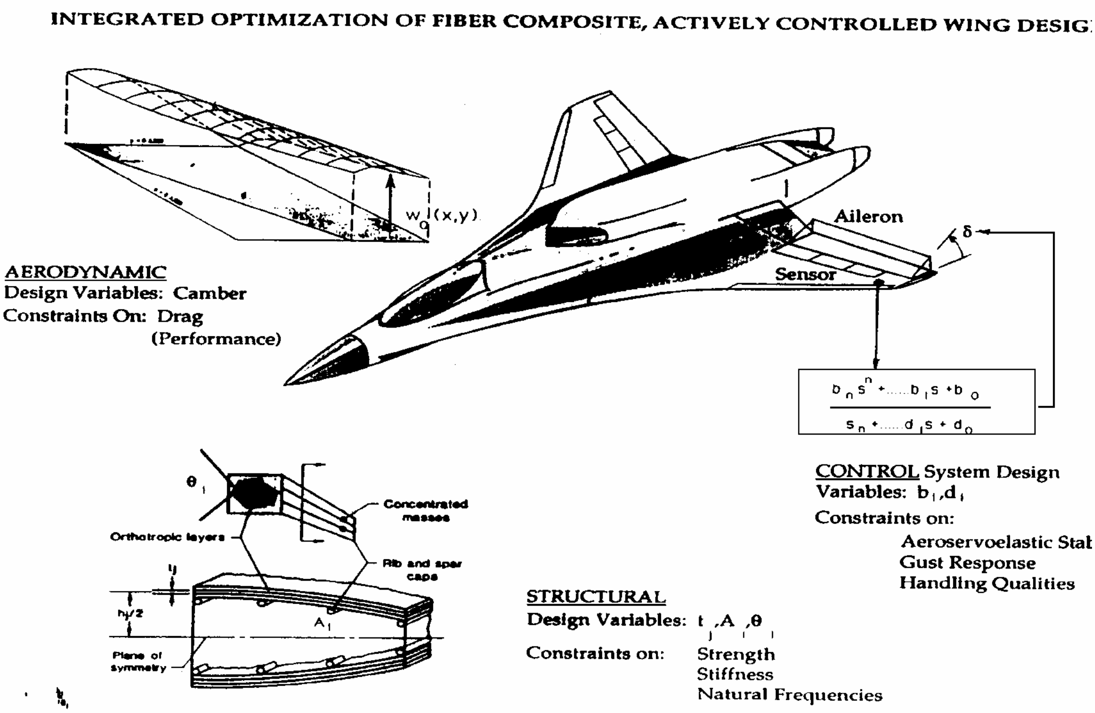

Fig. 11 "Truly" integrated aeroservoelastic optimization.

on actual airplanes. The cost of conducting active control experiments with actual airplanes, or wind-tunnel models representative of the complexity of real airplanes, might be another reason. Recent applications to wind-tunnel models, where neural networks are used for both system ID and control,[248] are encouraging, and, hopefully, development of this technology will be pursued.

Developments in actuation technology and failsafe MIMO control, allowing redundancy and high reliability of aeroservoelastic control systems, might also lead to the acceptance of active flutter suppression as safe and viable. This technology, when combined with load and gust alleviation and taken into account from the early stages of airplane design, will lead to major weight savings and performance improvements in future flight vehicles.

New Actively Controlled Vehicles: Morphing "Smart" Airplanes

Advances in structural materials, structural concepts, methods of actuation, and multi-input/multi-output control systems in the last 20 years are currently motivating research and development of a new type of shape-varying airplanes: the morphing vehicles.[253–288] What it is about these new concepts that goes beyond the shape-varying variable-sweep/variable camber/variable dihedral airplanes of the past with their high-lift flap systems, and what advantages can the new technology offer—these issues are not completely clear and settled yet.

At this point in time, it seems that the new morphing vehicles will employ some forms of "smooth" shape variation for camber and twist control as well as innovative mechanisms for major planform shape, incorporate new actuation technologies (such as those made possible by strain actuators embedded in the structure or strategically distributed modern miniaturized actuators), use active flow control[289–291] to produce desired flow patterns in areas of geometric and flow discontinuities, and rely on powerful high-authority modern control systems capable of adaptation and of controlling and managing many inputs and many outputs (MIMO). It is the distributed nature of sensing and actuation made possible by new sensor, communication, and actuation technologies that allows control with large numbers of inputs and outputs not practical before.

It is also evident, based on emerging literature, that the goal with the new morphing vehicles is to allow major shape variation throughout the flight envelope of an airplane, well beyond what could be achieved by the old variable-shape vehicles. Examples include folding and unfolding of wings, span variation, shape variation of wing-tip winglets, and aerodynamic wing-tip extensions of various types, etc.

Aeroelasticity and aeroservoelasticity together with multidisciplinary design optimization (MDO) will play a major role in the design and analysis of variable-shape airplanes. The integration of structures and materials technology, aerodynamics, sensing and actuation, as well as advanced control, becomes in this case much tighter than ever before. Such technology is a must if the new integrated systems are to be used to their full potential. And it is through such integrated MDO technology that it would be possible to assess the overall advantages and payoffs of morphing.

In the near future it is expected that morphing vehicle technology development will focus on small unmanned aerial vehicles (UAVs). Application to full-size manned vehicles, at this stage, does not seem to be imminent in the near future, except, maybe, in the case of trailing-edge and leading-edge camber variation in areas that are not significant load carriers.

Uncertainty

The need to address uncertainty in the design of any engineering system has long been recognized as a key element of what constitutes good design.[292–339] Uncertainty can arise as a result of incomplete information, errors in both analysis and design models, and the uncertain nature of inputs and system parameters. When subject to inputs of random nature, even a deterministic system responds with randomly varying outputs. When the nature of the system itself is subject to uncertainty (Fig. 12), when the system is one of a set of systems, each different in characteristics, or when the nature of a single system varies with time in an uncertain way, the problem is more complicated.

