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Renaissance of Aeroelasticity and Its Future

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Introduction

THIS paper is motivated, to some extent, by a review paper written by Ashley,[4] in which he stated:

> Study of the February 1970 review article has confirmed the authors conviction that, in the intervening period, the field of aeroelasticity underwent a rather gradual evolution. Most of the statements and conclusions therein are, consequently, believed to have retained their validity and timeliness. During those 15 years the flow of relevant publications increased, as it has in nearly every engineering discipline. Novelty and quality have not grown in proportion to numbers, alas, and someone updating has to be very selective when choosing topics for emphasis and literature for citation.

The impression gleaned from this quote is that aeroelasticity is a mature field and not much exciting research has taken place in the period covering 1970–1986, and that even less remains to be done.

This impression is somewhat inaccurate because it was influenced by the research interests that were emphasized by Ashley[4] and focused primarily on fixed-wing aeroelasticity. In fact, during this time period, several major advances have taken place in rotary-wing aeroelasticity, such as the understanding of the basic flap-lag instability; the recognition that the rotary-wing aeroelastic problem is inherently nonlinear because of moderate or large blade deflections; the fundamental mechanism of coupled flap-lag-torsional instability in hover and forward flight was clarified; the correct numerical treatment of equations with periodic coefficients that play a key role in the rotary-wing aeroelastic problem in forward flight was established; the fundamental understanding of the coupled rotor–fuselage aeromechanical problems in hover and forward flight was developed; tilt-rotor aeroelastic problems were considered; and methods for active control vibrations in helicopter rotors were formulated for the first time.[43] Another area that has undergone major advances in this period is the area of turbomachinery aeroelasticity.[40] In this area the most important advances during this period were the recognition that the bending degree of freedom plays a critical role in the computation of aeroelastic stability boundaries of fan and compressor blades, and that previous aeroelastic analyses based on a single-degree-of-freedom torsional model had to be replaced by coupled bending-torsion analyses; the role of mistuning was clarified; and the importance and fundamental mechanism of shocks and their effect on blade stability was understood.[9] However, all of these important aeroelastic problems that are more complicated and difficult than their fixed-wing counterparts were lumped under the heading of *rotating machinery* and discussed in a somewhat cursory manner. However, it should be noted that this level of conciseness was mandated by the length limitations imposed on Ashley's[4] survey paper.

The primary objective of this paper is to demonstrate that the field of aeroelasticity continues to play a critical role in the design of modern aerospace vehicles, and several important problems are still far from being well understood. Furthermore, the emergence of new technologies, such as the use of adaptive materials (sometimes denoted as smart structures technology), providing new actuator and sensor capabilities, has invigorated aeroelasticity, and generated a host of new and challenging research topics that can have a major impact on the design of a new generation of aerospace vehicles.

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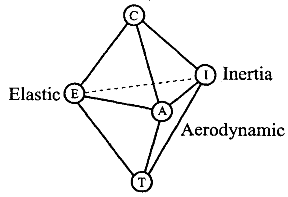

Fig. 1 Expanded collar triangle: aero-servo-thermo-elastic hexadron.

It is useful to remind the reader that aeroelasticity deals with the behavior of an elastic body or vehicle in an airstream, wherein there is significant reciprocal interaction or feedback between deformation and flow. While dramatic instabilities are often a cause for concern, it is important to emphasize that subcritical response, or the aeroelastic response problem is equally important, and for certain classes of vehicles, such as helicopters and tilt-rotors, it may be even more important.

In modern aerospace vehicles there is a strong potential for interaction between aeroelasticity and high-gain control systems leading to aeroservoelasticity. Furthermore, in high-speed supersonic or hypersonic vehicles, thermal effects can become important, producing an even more complex class of aerothermo-servoelastic problems. This situation is illustrated by Fig. 1, which represents a generalization of the classical collar triangle into a hexahedron that is more representative of modern aeroelasticity. The upper half of the hexahedron represents interactions between aeroelasticity and the control system, usually denoted as aeroservoelasticity. The lower portion of the hexahedron represents the interaction between aeroelasticity and thermal effects, denoted by the term aerothermoelasticity. The complete volume of the hexahedron represents aerothermo-servoelasticity, which is indicative of the broad nature of modern aeroelasticity.

The main emphasis in this paper is on developments that have taken place in the period since 1986. The earlier period is covered by several excellent review papers.[3,4,52,53] Since 1986 two books[34,35] have been published and a number of comprehensive review articles have appeared in a book edited by Noor and Venneri.[110] The review papers contained in this book cover the following areas of aeroelasticity: 1) experimental aeroelasticity in wind tunnels—history, status, and future in brief, with 58 references[127]; 2) aeroservoelasticity, with 59 references[107]; 3) nonlinear aeroelasticity, with 41 references[32]; aeroelastic problems in turbomachines, with 139 references[9]; 4) rotary-wing aeroelasticity with application to vertical takeoff and landing vehicles, with 347 references[43]; and 5) computational aeroelasticity, with 155 references.[36] In addition to these books and survey papers, the number of papers in aeroelasticity for the time period since 1986 varies between 40–90 per year, depending on the year and the specialized conferences that take place in any specific year. It is beyond the scope of this paper to review all of the papers published during this time period. Instead, this paper focuses on a selected number of topics.

The topics covered in this paper are 1) aeroservoelasticity; 2) selected topics in computational and nonlinear aeroelasticity; 3) rotary-wing aeroelasticity; 4) impact of new technologies on aeroelasticity; 5) concise comments on experimental verification of aeroelastic behavior, aeroelastic problems in new configurations, and aeroelasticity and design; and 6) comments about future developments in aeroelasticity.

Aeroservoelasticity

Aeroservoelasticity (ASE) is a multidisciplinary technology dealing with the interaction of the aircraft flexible structure, the steady and unsteady aerodynamic forces resulting from the motion of the aircraft, and the flight control system. Its role and importance are increasing in modern aircraft with high-gain digital control systems. ASE has been a primary research area in aeroelasticity for the last 25 years, and several recent survey articles[54,90,107] have been devoted to this topic.

Historical Perspective

It is useful to briefly review configurations that have been tested in flight or wind tunnels with active flutter suppression and load alleviation devices. The most comprehensive control configured vehicle, a B-52E airplane, was tested in a program conducted jointly by the Air Force Dynamics Laboratory, the Boeing Company, and NASA Langley Research Center. This aircraft had flutter mode control, maneuver load control (MLC), and ride control, as well as some additional features, such as gust load alleviation (GLA). A flutter suppression system was demonstrated in a flight test on Aug. 2, 1973, when a flight speed of 10 kn above the critical open-loop speed was attained.[131] Flutter was induced by ballasting the added tip tanks with 2000-lb lead weights; control was achieved by special outboard ailerons and flaperons, which controlled a 2.4-Hz wing bending mode.

Flight testing of flutter suppression control laws and GLA approaches was conducted by NASA in the late 1970s into the early 1980s under the drones for aerodynamic and structural testing (DAST) program.[103] This program was aimed at the testing of clean wings, representative of transport category airplanes, with supercritical airfoils in the transonic range. Failures during testing prevented the program from bearing fruit.

Aeroservoelastic encounters have also taken place on fighter-type aircraft such as YF-16, which experienced control system interactions with a flexible wing mode[113]; the YF-17, where control system interactions with the flexible wing as well as with a rigid body mode were observed[2]; the F/A-18, which experienced aeroelastic oscillations induced by the control system[157]; and finally, the X-29A, which experienced body degree-of-freedom interactions with the forward-swept wing.[24,60]

A very significant portion of the experimental research on flutter suppression has been conducted on aeroelastically scaled wind-tunnel models, with an emphasis on wing/store flutter suppression.[71,74,108,114]

Because of the complexity of the problem, a large number of studies have been theoretical in nature, aimed at understanding the basic problems, or supporting the experimental work conducted. Almost 25 years have gone by since the field has started, and it is valid to pose the question, "Is it mature?"

Analytical Methods and Observations

Early pioneering work on flutter suppression was based on the aerodynamic energy concept.[105] This approach is based on the energy required to sustain simple harmonic motion in a typical section, having pitch, plunge, and control surface generalized degrees of freedom. When the sign of energy is positive, energy must be supplied, and the system is stable. General criteria and control laws for system stability were derived and demonstrated in wind-tunnel tests. Other work pursued in parallel was on frequency-domain aerodynamics and classical control techniques.

A major breakthrough in ASE[38,130,160] has been the development of time-domain aerodynamics, based on rational function approximation to the unsteady aerodynamic loading in the frequency domain. These approaches add a considerable number of augmented states to the equations of motion. The number of these augmented states can be reduced using the minimum state method.[77,78]

Later, alternative two-dimensional compressible aerodynamic tools in the time domain were developed by Leishman and Nguyen.[86] This model is suitable for both incompressible and compressible cases. These models are based on indicial aerodynamics and require a fairly large number of augmented aerodynamic states. Recently, these time-domain unsteady aerodynamic models have also been extended to two-dimensional wing/control surface combinations.[64]

Time-domain aerodynamics can be conveniently combined with optimal control theory, and when full-state feedback is used, this produces the conventional optimal control problem or the linear quadratic regular (LQR) problem. However, full-state feedback is rarely feasible; therefore alternative methods using dynamic compensators based upon linear quadratic Gaussian (LQG) control techniques have been used. Formulation of the ASE problem in the state-space domain facilitates the use of recent methods developed in the area of controls for multi-input/multi-output (MIMO) systems, including robustness considerations.