Measures of robustness of controlled dynamic systems, representing their sensitivity or insensitivity to uncertainty in characteristics and inputs, and the associated robust controls design techniques, have been the subject of significant research and development in the area of control systems and are now widely used.[292–295] Reliability theory for engineering systems is now also well developed.[296–301] The problem of how to address uncertainty in the context of optimal engineering design has been studied for at least 20 years now with different approaches examined,[301–314] including the modeling of sources of system uncertainty as random variables, defined by their statistical characteristics and propagated through the system

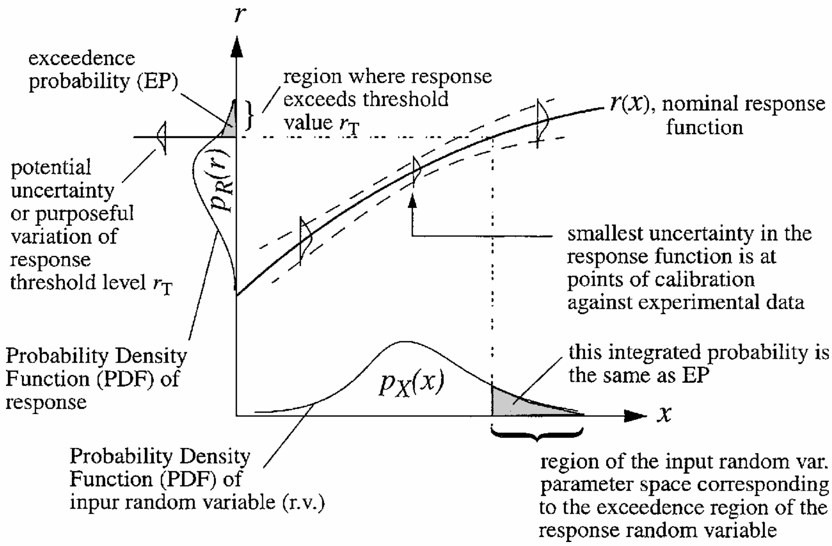

Fig. 12 Uncertainty propagation in uncertain systems (taken from Ref. 313).

to produce statistics of system responses, or, alternatively, modeling uncertainty in system parameters via bounds on their measures and using some form of interval analysis to quantify the resulting bounds on system behavior. It can be argued that in many engineering systems, especially those not produced in mass quantities, it is difficult if not impractical to obtain meaningful statistics of uncertainty sources and that interval analysis, based on bounds on those sources, is more appropriate. Selected publications describing recent developments in the area of uncertainty modeling, analysis, and optimization of complex system can be found in the bibliography[296–301] and can be used to lead the reader to the vast literature on this subject.

In aeroelasticity the traditional approach to uncertainty included a number of elements: careful consideration of all possible flight conditions and loads (supported by extensive analysis, vehicle analysis/test correlation, and by statistics based on extensive testing and on experience with previous airplanes) and the application of generous margins of safety to the resulting design in the form of increased design loads and required sufficient damping well outside the flight envelope; tight quality control of production, and strict maintenance procedures to ensure minimal variability of airplanes of the same model; and, finally, limitations on the operation of airplanes imposed via flight procedures and, more recently, by building limits on airplane maneuvering into the flight control system. The problem of airplane operations outside of maneuvers guiding limits is a serious problem especially in the case of fighter airplanes, whose maneuvering, whether because of aggressive pilot training or of real warfare conditions, is, many times, unpredictable.[324]

Sources of modeling errors and resulting uncertainty in aeroelastic models involve[315–317] unmodeled nonlinearity of the structure (especially in attachments, joints, and control actuators), poorly modeled damping, errors in aerodynamic predictions, variability of material properties (especially in the case of low-cost composite manufacturing), different fuel loadings, variability in stiffness and inertial characteristics of external stores, etc. Variability in aeroelastic characteristics within a fleet of a particular airplane model is expected to grow in the case of low-cost UAVs and in the case of morphing vehicles, unless a deliberate effort is made to reduce this variability. Morphing airplanes, because of the presence of many nonlinear actuators (either as separate components or embedded in the structure), can be subject to changes over time of material, actuator, and actuator attachment behavior. But even conventional airplanes during long years of service might develop damage in composite and other parts of the structure that might affect strength and stiffness.[321,322]

Aeroelastic analysis and design methods for the response to random atmospheric gusts or to runway roughness go back to the 1950s. An interesting study of reliability of aeroelastic panels and shells—a case where random material uncertainties and also random in-plane loading uncertainties affect the dynamic characteristics of panels—is described in Refs. 325–327, and it is quite straightforward to extend the methodology used to the case of complete vehicles. More recently methods developed for control system robustness analysis and design were applied to aeroservoelastic systems.[330–335] μ-Analysis concepts were used to measure the "distance" of an aeroservoelastic system from instability and to optimize aeroservoelastic systems in the presence of major uncertainties in their structural characteristics. In recent studies by NASA,[338,339] uncertainties in wing planform geometry of a prototype wing were "propagated" through a coupled FE/CFD aeroelastic solution to impact the results of integrated multidisciplinary optimization of the wing, where constraints were taken into account by consideration of the probabilities of exceedance of allowed values. The importance of these efforts is not only because of the methods and insights they provide, but also by the demonstration of the growing capabilities of modeling-for-uncertainty analysis made possible by advances in computing power and numerical methods. Progress in uncertainty modeling, based on better understanding of sources of variability in actively controlled future airplanes, and improvement in robust design methods for aeroservoelastic systems have the potential to lead in the future to more efficient, safer designs.

Multidisciplinary Design Optimization

If the potential benefits of emerging sensing, control, and actuation technologies together with emerging "control-friendly" structural concepts are to be materialized, design synthesis tools for complex multidisciplinary aeroservoelastic system must become available, and they must be based on modeling capable of capturing all important modes of behavior on real vehicles.[340–354] Automated design optimization makes it possible to reach efficient competitive designs—a task of extreme importance in airplane technology, where maximum performance at minimum weight and cost are the drivers of practically every successful design. Automated synthesis is valuable often just for the sake of obtaining feasible designs, in cases where the mix of design variables and constraints is so complex that even just a feasible design cannot be found by the intuitive "trial-and-error" methods of the past.

But design optimization offers more than that. When new technologies are emerging, and when it is not yet clear how to use them most effectively, optimization can be used to study tradeoffs in a consistent and rational way and to gain insight and design experience.

For example, future aeroservoelastic design synthesis capabilities should be able to synthesize morphing smart airplanes whose shape in flight is controlled by a mix of conventional and different types of strain actuators. Electrohydraulic or electric actuators can be used to deform certain parts of the structure, whereas strain actuators can deform other areas. "Strong" actuators might be used to change the camber and twist of the main-load carrying box of a wing, while strain actuators (with more limited force and strain capability, but with high bandwidth) can be used to deform the leading and trailing edges in a smooth way. Controlled deformation can be achieved using active spars and ribs (with actuators in the flanges or aligned along the diagonals of truss-like webs) in combination with active skins. Even articulated control surfaces might be improved by using conventional actuation of the large rotations on their hinges plus controlled deformation of the surfaces through strain actuation of their skins (both low frequency and high frequency).

The goal should be to learn what constitutes a best practical approach to the design of adaptive airplane structure given the strengths and limitations of different actuations technologies and different structural concepts.

To study the potential and limitation of new actuation technologies for full-scale airplanes, future design synthesis capabilities should include a comprehensive set of constraints on all important behavior entities and possible failure modes. Stresses (static and dynamic), deformations, fatigue and local failure of the actuator patches, power requirements and the resulting weight and cost of amplifiers, circuits, and control system required, etc. should be taken into account in addition to aeroelastic constraints on stability, dynamic response, structural integrity, shape, and aerodynamic performance.

Is there a preferred mix of control devices and structural concepts that will lead to best weight/cost/perfomance? Only a general analysis/synthesis/optimization capability that covers all practical constraints and performance measures and can capture with good accuracy the behavior of real adaptive structures (including sensitivities) can provide the answers.

The problems with development of such integrated aeroservoelastic synthesis capabilities are significant. Analysis modules representing different disciplines must communicate in a seamless way in an environment that allows modularity. Careful attention must be paid to the definition of the synthesis problem: objective or objectives, constraints, design variables. Uncertainty must be taken into account in a realistic but not overconservative way. Local and global effects must be accounted for. For example, to extend the life of old airframes active control can be used in a load alleviation mode to reduce the stresses in parts of the structure determined by inspections to be more sensitive from a damage tolerance perspective. This requires dynamic simulations capable of capturing global behavior as well as crack growth in the presence of active control.

The main problem, however, is the high computational cost of a single integrated aeroservoelastic analysis. If emerging high-fidelity simulation is used (in the form of coupled Navier–Stokes/advanced finite element for nonlinear response analysis and sensitivity analysis in the time domain), just a single set of analyses covering a number of flight conditions and load cases takes days to solve on the most advanced computers available today. Even when linear aerodynamic modeling is used, the computational cost of detailed analyses is such that only a small number of analyses can be carried out with practical computational resources.

In structural synthesis[220,224,355,356] this had led to the development of approximation concepts, where a small number of detailed analyses along the optimization search path is used to create computationally "cheap" approximations, and it is these approximations that optimization algorithms will use for the thousands and tens of thousands of system evaluations they need.

Given the formidable computational cost of high-fidelity aeroservoelastic analysis, it seems that an approximation-concepts based optimization strategy will continue to dominate airplane design optimization for years to come and that continued efforts in the area of model order reduction, sensitivity analysis, and approximation techniques, together with improvements in computer performance and parallel processing will lead to significant improvements and growing power of such methods.

Nonconventional Configurations

Aeroelasticity should be examined against the panorama of aviation history, by following the stories of nonconventional configurations of the past that challenged aeroelasticity, and the challenging nonconventional new configurations made possible by developments in aeroelastic technology. A thorough review of aeroelasticity and its role in the development of new airplanes of the past, as well as discussion of aeroelasticity of emerging new configurations, can be found in Ref. 43.

Swept-back wing jets with underwing engines (Fig. 13), T-Tail configurations, swept-forward and oblique wings, flying wings, supersonic transports and bombers such as Concorde and the B-70, the hypersonic SR-71 and X-15, control-configured vehicles, such as the F-16, high-aspect-ratio sailplanes and human-powered vehicles, structurally "tailored" fighters—the list of airplanes that saw significant aeroelastic interactions and made an impact on aeroelastic technology is long and rich.