The methodology for designing a large-order controller, without significant sacrifices in performance and robustness to the ASE problem, was developed by Mukhopadhyay.[101,102] Singular value analysis is the key for determining robustness of full-order controller, and it facilitates the selection of the significant states to be retained in the reduced-order controller. Design limitations on control surface deflection and its rate requires augmentation of this approach by constrained optimization.[102]

The aeroservoelastic problem in the transonic regime requires nonlinear aerodynamic loads based upon computational fluid dynamics (CFD); for such systems adaptive control techniques are required. Similar requirements will also exist in the presence of structural nonlinearities, or for aeroelastic configurations whose properties vary widely throughout the flight envelope. Some of the more interesting aspects of ASE can be illustrated by examples taken from recent applications.

Adaptive Control Example

A recent study[41,58] used a two-dimensional typical cross section with a trailing-edge control surface (Fig. 2), and combined it with unsteady aerodynamic loads obtained from the exact solution of the Euler equations using a mixed Eulerian–Lagrangian formulation.[10] Spatial discretization of the equations was based on Galerkin's method, and time-accurate simultaneous solutions of the combined fluid–structure equations of motion were obtained using a five-stage Runge–Kutta algorithm. A dynamic computational mesh deformation scheme accounting for pitch and plunge of the airfoil, as well as displacement of nodes caused by control surface motion, was implemented. This mesh is illustrated in Fig. 3. The total number of grid points used in the computational mesh was 4096 nodes. An adaptive controller was used, based on a deterministic auto-regressive moving average (ARMA) model, with on-line least-squares estimation. An adaptive optimal controller was designed. Flutter suppression in the presence of strong moving shock waves was demonstrated, using practical limitations on control surface deflection rates. A typical result illustrating the time response of the aeroelastic system is shown in Fig. 4, which depicts flutter suppression on a NACA 64A006 airfoil, at $M = 0.85$, at a nondimensional velocity U that is 20% above the flutter speed. For this case, the control surface deflection was limited to $\beta_{\max} = 2$ deg. Results were found to be sensitive to the sampling rate T_e.

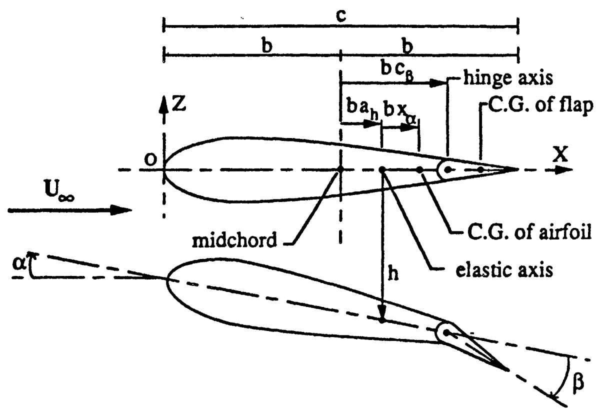

Fig. 2 Typical cross section for adaptive control example.

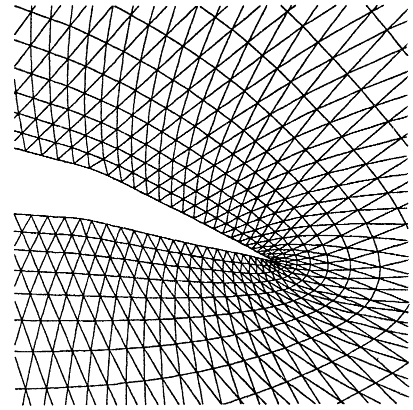

Fig. 3 Computational mesh around control surface. Partial view of deformed grid (α = 10 deg, h = −0.02b, and β = 10 deg).

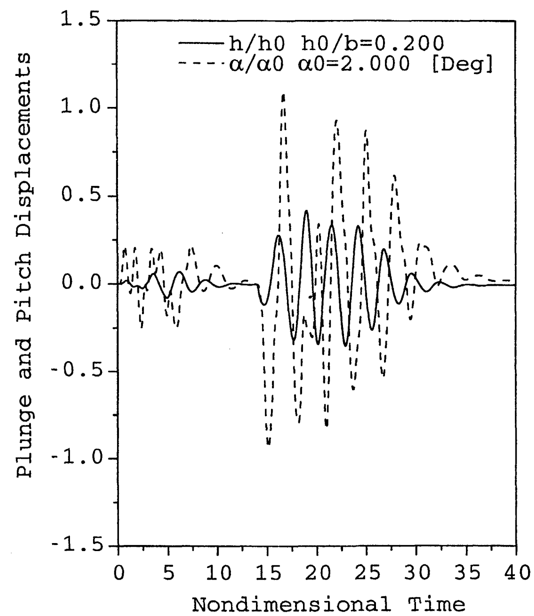

Fig. 4 Time response of aeroservoelastic system during flutter suppression for NACA 64A006 airfoil, M = 0.85, U = 3.0, 20% above flutter speed, $\beta_{\max}$ = 2 deg.

Active Flexible Wing Program

A comprehensive recent ASE program jointly conducted by Rockwell, Air Force Wright Aeronautical Laboratories, and NASA Langley Research Center, focused on an actively controlled, statically and dynamically scaled, full-span, wind-tunnel model of an advanced tailless fighter, with electrohydraulic actuators powered by an onboard system. The model was sting mounted and had roll capability. A schematic representation of the model and its control block diagram are shown in Fig. 5. The first series of tests, performed in NASA's Transonic Dynamics Tunnel (TDT), were aimed at MLC and active roll control. Subsequently, in a follow-on program conducted by NASA and Rockwell, digital active MIMO control concepts aimed at flutter suppression and roll maneuver load alleviation were studied.[109,115]

A wingtip store with ballast was used to induce flutter in the operational regime and also to stop it if encountered unexpectedly. Conventional subsonic and supersonic unsteady aerodynamics (doublet lattice, and Mach box) were used to formulate the aeroelastic model for the vehicle and to determine its flutter characteristics. For the transonic regime, nonlinear

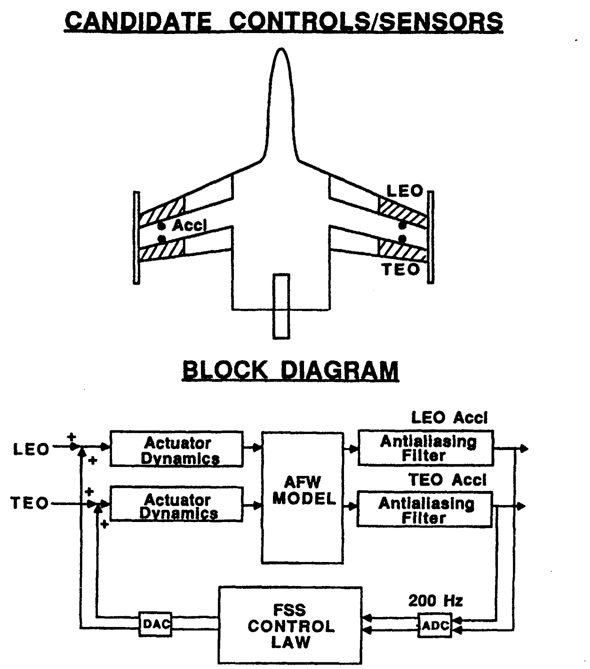

Fig. 5 Configuration and digital control loop for active flexible wing.

transonic analyses were conducted using the computational aeroelasticity program–transonic small disturbance (CAP–TSD) code.[137]

A flutter suppression system was designed to tackle both symmetric and antisymmetric modes, using discrete, low-order, robust control laws. Three control laws were studied: 1) LQG method,[101,102] 2) a sensor-blending approach that resembled earlier work,[74] and 3) an eigensystem assignment technique.[145,146] Among these three control laws, the first two approaches produced only marginal improvements in flutter margin. However, the flutter suppression system based on eigensystem assignment was tested successfully up to 24% of the unaugmented flutter dynamic pressure.

This concise description of ASE reveals that currently there is no vehicle in production that uses active flutter suppression, nor has any vehicle been recently flight tested with an active flutter suppression system. Wind-tunnel tests of flutter suppression systems have shown only relatively modest expansions of the flutter envelope. This seems to indicate that the field is far from mature, and much remains to be done before one can consider the routine incorporation of such systems in production aircraft.

Selected Topics in Computational and Nonlinear Aeroelasticity

Computational Aeroelasticity

Computational aeroelasticity is a relatively new field emphasizing those types of aeroelastic problems where loads based on CFD, which can be both unsteady and nonlinear, are used to obtain solutions.[36] Important applications areas are transonic aeroelasticity at low angle of attack, lower speed but high-angle-of-attack conditions, and high-speed hypersonic applications.

Transonic Flutter

Flow/structure interactions in this regime can produce alternate separation and reattachment of flow, motion of shock waves, and unusual aeroelastic phenomena that impose limits on the flight envelope of the vehicle. The transonic regime represents one of the most critical flutter conditions, and the flutter speed reaches its minimum at the high subsonic Mach number range (transonic dip). Simulation of this behavior using the tools that are continuously being refined in computational aeroelasticity has become *the holy grail* of computational aeroelasticity.