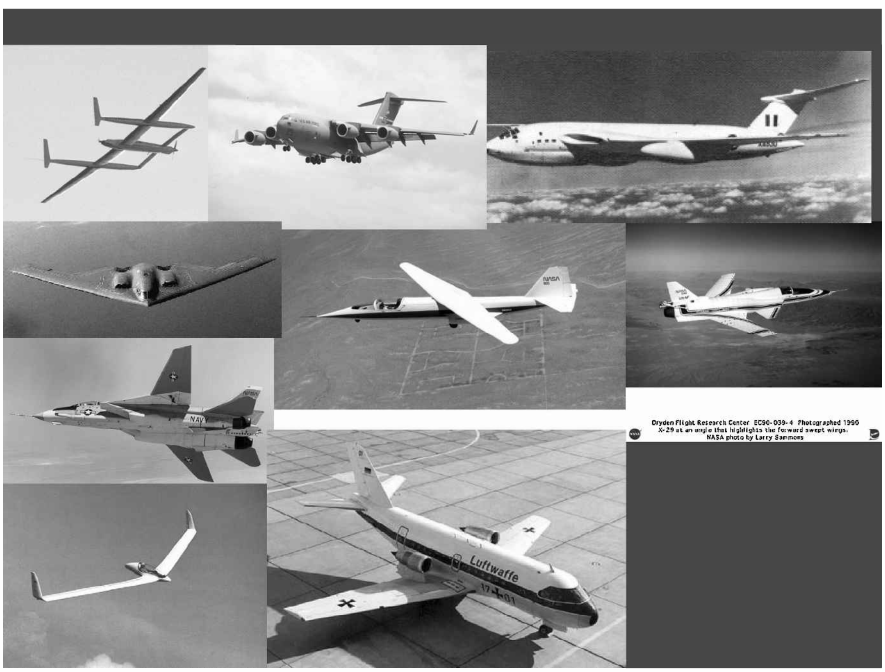

Fig. 13 Past nonconventional configurations (see Ref. 43).

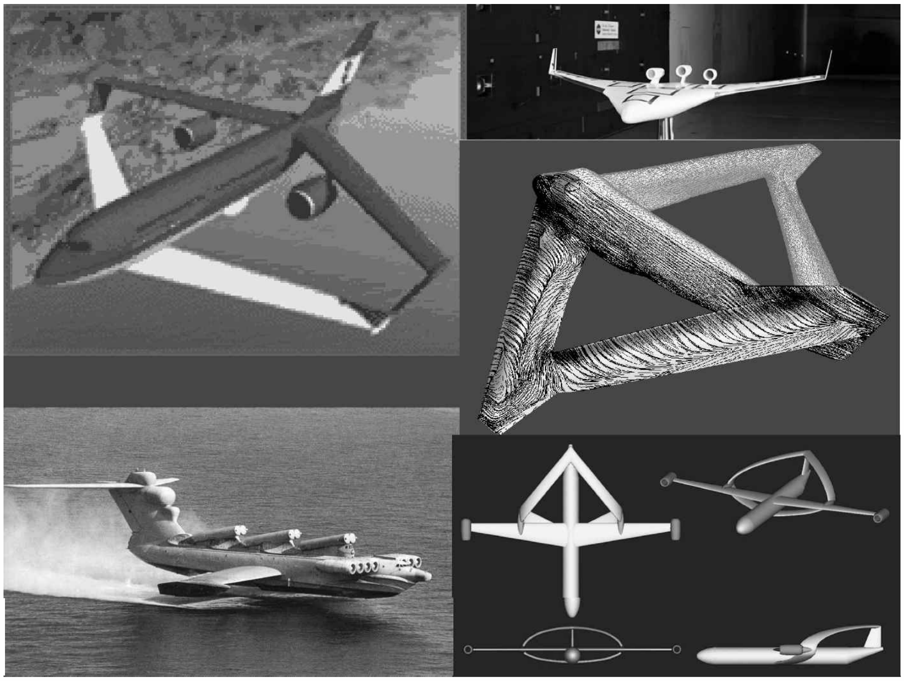

Fig. 14 Selected new potential configurations, from top right clockwise: Boeing Blended-Wing-Body, Boeing-NASA Joined-Wing, Virginia Tech strut-braced/Joined-wing, Wing in Ground Effect vehicles (past Russian design): Lockheed-Martin Box-Wing concept.

An examination of emerging new configurations[357–359] promises to make the aeroelastician of the future no less professionally challenged than the aeroelastician of the past. A number of configurations in various stages of research and development merit a brief mention here (Fig. 14).

Nonlinear aeroelastic effects caused by control-surface free play, several types of nonlinearities at joints, hinges, and fold lines, actuator nonlinearity, dry friction, stall, shock-induced separation, shock oscillation, and vortex motion are well known and have been the subject of research for years[41] with rapid progress in recent years as a result of the growing power of nonlinear structural/aerodynamic simulations. It has also been known that panels subjected to in-plane loading exhibit nonlinear aeroelastic behavior. Helicopter rotors—long beams subject to large deformation and inertial effects of rotation—are notoriously nonlinear.

Recently,[155] nonlinearity caused by large deformation of simple model delta wings and high-aspect-ratio fixed wings was demonstrated both analytically and experimentally. With highly flexible, structurally efficient wings of airplanes such as the large Airbus A380, structural geometric nonlinearity of the aeroelsastic behavior of such wings might become important, and we might soon see airplanes whose dynamic characteristics vary in flight with each maneuver depending the large deformation it introduces.[63] Such behavior has been identified in simulation studies of high-altititude/long-endurance UAVs. Similarly, in the joined-wing and strut-braced wing configurations[67,68] major wing or tail sections can be subjected, depending on the maneuver, to axial compression. Such components can become buckling critical; and if design optimization drives them to be as efficient as possible (that is, away from buckling only within small margins allowed) effective stiffness, natural frequencies, and aeroelastic behavior will change with maneuver loading, nonlinear aeroelastic behavior will have to be addressed in the design process from the start, and the whole process of flutter clearance and certification can become more complicated and costlier. Unmanned combat aerial vehicles (UCAVs) of the future, if designed for high maneuverability and high load factors, can exhibit nonlinear behavior of their wings under the loads in extreme maneuvers.

Current UAVs, emerging, and future UAVs cover a wide range of configurations to perform the multitude of different missions for which UAVs are developed.[357] Long-endurance/long-range UAVs have highly flexible high-aspect-ratio wings. UCAVs, currently in various stages of development, are compact, with low-AR wings and blended wing/body configurations for high maneuverability and low radar cross section. Small UAVs designed for quick assembly and launch in field conditions come in many shapes and form. Packaging requirements lead to configurations with hinges, joints, and fold lines, where nonlinear effects and variability from vehicle to vehicle (even the same vehicle at different deployments) contribute to uncertainty.