When discussing computational methods and related issues, it is important to distinguish between the fluid dynamic models and the methods used for their solution. The fluid dynamic models available for unsteady aerodynamic computations are 1) classical, linear, small-disturbance equations; 2) nonlinear potential equations, including both transonic small disturbance and full-potential equations; 3) Euler equations; 4) thin-layer Navier–Stokes equations; and 5) complete Navier–Stokes equations. The methods used in the solution of these equations also involve important choices, such as the choice of algorithms implicit vs explicit and their stability; the choice of discretization methods, finite differences vs finite volume or finite element (Galerkin); treatment of the computational grid (grid generation) and its modification in time; and coupling of the fluid and the structure-sequential, classical, or simultaneous, Euler–Lagrangian, solution of the coupled fluid/structure equations. Numerous contributions on various aspects of these problems have been made by many individuals.[7,13,16,57,61,62,123,129]

Computation of Transonic Bucket—Examples

A viscous–inviscid interactive coupling method for allowing the time-accurate computation of unsteady transonic flows involving separation and reattachment was developed by Edwards.[37] Interactive boundary-layer modeling (IBLM) provides an alternative to the direct computation of viscous flows with shear layers. Separate computations were carried out for an inner viscous boundary layer and an outer inviscid flow. A new coupling method was devised considering IBLM as a simulation of two dynamical systems, with a variable gain integral control element for displacement thickness and a first-order smoothing filter for the momentum thickness estimate. The whole process, called the lag-entraintment integral boundary-layer method, when combined with the CAP–TSD code, including extension in a stripwise fashion to the three-dimensional case, produces the computational aeroelasticity program–transonic small disturbance viscous (CAP–TSDV) code.[37]

The CAP–TSDV code was applied to an AGARD Standard Aeroelastic configuration tested in the TDT at NASA Langley Research Center. The AGARD wing 445.6 is a semispan model, built from laminated mahogany. The four lowest modes, two in bending and two in torsion, associated with this configuration span the frequency range between 9 and 91.5 Hz.

Comparison of the flutter calculations with the experimental data is shown in Fig. 6. Figure 6a shows a plot of the flutter-speed index as a function of the Mach number. The flutter speed index is given by $V_f = V/(b_s \omega_\alpha \sqrt{\mu})$, where V is the flutter velocity, b_s is the semichord, ω_α is the torsional frequency, and μ is the mass ratio. The experimental points and the calculations are in good agreement and capture the descent into the transonic bucket. The calculations for this case are incapable of capturing the ascent from the transonic bucket. Figure 6b depicts the flutter frequency ω_f nondimensionalized by the fundamental torsional frequency ω_α; again, only the descent into the transonic bucket is captured. It should be noted that other advanced CFD codes that have reproduced the descent into the bucket have also failed to represent the ascent.

The AGARD wing 445.6 was also considered by Gupta,[59] using an extension of the Structural Analysis Routines (STARS) program to a CFD-based aeroelastic analysis. In this code, a steady-state Euler solution is obtained first. The structural and fluid dynamic codes are coupled in a sequential manner, and structural modes are used to enhance efficiency. The state u and $\dot{u}$ are input to the CFD code and change the velocity boundary conditions at the solid boundary. This is followed by a one-step Euler solution using a global time-stepping scheme. Spatial discretization is treated using a finite volume discretization of the fluid, and the entire solution is

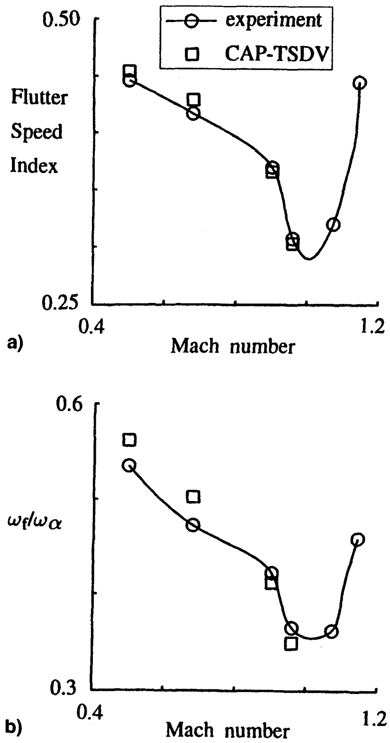

Fig. 6 Comparison of flutter calculations with experiment for AGARD 445.6 wing in air. -o-, experiment; and □, CAP-TSDV.

repeated for the required number of steps. The results are shown in Fig. 7.

The agreement between the flutter predictions obtained from the STARS code are in good agreement with the experimental data. Figure 7a shows the flutter frequency ratio and Fig. 7b shows the flutter speed index. While the comparison between the computations and the experimental data is not as good as that shown in Fig. 6, the STARS computations are remarkable because they capture not only the descent into the transonic bucket, but also the portion of the curve that represents the ascent from the bucket.

Another configuration to which the CAP–TSDV code was applied was the business jet wing, also tested in the TDT. A semispan wing–fuselage aeroelastically scaled model, mounted on the sidewall of the tunnel, was tested in air. The wing model was constructed from aluminum plate with fiberglass-wrapped foam for airfoil contour. It had a 4.4-ft semispan, a 2.0-ft root chord, a wing thickness variation between $8.5\% < t/c < 13\%$, and a midchord sweep of 23 deg.

The results from the computation are compared with experimental data in Fig. 8. Inviscid calculations agree among themselves and are in very good agreement with the experiment for lower Mach numbers; for higher Mach numbers in the transonic dip region, the results based on the inviscid codes become conservative and should not be used for $M > 0.80$.

At a Mach number below the minimum transonic flutter speed index, the viscous methods CAP–TSDV, computational flutter, three-dimensional Navier–Stokes CFL 3D–NS[55] are in agreement, and provide good agreement with experiment. It should be also mentioned that the CAP–TSDV code also predicted large-amplitude limit-cycle oscillations at $M = 0.888$. Linear flutter calculations are in good agreement with experiment up to $M = 0.85$, and are unreliable thereafter.

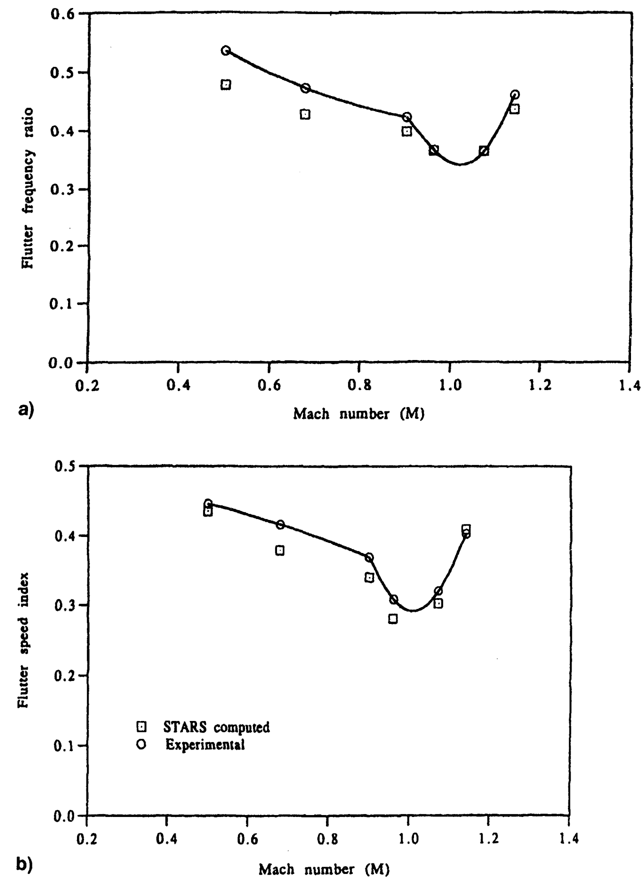

Fig. 7 Comparison of STARS flutter prediction with experimental results of AGARD wing: a) flutter frequency ratio and b) flutter speed index.

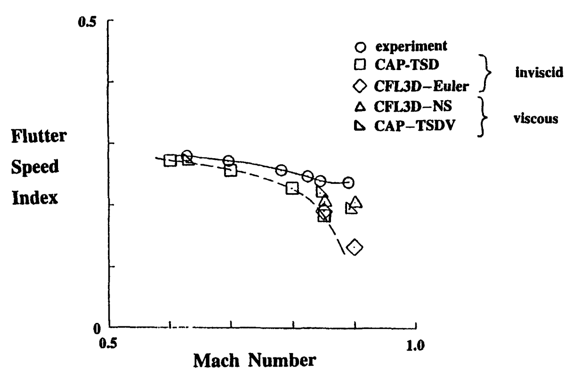

Fig. 8 Flutter boundary for business jet wing model $M = 0.89$, $\alpha = 0.2$ deg, $R_e = 1.136 \times 10^6$, wing alone.

Mixed Eulerian–Lagrangian Approach

In the classical approach, the fluid and structure are modeled separately and coupled by specifying kinematic boundary conditions at the fluid structure boundary. Kinetic or natural boundary conditions are not treated conventionally; instead they are considered as forcing terms in the structural equations of motion. The fluid/structure boundary is a Lagrangian surface, and its state (u, $\dot{u}$) must be known to impose kinematic boundary conditions at the surface. The classical approach, often called the sequential approach, requires approximations because the exact boundary state requires a solution of the complete system, which depends on surface pressure at Δt, which in turn depends on unknown boundary conditions. Separate integration, associated with this approach, introduces phase and integration errors.

In the mixed Eulerian–Lagrangian scheme,[10,12,31] the fluid/structure system is treated as a single continuum dynamics problem. The formulation is based on Hamiltons principle in mixed coordinates. Kinematic and kinetic boundary conditions are satisfied locally at the fluid/structure boundary by switching from the Eulerian to the Lagrangian formulation at the boundary. Both Galerkin-type finite elements and Jameson-type volume schemes[73] have been used to discretize the Euler equations, and the structure is discretized by a Galerkin-type finite element approach, which yields a similar system of equations. The resulting equations are integrated simultaneously in the time domain using a multistage Runge–Kutta scheme.

An example for the application of the mixed Eulerian–Lagrangian approach to transonic flutter of airfoils, modeled as a typical section, with camber bending (chordwise flexibility) using a special plate-type element with unit width, was presented by Bendiksen.[10] The classical method underpredicts limit-cycle amplitudes beyond the linear flutter boundary. Integration of the energy equation provides an independent check on both the accuracy of the method and the Runge–Kutta integration scheme, and attests to the fidelity by which the transfer of energy and momentum between fluids and structures are reproduced.

Typical results illustrating these statements are shown in Figs. 9 and 10, taken from Ref. 10. Figure 9 depicts the total nondimensional energy of the wing section (kinetic plus strain energy ETOT) plotted against nondimensional time, and the work done by the fluid elements making up the airfoil (work). Note that the structure is modeled without damping, thus the difference between total energy and the work is equal to a constant, $E0$, the initial energy of the structure. By integrating the energy equation, an independent check on the accuracy of the method, as well as the Runge–Kutta integration procedure, is obtained. Excellent agreement between the initial energy and the difference (ETOT–WORK), represented by the diamonds for the Eulerian–Lagrangian method, is shown in Fig. 9 for the initial period. However, in the classical method of computation, this ETOT–WORK difference, represented by square symbols in Fig. 9, shows a systematic divergence from the initial energy value $E0$. This error grows with increasing time, as is clear from the long-term plot shown in Fig. 10. This violation of the energy balance can lead potentially to spurious instabilities.

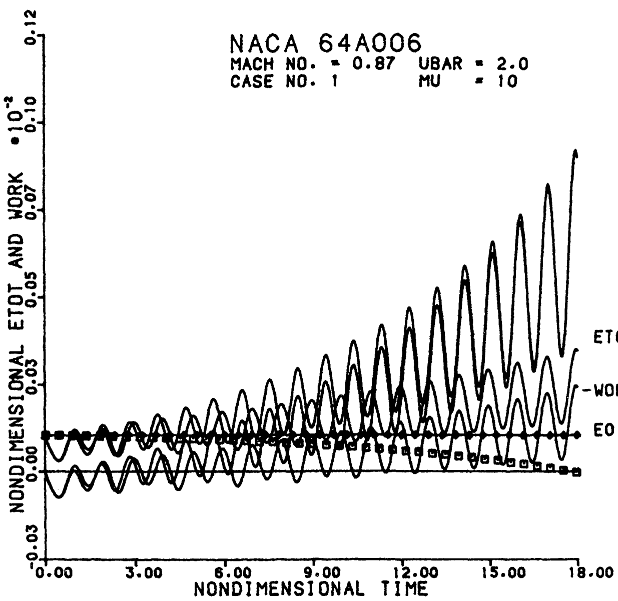

Fig. 9 Initial energy $E0$, and the difference (ETOT–WORK) for initial nondimensional time period. ♦, Eulerian–Lagrangian approach; and □, classical approach for NACA 64A006.

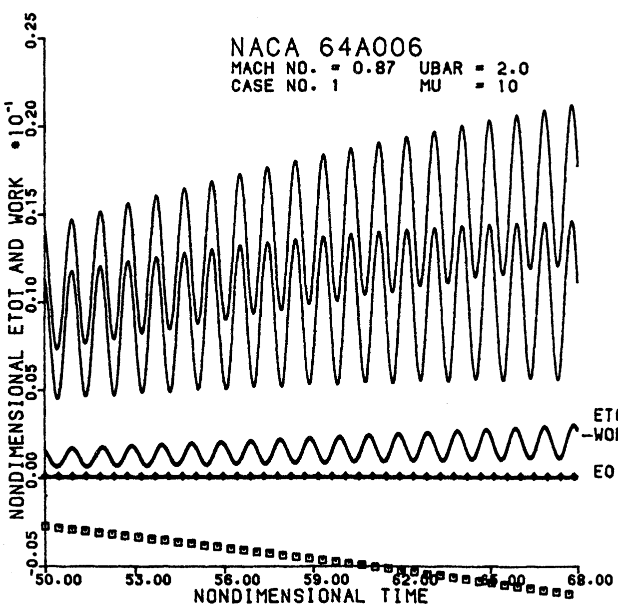

Fig. 10 Initial energy $E0$, and the difference (ETOT–WORK) for long time period ($50 < t < 68$). ♦, Eulerian–Lagrangian approach; and □, classical approach for NACA 64A006.

Another interesting application of the mixed Eulerian–Lagrangian method was the study of nonclassical aileron buzz.[11] At the upper transonic range ($0.9 < M < 1.0$), shocks are confined to a trailing-edge region, and during flutter they do not move, but change in strength, producing localized loading on the trailing-edge region. Under appropriate conditions, on a NACA 64010 airfoil, type B, nonclassical shock-induced aileron buzz is observed, which resembles behavior obtained in wind-tunnel tests.

Reduced-Order Models

A novel and computationally efficient technique for calculating unsteady flows about isolated airfoils, wings, and turbomachinery cascades, was developed by Dowell and his associates during the last eight years.[33,93,132] Using time-domain unsteady CFD analyses, such as two-dimensional Euler equations, the flow around an airfoil is solved using an appropriate CFD code. Linearizing these equations about a mean nonlinear input, by writing small dynamic perturbations about the mean state, allows calculation of the eigenvalues and eigenvectors of the linearized system, which, in turn, enables one to determine the modal structure of the fluid, by solving a large, sparse eigenvalue problem.

This reduced-order model facilitates the rapid and accurate unsteady aerodynamic loading calculation and, therefore, is suitable for aeroelastic and aeroservoelastic applications, because the method can be conveniently combined with structural modes. The eigenmodes are used to transform the large set of coupled, primitive variables (such as density, pressure, velocity, etc.) obtained from the time-marching finite difference (or finite volume) approximation of the Euler equations, into a much smaller set of decoupled (modal) equations, which represents the reduced-order aerodynamic model. Despite the attractiveness of the method, there may be difficulties with its implementation in strongly nonlinear problems. The method is potentially very valuable as a postprocessor to reliable CFD codes for the unsteady solution of Euler equations or Navier–Stokes equations. It is also potentially useful for aeroservoelastic applications.

Nonlinear Aeroelasticity

Ascending complexity of aeroelastic problems when moving from linear to nonlinear aeroelastic formulations is briefly summarized.

1) Completely linear models: These imply that both the static and dynamic behavior of the physical system are described by linear models. Classical fixed-wing aeroelasticity and ASE belong to this category.

2) Linearized models: An equilibrium position, static or dynamic, can be obtained from the solution of a nonlinear response problem. Subsequently, by writing perturbation equations about the equilibrium position, linearized dynamic equations about this equilibrium are obtained, which provide linearized aeroelastic stability boundaries. The dynamic prob-

lem is dependent on equilibrium position. Rotary-wing aeroelasticity belongs to this category.

3) Completely nonlinear models: A nonlinear physical system must be considered in its entirety. Behavior can depend on both initial conditions and system parameters. High-angle-of-attack problems (stall flutter) and complete treatment of transonic flutter belong to this category.

Some of the more important nonlinear aeroelastic problem are 1) rotary-wing aeroelastic problems; 2) transonic aeroelastic problems in airfoils, wings, and limit-cycle oscillations (LCO); 3) flutter of airfoils at high angles of attack (stall flutter, aeroelastic problems in maneuvering flight); 4) panel flutter (plates, shells); and 5) flutter of airfoils with a freeplay type of structural nonlinearity.

A few interesting nonlinear aeroelastic problems are discussed next, to provide some indication of recent research.

1) Transonic LCO[30,94]: This problem was encountered on highly maneuverable fighter aircraft operating in the transonic regime ($0.8 < M < 1.1$); LCOs are produced by structural/aerodynamic interactions. The phenomenon is related to buffet, but it also is similar to classical flutter because it occurs at a single frequency (torsion). It involves mixed attached/separated flow and imposes severe limitations on the operational envelope of the aircraft. The hypothesis is that it is induced by nonlinear aerodynamic forces. Qualitative understanding was developed in late 1970s. Quantitative understanding based on F-111 TACT aircraft, developed in the 1980s, identified wing torsional motion because of shock-induced trailing-edge separation (SITES) as a primary cause. Research in this area is still ongoing.

2) Flutter of airfoils with freeplay type of structural nonlinearity: Brase and Eversman[19] considered a typical cross section, with pitch and plunge degrees of freedom, and nonlinear restoring force/moment vs amplitude for a nominal linear spring and comparable nonlinear springs with friction and freeplay. The nonlinear spring characteristics are shown in Fig. 11. The freeplay (or dead band) produces a nonlinear relation between restoring force and amplitude because positive and negative amplitudes correspond to a zero restoring force. Cross-sectional aerodynamics in the time domain were represented by Roger's approximation,[130] and equations were numerically integrated using a Runge–Kutta scheme. Only structural nonlinearity, shown in Fig. 11, was used with freeplay limited to pitch degree of freedom, and with initial conditions only in pitch. Typical results obtained in this study are shown in Fig. 12. Nonlinear flutter was dependent on initial conditions, and all freeplay bands were symmetrical about the origin, as evident from Fig. 11. Flutter speed increases 30 ft/s above the linear value (160 ft/s) as initial pitch increases from 0.1 deg, in freeplay region (FPR) to 20 deg (outside FPR); flutter speed then drops for initial pitch rotation outside the FPR.

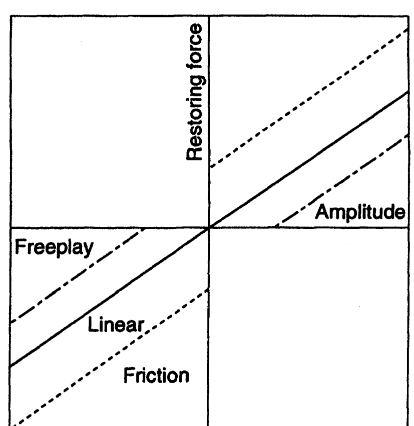

Fig. 11 Typical nonlinear spring characteristics with freeplay and friction.