Such uncertainty can be expected in typical configurations of the Mars Plane, now under development for NASA. This vehicle has to be packaged into the spacecraft that will carry it to Mars, then unfold and lock into its flight configuration for the Mars surveying mission. Discussion of structural and systems aspects of future airplanes from general aviation airplanes, through subsonic and supersonic transports and up to hypersonic vehicles, can be found in Refs. 358 and 359.

Frontiers of Flight—Supersonic and Hypersonic Vehicles

With the elimination of Concorde service by Air France and British Airways, the first age of supersonic commercial flight comes to an end.[360–374] Repeated efforts to design a modern supersonic transport all ended without commitment to the construction of an actual vehicle. Technology in a number of areas, including propulsion efficiency, emissions, noise, and sonic boom, was deemed not ready for implementation in an economically viable way. In the structures area, although major progress had been made, the drive to reduce structural weights and a host of aeroelastic problems fueled intensive research and development effort, which, in turn, is already making an impact on the design optimization of other airplanes.

Efficient supersonic airframes have thin, low-aspect-ratio wings, connected to a long and slender fuselage along a long root. This leads to strong structural dynamic coupling between fuselage and wing motions. Engines nacelles, placed toward the rear of the wing, can affect flutter unfavorably. Outer-wing aileron (or elevon) effectiveness suffers because of the low torsional stiffness of the thin outer-wing section, unless the structure is stiffened. Vibration levels along the fuselage, and especially in the cockpit, can affect ride comfort and handling qualities negatively. If Mach numbers above 2 are sustained during cruise, aerodynamic heating plays a significant role, and aerothermoelasticity will drive material selection, structural layout, and structural sizing. Future supersonic transports are expected to rely heavily on active control for static and dynamic

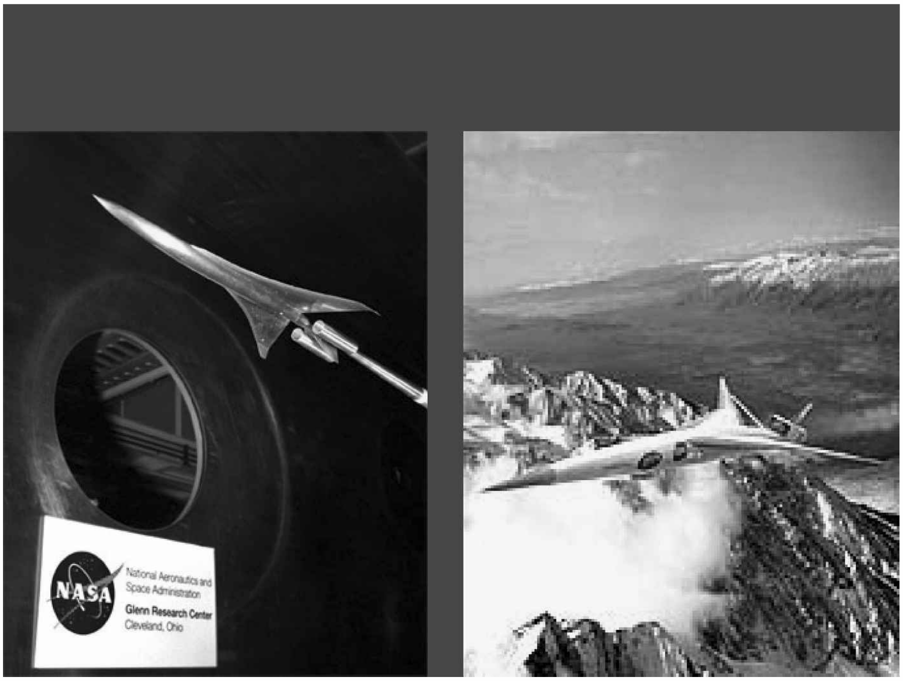

Fig. 15 Quiet supersonic platforms (NASA and Northrop-Grumman).

load alleviation, configuration shape control [for optimal lift-to-drag ratio (L/D) in flight], and ride comfort. Current work on quiet supersonic platforms[373,374] (Fig. 15), driven by funding from Defense Advanced Research Projects Agency and the examination by a number of aircaft manufacturers of the economy and markets for supersonic business jets, has led to the emergence of a number of new "quiet" configurations, with long and slender fuselages, and engines mounted either to the sides of the back of the fuselage or on top of the fuselage. Acoustic fatigue, for airframe panels or control surfaces subject to engine exhaust noise, becomes an important design consideration in such cases. In one of the configurations studied by Northrop–Grumman, a joined-wing concept is used, and joined-wing aeroelasticity, as just discussed, will be important.

The design of future efficient supersonic transports, large and small, will depend heavily on coupled CFD/CSM high-fidelity modeling, multidisciplinary design optimization, and integrated aeroservoelastic synthesis of structures, controls, and aerodynamics simultaneously.

Interdisciplinary coupling becomes more complex and the need to advance the state of the art in aeroelasticity more urgent in the case of hypersonic vehicles development.[375–402] The harsh thermal and loads environment in which hypersonic vehicles operate is a challenge to structural technology, where thermal effects affect material selection, structural layout, and cooling methods. Accurate prediction of stiffness variation (both global and local) caused by temperature and thermal stress effects on material property and effective stiffness, respectively, must be combined with accurate steady and unsteady aerothermodynamic analysis. Thermal inputs to the structure affect deformation of the vehicle. The resulting changes in the flowfield lead to changes in thermal inputs to the structure. In airbreathing configurations with engine inlets located under the body, and where the forward part of the body is used as the ramp that leads air into the inlet, any deformation of the body results in perturbation to the inlet airflow. A propulsion-aeroelastic coupling develops and must be accounted for when overall aeroservoelastic analysis and design of the vehicle are carried out. Typical hypersonic vehicles also have to operate subsonically, transonically, and supersonically. Their aeroelastic and aeroservoelastic design must cover a wide range of flight conditions, where different instabilities can occur, depending on Mach number and dynamic pressure, and also the weight of the vehicle as it encounters a new condition. Typical lifting-body or winged lifting-body configurations require unsteady aerodynamic and aerothermodynamic analysis tools capable of accurately simulating the flow around such vehicles throughout their flight envelope. A research effort to develop CFD/FE-based aeroelastic analysis and design technology for reusable launch vehicle is currently underway, funded by NASA and the U.S. Air Force.[398]