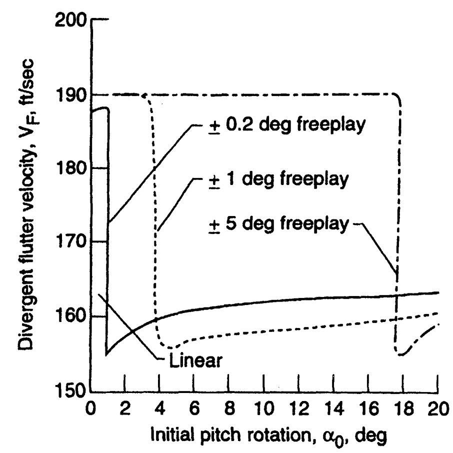

Fig. 12 Two-degree-of-freedom transient flutter, with spring nonlinearity, onset of divergent oscillations in flutter.

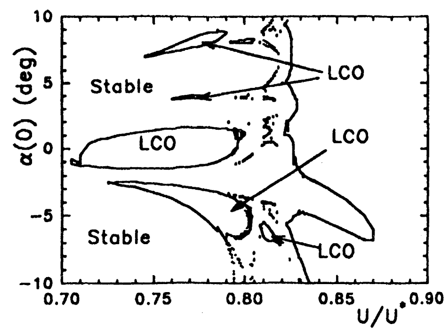

Fig. 13 Stability boundary for airfoil, with structural nonlinearity, as a function of initial pitch rotation; U^*-nondimensional flutter velocity for linear system.

Price et al.[122] considered a similar two-dimensional airfoil, with preloaded freeplay-type nonlinearity in pitch, using time-domain aerodynamics based on Wagner's function (see Ref. 18). Solutions were obtained by numerical integration. Regions of LCO were detected for velocities well below the linear flutter boundary, and the existence of these regions was strongly dependent on the initial conditions and the properties of the airfoil. For small structural preloads, narrow regions of chaotic motion were obtained.

A stability boundary obtained in this study is depicted in Fig. 13. The vertical axis depicts the initial pitch rotation $\alpha(0)$, and the horizontal axis depicts the nondimensional flutter velocity U/U^*, where U^* represents the nondimensional flutter velocity for the linear system. This plot conveys the intricate nature of the nonlinear solution with multiple LCO regions, and the multiple stable and unstable regions.

Rotary-Wing Aeroelasticity

When drawing comparisons between fixed wing and rotary-wing aeroelasticity (RWA), it is important to mention a few historical facts. The Wright brothers flew in 1903, and Sikorsky built the first operational helicopter, the R-4 (or VS-316) in 1942. The R-4 was a three-bladed helicopter with a rotor diameter of 11.6 m and was powered by a 185-hp engine. Thus, the initial gap between the fixed-wing and rotary-wing technologies is approximately 39 years. Therefore, it is not surprising that certain rotary-wing problems, particularly those pertaining to unsteady aerodynamics, are still not well understood. This situation is also compounded by the complexity of the vehicle when compared to fixed-wing aircraft. RWA has been the most active area in aeroelasticity during the last 25 years. Two recent books, containing a substantial amount of information in this area, have been published.[17,75]

Fundamental Differences Between Rotary-Wing and Fixed-Wing Aeroelasticity

The basic problem in fixed-wing aeroelasticity is the coupled bending-torsion problem which is essentially a linear problem. The basic problem in rotary-wing aeroelasticity is the coupled flap-lag-torsion (CFLT) of an isolated blade. CFLT is inherently nonlinear because of the geometric nonlinearities associated with moderate (or large) blade deflections, that must be incorporated into the structural, inertia, and aerodynamic terms associated with this aeroelastic problem. A typical hingeless blade with an advanced geometry tip is shown in Fig. 14. The geometry associated with the basic CFLT problem is depicted in Fig. 15.

Rotary-wing aeroelastic problems can be separated in two regimes: hover and forward flight. In hover, the equations of motion have constant coefficients, whereas in forward flight the equations have periodic coefficients. The fundamentally nonlinear nature of RWA requires coupling between the aeroelastic problem and the flight condition of the entire helicopter as represented by its trim state. Two types of trim procedures, propulsive trim and wind-tunnel trim, have been used. The first trim procedure simulates straight and level forward-flight conditions, as shown in Fig. 16, and the second trim procedure corresponds to the conditions experienced when testing the rotor on a support in the wind tunnel. Aeroelastic stability boundaries can be obtained by linearizing equations of motion about the equilibrium position determined from trim. In hover, linear eigenanalysis is used to obtain the aeroelastic stability boundaries, and in forward flight, aeroelastic stability is usually determined from Floquet theory.[43]

The lead–lag degree of freedom, with its low aerodynamic and structural damping, is a critical degree of freedom in most rotary-wing aeroelastic problems. Another important class of problems is coupled rotor/fuselage aeroelastic problems, denoted aeromechanical problems. This problem involves coupling of the fuselage rigid body degrees of freedom (primarily pitch and roll) with the blade of degrees of freedom (primarily lead–lag). The geometry depicting a typical coupled rotor/fuselage of a system is shown in Fig. 17. On the ground, the aeromechanical instability is called ground-resonance, and in flight it is known as air-resonance. It is interesting to note that while active flutter suppression has not been an area of concern in RWA, active suppression of aeromechanical instabilities has received considerable attention.[151]

The aeroelastic response problem that manifests itself as blade loads, hub loads, or fuselage vibrations, plays a key role for rotary-wing vehicles and, therefore, vibration prediction and its control has been an area of intense activity. Modeling unsteady aerodynamic loads on the blade (and the rotor) is a major challenge. The combination of blade advancing and rotational speed is a source of complexity. At large advance ratios, many different flow regimes coexist: transonic flow with shock waves on the advancing blade, and flow reversal and low-speed unsteady stall or the retreating blade. Time-varying unsteady wake geometry, which is an important source of unsteady loads, vibration, and noise, is excruciatingly complex. Computation of the unsteady free wake has been a major challenge, and it is essential for correct computation of vibrations and noise. Figure 18, taken from Ref. 154, depicts three free-wake calculations based upon three different free-wake models. Rotor–fuselage interactional aerodynamics is another difficult problem.[43]

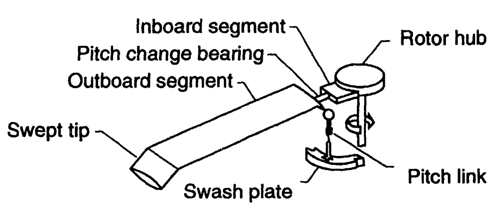

Fig. 14 Typical hingeless blade with advanced geometry tip.

Primary Activities During the Last Six Years

Composite blade structural dynamic and aeroelastic models and their application to the study of hingeless, bearingless, and tilt-rotor blades, as well as coupled rotor fuselage problems[21,43,45,46,69,106,140,150,156,165–168] has been a particularly active area of research. A considerable amount of research has also been focused on tilt-rotor aeroelasticity[106,121,147] because this new type of vehicle is becoming more prevalent. Another interesting area of research was the study of the role of blade aeroelasticity in maneuvering flight, and its effect on handling qualities.[20,29,144]

The effect of lag dampers on aeroelastic and aeromechanical instabilities has always been an important area of endeavor. Recent developments in this field have focused on modeling the nonlinear properties of elastomeric dampers.[49,50,83,111,139]

The development and validation of comprehensive helicopter analysis codes such as CAMRAD II[76]; 2GCHAS[1,100,111,133]; and RDYNE, COPTER,[29] UMARC,[28] and CAMRAD/JA has been another topic that has received considerable attention. Application of multibody dynamics to the treatment of complex dynamic configurations has been shown to be useful.[8,70,134] The aeroelastic behavior of rotor blades with advanced geometry tips[79,155,165–168] has received considerable attention

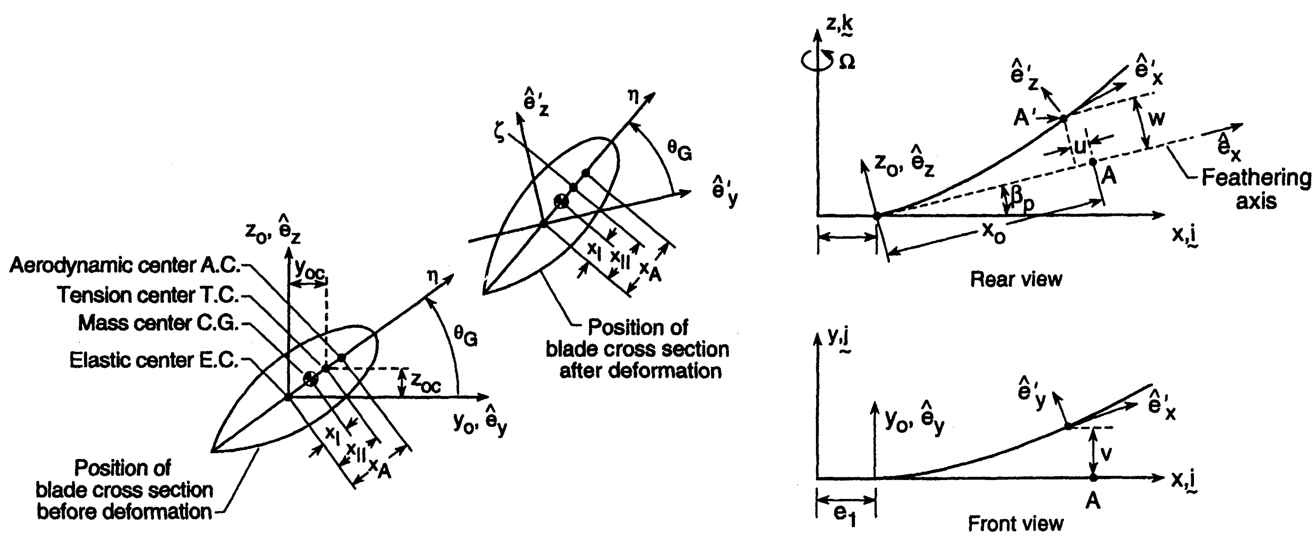

Fig. 15 Undeformed and deformed blade configuration, illustrating geometrically nonlinear aspects of basic coupled flap-lag-torsional problem.

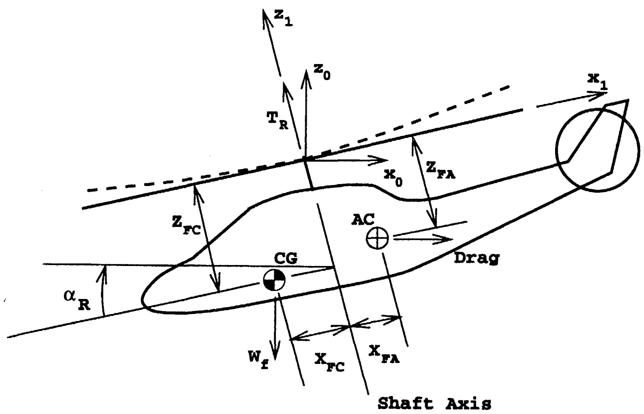

Fig. 16 Schematic of helicopter in level forward flight used for coupled trim/aeroelastic analysis.

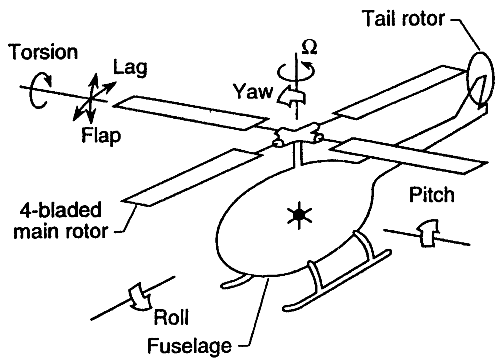

Fig. 17 Coupled rotor/fuselage system.

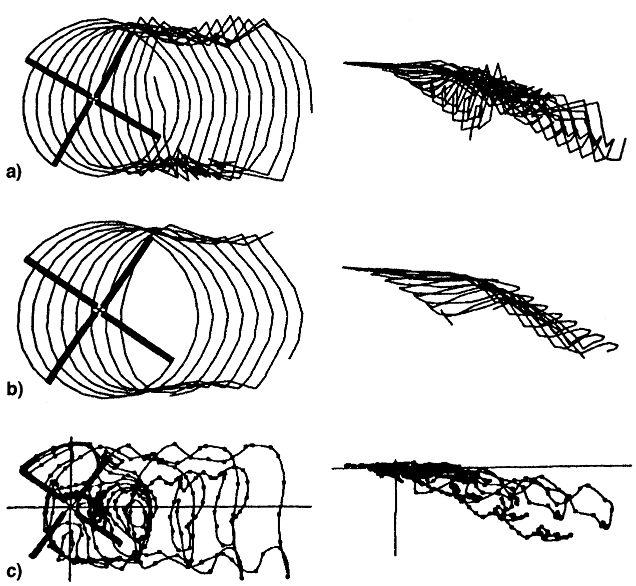

Fig. 18 Qualitative features of three different free-wake models at an advance ratio of μ = 0.1. Wake geometry a) FREEWAKE model, μ = 0.1; b) Johnson (modified Scully) model, μ = 0.1; and c) RotorCRAFT model, μ = 0.1.

because modern helicopter blade tips have sweep, taper, and anhedral.

Improved and approximate wake models,[5,118,119,154] and improved methods for dealing with periodic systems and trim procedures,[6,116,117,138] have also been topics where improved techniques have been developed.

Aeroelastic response or vibration in coupled rotor/flexible fuselage systems[25–27,68,112,120,159] and vibration reduction at the hub and in the fuselage using active control[27,95–99,104,149] has been another area of research where significant progress has been achieved. Lack of space prevents one from reviewing the whole spectrum of this research in a comprehensive manner and, therefore, three examples are described next in detail to provide a better perspective on this diverse activity.

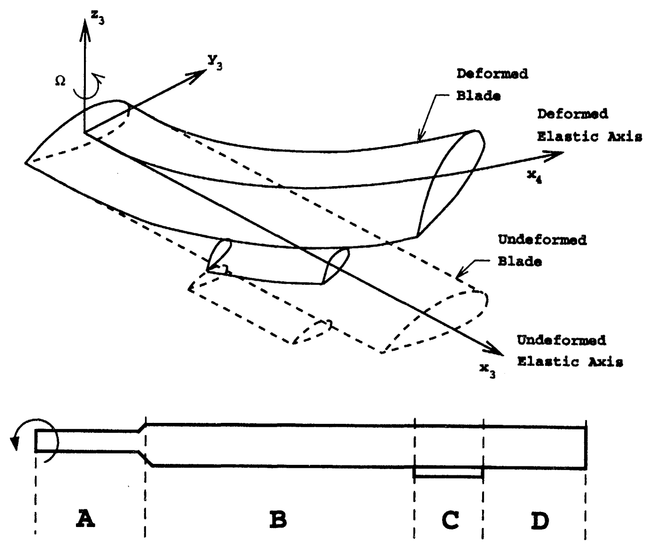

Fig. 19 Fully elastic blade model incorporating a partial-span trailing-edge flap.

Vibration Reduction Using an Actively Controlled Flap

A comprehensive study of vibration reduction in four-bladed hingeless rotors in forward flight using an actively controlled trailing-edge flap was conducted.[96–99] The geometry of this problem is illustrated in Fig. 19. Vibration reduction performance was compared with conventional individual blade control (IBC), where the whole blade is given a pitch input, at its root, in the rotating reference system. Each blade had fully coupled flap–lag–torsional dynamics, including moderate deflections, and the coupled aeroelastic/trim problem was solved for the case of propulsive trim.

A simple adaptive optimal control algorithm based on minimization of a quadratic cost functional containing the squares of the vibratory hub loads (4/rev) was used to minimize vibrations,[44] resulting in a discrete time controller. Flap-angle input, used for vibration reduction, consisted of a combination of 2/rev, 3/rev, 4/rev and 5/rev. The actively controlled flap (ACF) was centered at 75% span, extended over 12% of blade span, and the chord of the flap was 0.25 of the blade chord. A four-bladed soft-in-plane blade configuration resembling an MBB BO-105 type rotor was considered. Hub shear reduction for the ACF was 91%, which compared very favorably with the vibration reduction obtained, 96%, with the IBC approach, where the whole blade is rotated at its root by the pitch input. However, the most remarkable difference between the two approaches was the power requirement, which was 10–20 times higher for IBC than for ACF, depending on the torsional frequency of the blade. Another important benefit of the ACF approach is that it has no effect on vehicle airworthiness, whereas the IBC approach uses the same mechanical system employed for the helicopter flight control, and can significantly influence airworthiness.

Aeroelastic Stability of Helicopters with Elastomeric Lag Dampers

A nonlinear anelastic displacement field (ADF) damper,[139] based on accurate three-dimensional material modeling and irreversible thermodynamics, was developed from basic principles. The displacement field was separated into elastic and anelastic parts. For a simplified case, corresponding to pure shear behavior, two coupled partial differential equations are obtained: one describes motion and the second governs creep evolution in time. The parameters required for the model implementation are obtained from suitable material characterization tests. Damper behavior was solved by the finite element method, and combined with a three-degree-of-freedom offset hinged-spring restrained-blade model. Nonlinear damper equations are coupled with blade equations and are solved simultaneously. Nonlinear equations are linearized about the steady-state response point. Blade stability in forward flight is obtained from the Floquet theory. The silicon rubber damper was modeled with a single finite element. The ADF damper model predicts substantial variations in the area and aspect ratio of the damper hysteresis loops with advance ratio, as shown in Fig. 20.

Active Control of Structural Response Approach to Vibration Reduction in a Helicopter Rotor/Flexible Fuselage System

Active control of structural response (ACSR) was developed by Westland,[80,148] and is operational on the EH 101 helicopter. A somewhat similar version was also tested at Sikorsky.[163] In this approach, the fuselage, at selected locations, is excited by controlled forcing inputs, such that the combined response of the fuselage, caused by rotor loads and applied excitations, is minimized. While considerable experimental research on this topic has been carried out, it was only recently that a comprehensive analytical simulation capability allowing computer modeling of the ACSR system has been developed.[25–27] In these studies, a refined coupled rotor/flexible fuselage model has been developed, consisting of a four-bladed hingeless rotor, combined with a finite element model of the fuselage, consisting of beam and plate elements, combined with nonstructural masses. This coupled rotor fuselage model is shown in Fig. 21. The model contains an ACSR platform, with four actuators at its corners. Two different control algorithms based on the disturbance rejection approach have been developed and implemented with the ACSR system. The first algorithm is a basic, relatively simple algorithm, and the second one is a more refined version that utilizes the internal model principle, to enhance its performance. Figure 22 shows the vibration reduction achieved with the ACSR system using the refined control algorithm at various fuselage locations. When the refined algorithm is used, all vibratory components of the acceleration at selected fuselage locations are reduced below 0.04 g at advance ratios of 0.30. These calculations were carried out on a four-bladed hingeless rotor-flexible fuselage combination, resembling an MBB BO-105 helicopter. It was shown that very low power requirements (less than 1 hp) are adequate for this remarkable level of vibration reduction.