Micro-UAVS and Flapping Flight

"Biologists have studies bird and insect flight empirically for quite some time. One thing is clear. . .all these creatures use two specific mechanisms to overcome the small-scale limitations of their wings: flexibility and flapping."[403] It was recognized early in the history of unsteady aerodynamic theory development for flutter analysis that the same theory could be extended to address the problem of flapping flight.[404] Mankind's fascination with flapping flight had not been abated even after a 100-year history of powerful and successful airplanes. The desire to design and build flapping wing flight machines led to the development of a number of toy airplanes and to a quarter-scale proof-of-concept ornithopter, which flew successfully in 1991.[405–408] This was followed by the development of a full-scale engine-powered human-carrying ornithopter.[409,410]

Aeroelasticity plays a crucial role in the analysis and design of flapping-wing vehicles. A number of developments in areas of aeroelasticity have to be integrated to create analysis and design tools for flapping flight. These include unsteady aerodynamics of wing thrust and drag production, unsteady aerodynamics of attached and separated flows, aerodynamics of low Reynolds airfoils, coupled nonlinear structural dynamic/nonlinear aerodynamic aeroelastic equations in the time domain, and optimization of flapping frequency and flapping motions phase and amplitude relations for maximum efficiency and minimum power.

Using miniature powerplants, mechanical drives, electronics, and instrumentation, and construction technology for miniature structures, it has now become feasible to build very small UAVs for a variety of intelligence, observation, surveillance, communications, and detection missions. Many configurations of micro-UAVs have been developed[411–417] or are at different stages of development, including vehicles with membrane wings. Analysis challenges include modeling the low-Reynolds-number unsteady flow, structural modeling for miniature structures, coupling of CFD and FE equations, and the generation of well-behaved grids capable of adapting to large motions and significant deformation. The area of micro-UAVs is currently a very active area of research and development, where aeroelasticity is expected to play a significant role.

Testing

Structural dynamic testing of scaled models and full-size vehicles, followed by aeroelastic tests in the wind tunnel and in flight[418–472] will continue to be an essential part of the science and practice of aeroelasticity. It is not expected that mathematical modeling in the foreseeable future will reach levels of accuracy and reliability that will deem testing of actual systems unnecessary. Sources of error in the structural modeling include damping effects, stiffness variation with loading and temperature, unmodeled or poorly modeled nonlinearities of joint and actuator behavior for some loading cases and operational environments, material degradation, manufacturing and maintenance tolerances, and local effects not captured by the meshing and modeling used in mathematical models. Even though major progress has been made in CFD simulations of complex flows and the frontiers of aeroelastic numerical simulation are constantly being expanded, practical reliable implementation, capable of capturing all important mechanisms of flow unsteadiness and flow/structure interactions, is still years away.

Examination of the current state of the art in ground and flight testing in light of its state of the art 30 years ago reveals major progress in instrumentation, communication, computing power, and associated system identification methods. As we look to the future, we can expect continuous improvement in all of these elements of testing technology. New sensors, miniaturized and accurate, will be available for distribution in the structure in large numbers to measure motion, stress, temperature, damage propagation, and local changes in stiffness. Their outputs, transmitted wireless or by thin fiber-optic wires, will reach powerful onboard and ground computers, capable of real-time accurate identification of large-scale MIMO systems. New actuators, structural and aerodynamic, will be used in large numbers (if necessary) to excite all important dynamic behavior modes. Noninvasive measurement technology, based on photogrammetry or other optical methods,[441–448] is already making an impact on small-model structural dynamic and aeroelastic tests and will continue to be improved.

In the context of increased emphasis on uncertainty modeling and reliability-oriented approach to aeroelastic flight envelope clearance, advances in testing techniques for experiment-based uncertainty estimation are expected to continue.[315–317,330,334,335,468] Such efforts also focus on the uncertainty and repeatability issues introduced by the testing itself.

With improving wind-tunnel testing technology for unsteady aerodynamic testing and the growing flexibility in model design made possible by morphing smart structures concepts, the direct measurement of unsteady aerodynamic loads on models that deform to simulate vehicle motion in particular modes of interest becomes possible.[449] So far, unsteady aerodynamic tests were limited to cases where wind-tunnel models are oscillated in rigid-body motion or rigid control surface rotation on its hinge. But recent tests of smart wings with smoothly varying camber suggest that we might not be too far away from an unsteady aerodynamic testing technology equivalent to the established modal testing for structural dynamics. That is, enough information from unsteady aerodynamic tests will become available to "calibrate" CFD models, or to even carry out flutter analysis directly with measured aerodynamic matrices. This should not be confused with aeroelastically scaled model tests. Deforming models whose shape of oscillation can be controlled do not have to be scaled structurally and inertially to simulate the actual vehicle. They only have to be capable of executing motions that simulate the motion of the actual deformable vehicle. A recent effort to examine direct identification of unsteady aerodynamic loads is reported in Ref. 451.