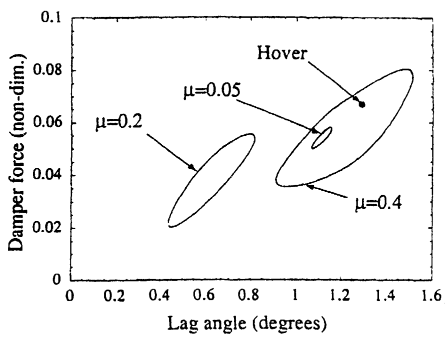

Fig. 20 Hysteretic characteristics of damper force vs lag angle for ADF damper model.

Impact of New Technologies on Aeroelasticity

Four decades ago, composites were identified as a new technology that would revolutionize aeronautical engineering. Since then, numerous studies have been conducted on the use of composites in wing design, leading to the establishment of aeroelastic tailoring based on a combination of ply layup and fiber orientation. Few wings have been built using aeroelastic tailoring; all modern rotor blades, with a few exceptions, are built of composites. The advantages of aeroelastic tailoring for composite blades have been amptly demonstrated,[168] yet aeroelastic tailoring is not being exploited in composite rotor blades, and the widespread use of composite blades is primarily a result of their excellent fatigue characteristics.

Approximately 15 years ago, active materials were identified as potentially useful for a variety of aerospace applications as both sensors and actuators, and since then, the area of *smart structures* or *adaptive structures*, combining active materials, controls, and microprocessors, has been burgeoning. Many important applications are related to aeroelasticity, both fixed-wing and rotary-wing, and a number of survey articles on this topic have been written.[56,67,92,161] It is interesting to speculate whether the future of adaptive materials-based actuation for aeroelastic applications will resemble that of composite materials and their application to aeroelastic tailoring.

Table 1 summarizes the most important characteristics of adaptive materials that are considered for actuator applications in problems involving aeroelastic effects. The table also con-

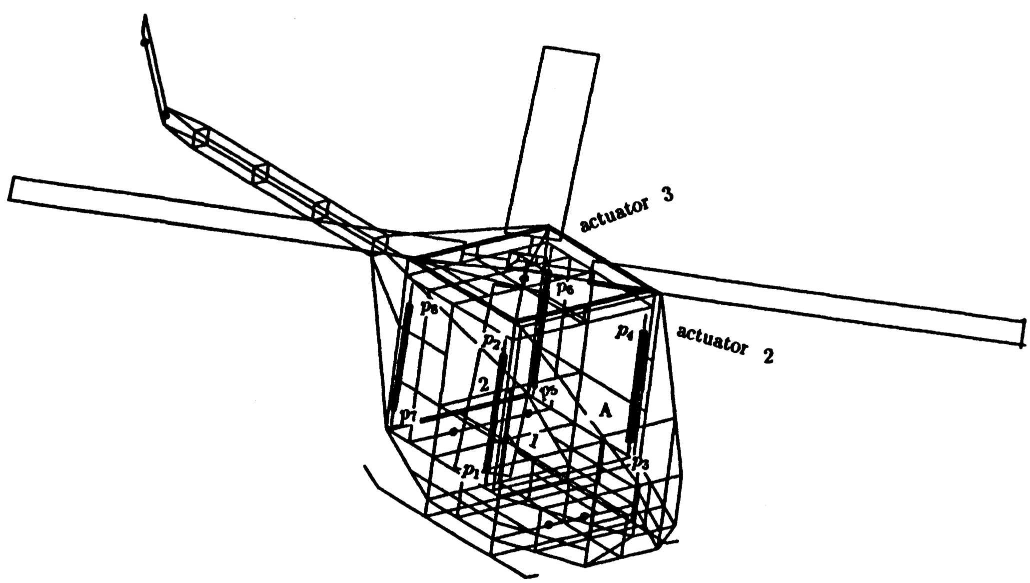

Fig. 21 Coupled rotor/flexible fuselage model including ACSR platform and actuators.

tains concise remarks on their suitability for such applications, together with comments on their special characteristics.

It is important to mention that shape memory alloys produce large amounts of strain and force; however, heating and cooling poses serious restrictions on frequency response and, therefore, are applicable to low frequency, or static aeroelastic applications. Piezoceramics have excellent frequency-response characteristics; however, currently, serious limitations on their force and stroke-producing capability exist.

Active materials have been applied to a variety of aeroelastic problems, such as static aeroelasticity, wing-lift effectiveness, divergence[141,162] supersonic panel flutter,[135,136] flutter and dynamic load alleviation,[65,84,89] vibration reduction in helicopter rotors,[23,143,149] and wing/store flutter suppression.[47,48]

The potential as well as the limitations of applying active materials-based actuation to aeroelastic problems is evident from considering a few specific examples.

Strain-Actuated Active Aeroelastic Wing

An interesting, comprehensive, combined theoretical and experimental study of a piezoelectrically actuated transport-type wing intended to demonstrate both subcritical vibration suppression and load alleviation, as well as flutter suppression, was conducted jointly by the Massachusetts Institute of Technology (MIT) and NASA Langley Research Center.[85,87–89] The theoretical portion of the research was done at MIT, and the experiments were conducted at NASA in the TDT. The actively controlled wing used piezoelectric patches, bonded to the top and bottom surfaces of a composite sandwich structure, with 2% thickness to chord ratio, representing the primary load-carrying element. The composite surface was surrounded by a shell representing a NACA 66-012 airfoil. The wing model had a 30-deg quarterchord sweep, a span of 48 in., an aspect ratio of 8, a weight of 11.4 lb, and an approximate chord of 15.6 in. Aeroelastic scaling considerations were not used in the design of this transport-like wing model. Graphite/epoxy laminate lay-up, allows in-plane isotropic piezoelectric actuators to produce bend–twist coupling that change angle of attack or torsional motion of the wing. The actuators are paired at top and bottom surfaces and are actuated in a bender configuration. They have been hardwired into 15 individual actuation groups.

The control approach used LQG design methodology based on an output feedback scheme, utilizing LQR for a full-state feedback law and a Kalman filter for the state estimator. Three different approaches were used to enhance the robustness of the controller design. A state-space model was identified from open-loop transfer functions at a dynamic pressure of 50 psf. Both single input/single output (SISO) and MIMO controls laws were designed. During the first entry in the tunnel, both types of control laws produced minor load alleviation, but no flutter suppression, because control law emphasized damping in the first three modes. This emphasized an important characteristic of active flutter control, indicating that increasing system damping may not neccessarily produce increases in the flutter margin.

In a second entry, conducted several months later, open-loop flutter dynamic pressure was considerably lower (76 psf) compared with the earlier value (85 psf), and the control laws were redesigned. Four SISO and one MIMO control law were tested, but the SISO control law was most successful. Now a strain gauge close to the trailing edge at 60% span and an accelerometer at the outboard trailing edge were used for measurement, and the emphasis was on separating poles, without sacrificing damping. Hard flutter was encountered at 85.5 psf (12.5% increase in envelope) with a peak-to-peak displacement of 20 in. It is interesting to note that the weight of the piezoelectric patches was approximately equal to 12% of the wing weight. The principal performance limiters encountered in this test were 1) saturation of piezoelectrics, 2) choice of performance metric, and 3) sensor locations and their ability to detect the three critical aeroelastic modes.

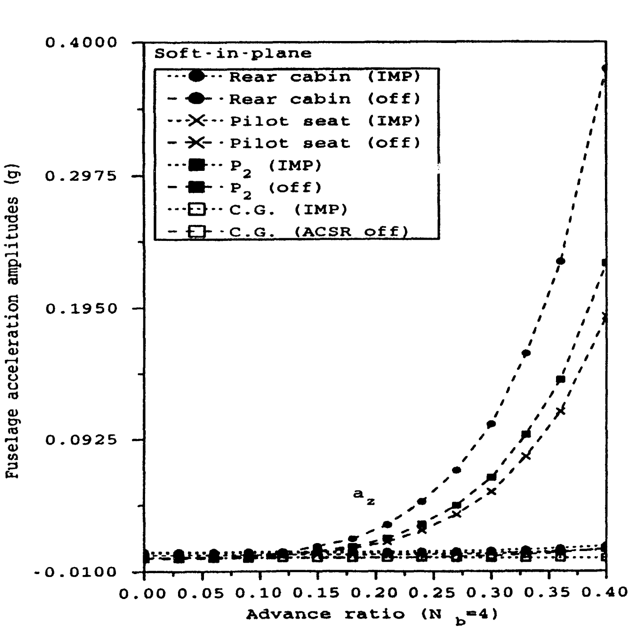

Fig. 22 Baseline and controlled fuselage accelerations in vertical direction, at various fuselage locations, for four-bladed rotor, with refined control algorithm.

Table 1 Useful properties of active materials

Material	Manufacturer's designation[a]	Actuation principle and maximum strain capability	Comments
Ceramic (lead, zirconate-lead, titanate)	PZT	Piezoelectric 600–1000 μ	Active characteristics induced by poling, i.e., applying an electric field, typically ≈2500 V/mm High-frequency capability Maximum excitation field ≈2000 V/mm
Polymer (polyvinylidyne fluoride)	PVDF	Piezoelectric 150 μ	Induced strain very different in two directions
Rare Earth elements alloyed with iron	Terfenol Samfenol	Magnetostrictive 1400–2000 μ	Requires compressive prestress and magnetic field generating coils and flux guidance material High-frequency capability, but with reduced amplitudes as frequency increases Max induced strain ≈2000 μ
Nickel titinate (or compounds with copper, or Aluminum; NiTiCu or CuAlNi)	Nitinol Flexinol	Shape memory alloy 4000–5000 μ	Actuation requires heating and cooling; unless special cooling is provided, cycling probably restricted to <5 Hz Material behavior is highly nonlinear, i.e., bang–bang Maximum induced stress 20 × 10^3, psi

[a]Tradenames.