A number of significant challenges still remain in the area of ground and wind-tunnel testing. Proper scaling laws must be developed for actively controlled vehicles, hypersonic vehicles, and vehicles like the joined-wing and strut-wing configuration, where internal stress distribution has to be captured for both component buckling and aeroelastic instability simulation.[11,23,67,68,249,433] Even in the case of unsteady subsonic flow at high angles of attack, we should remember, proper scaling of wind-tunnel models and extrapolation of wind-tunnel test results to flight Reynolds numbers is not trivial.[430–432] Wind-tunnel wall effects must be accounted for,[182] as well as support conditions in ground-vibration and wind-tunnel tests. Support conditions are especially important in cases where vehicle structural frequencies are low and some form of rigid-body-motion structural dynamic interaction is expected. Model design and cost and test cost must be reduced through automation, data processing, and system identification improvements.

The following quote from Ref. 457 expresses the essence of the state of the art in flight flutter testing:

> Even in the days of high speed computers and sophisticated data measurement and analysis tools, flutter testing remains as much an art as a science. Subcritical damping data cannot always be safely extrapolated to obtain an accurate prediction for the flutter velocity. Nonlinearities in the control system or in the aerodynamics and structures of an aircraft can critically affect the aeroelastic behavior. Finally, the aeroelastic stability can change from positive to negative with an increase in air speed of only a few knots, and the whole procedure is very dangerous and time consuming.

Despite major progress in excitation techniques, instrumentation, data processing, and system identification technology, flutter flight testing is still dangerous, time consuming, and expensive, and it is expected to motivate research and development for years to come.[452–472] In the case of hypersonic flight, expanding flight envelope clearance into the hypersonic range is promising to be challenging. The problem is especially severe in the case of launch vehicles, where flutter tests might not be feasible at sustained critical conditions the vehicle can only pass rapidly along its trajectory.

A final note is in place here to connect adaptive control to the state of the art in flight flutter testing. The challenge that nonlinearity, noise, and uncertainty present to the accurate identification of an aeroservoelastic system in flight is also a challenge to adaptive control, where control law evolution depends on reliable identification of the system. Active control and flutter flight testing, then, are tightly connected, and advances in one can immediately affect the other.

Science of Aeroelasticity

It is easy, when the future of aeroelasticity is considered, to be captivated by the complexity of future flight machines and the technological developments required to address that complexity. As Ref. 43 shows, great discoveries and great contributions in aeroelasticity were made through the work on real airplanes. Compared to the thrill of testing real, full-size, airplanes and applying the most powerful computational tools available to analyze them during a massive design effort, the careful, methodical, meticulous work of basic research seems uninspiring, even boring.

Yet, it is this basic research that creates the foundation of a discipline, sheds light on the physical processes involved, brings clarity to confusing situations, and builds the analytical and numerical concepts that will later grow to become production tools. It is basic research, with the simple test systems it focuses on, that lays the foundation for national and international collaboration. Such simple test systems—benchmark systems—fully described in scientific publications make it possible for researchers all over the world to duplicate reported results and test their own simulations. Benchmarking is extremely difficult, if not impractical, when it comes to the detailed aeroservoelastic systems industry works with. The proprietary nature of actual airplane models together with the complexity and potential for inconsistency and confusion make such models not very useful for scientific work, nor are they necessary.

In universities, industry, and government research organizations basic research in aeroelasticity, aeroservoelasticity, aerothermoelasticity, flight mechanics, and MDO will continue to advance the state of the art. New generations of aeroelasticians will be educated and trained using simple systems and manageable test and computation challenges that capture the essence of the field.

A few, out of the many excellent basic research contributions to aeroelasticity worldwide, are mentioned here.[473–483] With low-cost aeroelastic models of composite wings and a small wind tunnel at the Massachusetts Institute of Technology in the early 1980s, a series of flutter and stall-flutter tests on tailored forward-swept wings were carried out.[473–475] At Duke University, using a dedicated wind tunnel and a series of low-cost models of two-dimensional sections-control surface combinations and three-dimensional low-aspect-ratio and high-aspect-ratio wings, fundamental mechanisms on nonlinear aeroelastic behavior were studied, including active control in the presence of nonlinearity.[476–479] Similar tests on nonlinear aeroelastic systems were performed at Texas A&M.[480,481] NASA at the Transonic Dynamic Tunnel at Langley Research Center has contributed to the science of aeroelasticity by a number of carefully designed and planned benchmark tests to study unsteady aerodynamics, aeroelasticity, and active control. What is common to all of these basic research efforts is the carefully documented details of the test equipment and test results and studies of test/analysis correlation. Those will serve for years to come to help researchers. Basic research, of course, is not only experimental. Similar basic research contributions in the areas of computational structures and fluids technology start with simple models, whose simulation can be repeated by researchers and which serve for the testing of new numerical techniques. The future of aeroelasticity depends on basic research.

Practice of Aeroelasticity

Even with the well-established linear aeroelastic analysis and test methods for modern airplanes and even if we assume that those are sufficient, industry still struggles with the long cycle time it requires to create aeroservoelastic models and use MDO for truly integrated design. Its capacity to bring aeroservoelasticity to the early stages of the design process, where it can make an impact, is still very limited.

The challenge is more formidable when the need for strict modeling fidelity is recognized, and, when, as a result, large-scale FE and CFD computations are required. State-of-the-art FE/CFD modeling is a must when it comes to new configurations that expand the frontiers of flight. Nonlinear CFD must be used for performance (L/D, etc.) and aeroservoelastic stability and response predictions in the transonic regime. High-supersonic and hypersonic flight of lifting-body, wave-riders, and other configurations requires CFD simulations capable of capturing flowfields around complex configurations in extreme flight conditions, involving strong shocks, heat transfer, as well as chemical and electromagnetic reaction. Detailed CFD/FE modeling is also required in the design of quiet supersonic platforms,[374] or, for flow and structural stress simulations at high angles of attack, under stall and buffeting conditions.

To create the engineering environment that will allow rapid model generation and multidisciplinary design optimization early in the airplane design stage, industry will continue to invest in methods development.[484–499] Progress in a number of areas is required. CAD models must be parametrized for MDO application from the start and integrate seamlessly with structural and meshing capabilities for the different FE and CFD solvers that can serve as industry standards. A mutidisciplinary-design-optimization system must be modular and allow quick replacement of any contributing module by another module performing the same tasks.[491–493] This goes to the heart of aeroservoelasticity, where structure/flow interfacing is a fundamental building block, and proper integration of sensors, actuators, and controllers is the key to successful aeroservoelastic simulation and design.

Parallel computation and methods of complex-system project planning should be used for breaking the design process into optimally scheduled tasks. Communication between departments representing different disciplines should be improved, and a culture change must take place, where members of a design team understand and contribute to the multidisciplinary design effort. To accelerate model generation and automate those parts of the modeling process that follow clear practices and rules, knowledge-based engineering systems[494–499] should be developed.

One of the most difficult problems industry faces in the course of design and certification of a new airplane is the large number of load cases that have to be considered,[488,489] and, in the case of fighter/attack aircraft, the large number of external stores combinations they carry.[500–502] Thousands of loads cases have to be considered in design, covering flight loads in all possible flight conditions, weight distribution changes, ground loads, thermal inputs, etc. In the case of actively controlled airplanes, changes in the control system done late in project development to improve handling qualities or for other reasons can throw the whole loads/fatigue design work into question. Pilot action and control system dynamics, coupled with the dynamics and aerodynamics of the airplane, affect its maneuvers, and, hence, its deformations and stresses.[324] Another important problem, not usually discussed in aeroelasticity publications, is the evaluation of mass properties early in the design stage and creating an inertia model, which represents with good accuracy the inertia distribution of the final airplane.[503–508]

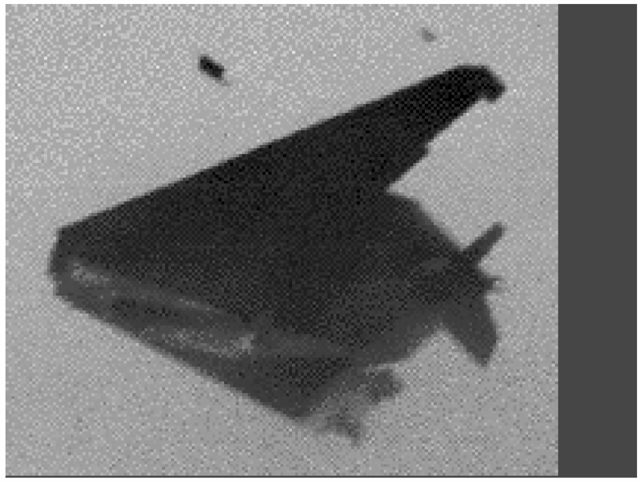

Fig. 16 Elevon flutter accident on the F-117 (1997).

An efficient design environment of the future must include tools for addressing the multiple-load-cases problem reliably and rapidly. Parallel computing and careful planning must be employed. To deal with the enormous amounts of information generated by such processes, advanced scanning and visualization tools must be and will be developed. The goal in the next few years should be reduction of design cycle times from months to weeks and better integration of all disciplines involved in airplane design.

Control-Surface Flutter

Control-surface flutter (Fig. 16), sensitive to actuator stiffness, damping, and control-surface mass distribution, is one of those problems that runs the risk of being considered minor and secondary in the excitement of developing new configurations. Yet, unfortunately, it has a major presence in the history of aeroelasticity and can be a major source of aeroelastic problems in the future if not addressed carefully. The problem is not limited to old articulated control surfaces. The design of new smooth controls and compliant structures must strike a balance between enough stiffness to prevent local softness (that would couple with the wing to produce instability) and enough flexibility that would allow small actuators to achieve sufficient camber changes for aerodynamic control. It is important to continue paying close attention to actuators, control surfaces, and any part of the structure they move. The local structural effects and aerodynamic effects of controls' motions will continue to play an important part in aeroelasticity in the future.

Conclusion

Today, 30 years after the development of airplanes like the F-16, 40 years after Concorde, and almost 50 years after the appearance of the swept-back jet transport airplane, the generation of aeroelasticians who brought aeroelasticity to its current advanced state is retiring or already retired. A major effort (when we think about the future of aeroelasticity) should be made to preserve the "art" of aeroelasticity—that body of knowledge, skill, and creative mastery shaped by extensive experience. Documentation of aeroelastic experiences and their lessons should be encouraged. Test cases, accessible in terms of the resources they need to duplicate and work with, should be prepared for students in the field. These cases should cover all major phenomena and problems, and, ideally, allow for simulation/test correlations. Government and industry should continue to support education and offer internships. The present paper and its companion papers[36–45] are part of this educational effort. The paper includes a selection of references covering all of the contributing disciplines in the field of aeroelasticity. These references should be used as guides to more extensive bibliographies by readers interested in particular areas.

The present paper did not discuss computational aeroelasticity and nonlinear aeroelasticity in detail. These areas are covered well by recent review articles. The list of topics discussed in this paper includes a "taste" of frontiers of numerical simulation, modeling for capturing local and global behavior, order reduction of large FE and CFD models, sensitivity analysis and coupled structures/aerodynamic optimization with FE/CFD models, aeroservoelasticity and aeroservoelastic optimization, morphing, smart airplanes, accounting for uncertainty in aeroelastic analysis and design, multidisciplinary design optimization, aeroelasticity of selected future nonconventional configurations, aeroelastic challenges associated with supersonic and hypersonic flight, as well as aeroelastic contributions to flapping flight and micro-UAVs. Developments in ground and flight testing were discussed, followed by sections dedicated to basic research—the science of aeroelasticity—and to the practice of aeroelasticity—aeroelastic clearance schedule, cost, and reliability in airplane design. It is impossible to thoroughly cover aeroelasticity and its derivative areas in a single paper. Hopefully, readers will find this paper useful and become motivated to further explore this rich and exciting field.

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