Wing/Store Flutter Suppression Using a Piezostrut[47,48]

The purpose of this study was to examine a concept based on using a piezoceramic wafer actuator, combined with a control system as a replacement of the passive decoupler pylon pioneered by Reed et al.[124] This analytical study was based on a very simple aeroelastic model of a wing/store configuration. Consisting of a typical cross section with pitch/plunge degrees of freedom, combined with a store having pitch degree of freedom about the pivot point. Time-domain incompressible aerodynamics, based on a two-pole approximation, were used and store aerodynamics were neglected.

Reference 48 focused on three control designs: LQR, LQG/LTR, and LQG, and placed emphasis on robustness (unmodeled dynamics). Of these three designs, LQG produced the best results, resulting in a 6.25% increase in flutter speed, at a low control effort when compared with LQG/LTR. The design suffered from low stability margins for low-frequency parameter variations. In the second paper[48] an H_∞ controller was studied. This controller design failed to provide any increase in flutter margin.

Magnetostrictively Actuated Control Flaps for Vibration Reduction in Helicopters

Control flap actuation using a magnetostrictive rod made of terfenol-D was studied[42,98] with considerable detail. A minimum weight actuator, subject to actuation and stress constraints, was designed and shown to be capable of vibration reduction in excess of 90% at cruise conditions, on a four-bladed soft in-plane hingeless rotor system. Mass of the magnetostrictive actuator material was found to be equal to 1.2% of blade mass, the total mass of the vibration reduction system was found to be approximately 6% of blade mass, and the magnetic field strength for actuation was less than 500 Oe, for all operating conditions. Ambient temperature changes in a range between −10°C and +60°C were shown to raise magnetic field requirements considerably. The influence of operating in a centripetal acceleration field near the rotor tip increases magnetic field requirements by approximately 20%. Power requirements for actuation were very low.

Smart Rotor Program at the University of Maryland

This activity concentrated on four different topics and considerable progress has been made on a variety of configurations: 1) controllable twist rotor with embedded piezoceramic actuators,[23] 2) trailing-edge flap actuated with piezoceramic bimorphs,[81] 3) trailing-edge flap with piezoinduced bending-torsion coupled actuator,[14,15] and 4) trailing-edge flap actuated by piezostacks.[22]

Among these designs, the trailing-edge flap with a piezoinduced bending-torsion coupled actuator was the most promising. A schematic representation of this configuration is shown in Fig. 23. In this configuration the empty space available in the spar is utilized to lay up a long beam with alternating composite lay-up, excited by surface-bonded piezoceramic elements. By alternating the lay-up directions of the bending-torsion coupling-producing laminates from section to section along the length of the composite beam, and alternating the polarity of the piezoelectric layers as well, it is possible to have induced bending curvatures canceling and torsion adding, from beam segment to beam segment. A disadvantage in this configuration is that the outboard bearing is loaded by a moment caused by centrifugal forces acting on the flap. This potential difficulty was eliminated by replacing the trailing-edge flap with a swiveling blade tip.

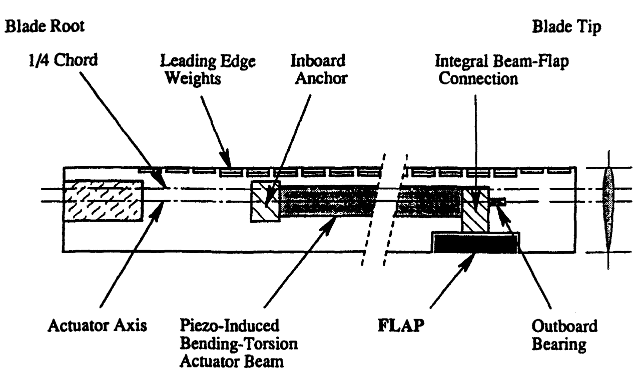

Fig. 23 Schematic representation of integral trailing-edge flap with piezoinduced bending-tension actuation.

Mesoscale Actuator Devices for Rotorcraft

A combination of active materials research with manufacturing techniques developed in the micro-electro-mechanical-systems area is currently being used at UCLA to develop piezoceramic-based mesoscale actuators. This is an improvement on the inchworm concept, utilizing micromachined grooves, to substantially enhance the force and stroke-producing capability of the device, compared with a conventional piezoceramic stack actuator. The intended application of this device is the design of an actuator that will be used in conjunction with an actively controlled trailing-edge flap, for vibration alleviation in helicopter rotors.[169]

Experimental Verification of Aeroelastic Behavior

Analytical predictions of aeroelastic behavior are usually verified by comparisons with flight tests or wind-tunnel tests, using aeroelastically scaled models.[127] For rotorcraft, the 40 × 80 ft wind tunnel at NASA Ames Research Center, which also has a lower speed section with dimensions of 80 × 120 ft, provides a full-scale testing alternative. It is interesting to note that very few correlation studies have been conducted comparing aeroelastic stability boundaries obtained on aeroelastically scaled models with those obtained from full-scale tests and analytical predictions.[125] It should be emphasized that comparisons between full-scale flight testing, tests conducted on an aeroelastically scaled model, and analytical predictions are often performed by aircraft manufacturers. However, these comparisons are rarely published in the open literature. Furthermore, full-scale tests of ASE configurations are very rare, as shown in the first section of this paper.[63]

Classical aeroelastic scaling concepts[18,126] have been developed for simple aeroelastic stability problems using Theodorsen's theory. These scaling laws are not suitable for ASE testing, where actuation power, hinge moment, and force play an important role, particularly when using active materials for actuation. Improved scaling laws can be obtained from computer simulations,[41] and their use is recommended when using actuators based on active materials. It should be mentioned that wind-tunnel or flight-test results obtained on small models using adaptive materials technology for actuation can produce overly optimistic results, when aeroelastic scaling is not carefully considered.

Aeroelastic Problems in New Configurations

New, unusual configurations provide the impetus that stimulates aeroelastic research. Representative examples from the past are the oblique wing aircraft, the X-29 forward-swept experimental research aircraft,[24] the tilt-rotor,[72] the human-powered vehicles developed at MIT,[158] et al.

A new configuration in this category is the X-33 Advanced Technology Demonstrator. It is a true hypersonic vehicle, which may require unsteady solution of Navier–Stokes equations, coupled with vehicle rigid body and flexible dynamics to provide aero-thermo-servo-elastic modeling. It will present some formidable challenges to the aeroelastician.[66,128,142,153]

Large, high-flying unmanned aerial vehicles such as Darkstar, Global Hawk, or Pathfinder, or the recently departed Theseus (built by Aurora Flight Sciences), are very flexible and operate at high altitudes and low Reynolds numbers, where unsteady aerodynamic loads are not well known. The autonomous nature of these vehicles requires a high-gain control system, which will interact with flexible and rigid-body dynamics; thus aeroservoelastic problems in this class of vehicles could be quite important.

A number of vehicles mentioned in the U.S. Air Force New World Vistas document are intended for uninhabited combat air vehicles (UCAVs) or high-altitude long-endurance air vehicles. Without pilots, UCAVs can maneuver at high speeds and high-*g* conditions, and these vehicles will also provide ASE challenges.

Aeroelasticity and Design

ASE plays a major role in modern aircraft design, and unless it is properly integrated in the design process, optimal configurations will not be developed. Wing/control shape optimization[91] with active controls and ASE constraints is a formidable problem that can be treated only after introducing many simplifications.

The rotary-wing design problem is easier, because the focus is on vibration reduction in the rotor.[51,168] Low-vibration rotors have been designed, built, and tested in the wind tunnel, demonstrating vibration reduction between 30–50%.[152,164] As a consequence, structural optimization with multidisciplinary constraints is accepted as a valuable tool in the helicopter industry. In view of the relative success experienced with rotary-wing vehicles, one may also wish to develop a similar combined experimental/theoretical demonstration project for fixed-wing-type applications.

Predicting the Future

Predicting the future can be dangerous to one's reputation; however, this author is not worried by the risk. From this paper it is evident that ASE has not fulfilled its promise for manned and commercial applications. Store flutter appears to be one application where actual FS systems can be implemented on practical configurations. The LQR, LQG, and other control methods related to linear optimal control theory do not seem to be well matched to ASE applications. In particular, these approaches have difficulty when realistic constraints are imposed on the maximum rate and deflection of the control surfaces used for flutter control. Adaptive[39] and nonlinear control methods[82] may hold more promise. A highly maneuverable UCAV operating at high speeds and high *g* may be a suitable candidate for the practical implementation of a flutter suppression system.

Rotary-wing aeroelasticity will continue to represent a major challenge. Computational unsteady aerodynamics for rotary-wing vehicles are needed for improved load prediction and blade vortex interaction studies. The ACF will become a practical vibration- and noise-reduction device in rotorcraft. Improvements in computer power will allow the use of free-wake models in routine aeroelastic and ASE computations for rotorcraft.

The role of adaptive structure-based actuation will continue to generate considerable research activity in aeroelasticity for both rotary-wing and fixed-wing applications. However, it is worthwhile keeping in mind the analogy drawn in the paper with composites and their application to aeroelastic tailoring, before overselling this new and exciting field.

Turbomachinery aeroelasticity, not considered here, will continue to provide formidable challenges. Finally, it is evident that while aeroelasticity is perceived (by some) to be a mature subject, new applications continue to provide challenges that often exceed those of the past.

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