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Integrated Aeroservoelastic Optimization: Status and Direction

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Nomenclature

$[\bar{A}]$, $[\bar{B}]$ = aeroservoelastic state-space matrices in the Lyapunov's equation for response to white noise
$[A]$, $[B]$, $[C]$, $[D]$ = state-space system and observation matrices of a linear system
$[\tilde{A}]$, $[\tilde{B}]$, $[\tilde{C}]$, $[\tilde{D}]$ = reduced-order state-space system and observation matrices of a linear system
$[A(k, M_\infty)]$ = matrix of aerodynamic influence coefficients
b = representative semichord
b_i = coefficients in the numerator of a typical transfer function for a control-system element
$[C]$ = damping matrix
c_0, $\{c_1\}$, $[c_2]$ = planform-dependent constant, vector, and matrix, respectively, in the equation for drag caused by lift, Eq. (7)
Dv_i = ith design variable
d_i = coefficients in the denominator of a typical transfer function for a control system element
$[E_i]$ = real matrices in the Roger approximation or the minimum state approximation of unsteady aerodynamic generalized forces
$[\tilde{E}_i]$ = real matrices in the Roger approximation or the minimum state approximation of unsteady aerodynamic generalized forces after transformation from one set of modes to another
$f_i(x, y)$ = shape functions for variable camber shape definition
$f(\{x\})$ = objective function
$\tilde{f}(\{x\})$ = approximate objective function
$\{g\}$ = vector of nonlinear constraint functions
$\{\tilde{g}\}$ = vector of approximate constraints
$\{h^j\}$ = displacements at aerodynamic downwash points in mode j
$\hat{j}$ = $\sqrt{-1}$
$[K]$ = stiffness matrix
$[K_G]$ = geometric stiffness matrix
k = reduced frequency
$[M]$ = mass matrix
M_∞ = Mach number
$\{ML\}$ = vector of move limits
m_i, n_i = powers of terms in the polynomial parametrization of skin thickness
m_L = number of lag terms in the Roger approximation
p = Laplace variable
$[Q(p)]$ = matrix of generalized aerodynamic forces
$[\hat{Q}_w]$ = intensity matrix of a Gaussian white noise driving a gust filter
$\{q\}$ = modal generalized displacement vector
$\{q_c\}$ = control surface rotations
q_D = dynamic pressure
q_w = pitch rate in a symmetric pull-up maneuver
r = input to a control system element
r_i, s_i = powers of terms in the polynomial parametrization of jig shape
$[T_{hd}]$ = interpolation matrix relating structural deflections to downwash at downwash points
$[T_{hp}]$ = interpolation matrix to determine structural deflections at pressure points
T_i = coefficients in the polynomial parametrization of skin-thickness distribution
$[T_{\alpha d}]$ = interpolation matrix relating structural deflections to slope (geometric angle of attack) at downwash points
$t(x, y)$ = thickness distribution for a skin layer
U = true airspeed
$[U]$, $[V]$ = aeroservoelastic state-space system matrices
$\{u\}$ = rigid body and elastic generalized displacements

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$\{\bar{\bar{u}}\}$	= see Eq. (8)
$\{u_0\}$	= generalized coordinates defining initial (jig) shape
W_i	= coefficients in the polynomial parametrization of jig shape
$\{w\}$	= vector of downwash entries for a lifting surface
w_G	= gust vertical velocity
$w_0(x, y)$	= jig shape of the wing
$[X]$	= aeroservoelastic state covariance matrix
x	= axis pointing along the fuselage in the wind direction
$\{x\}$	= vector of design variables, also vector of state variables, Eq. (39)
$\{x_L\}$, $\{x_U\}$	= lower and upper bounds on the design variable vector $\{x\}$
$\{x_0\}$	= vector of design variables at base (reference) design, where detailed objective and constraint functions are evaluated
y	= output from a control system element
y_{meas}	= measured response, as output of a sensor (accelerometer, strain gauge, or rate sensor)
y_{str}	= actual structural response (displacement, velocity, acceleration, strain) at a measurement point on the structure
β_i	= lag roots in the Roger approximation
$\{\Delta p^j\}$	= vector of pressure differences on a lifting surface in mode j
$[\Delta S]$	= diagonal matrix of panel areas
$\{\eta\}$	= aeroservoelastic eigenvector
$[\Lambda]$	= diagonal matrix in the minimum state rational function approximation, containing the real aerodynamic poles
λ	= buckling eigenvalue or aeroservoelastic pole
$\{\phi\}$	= mode shape vector
$[\Phi]$	= matrix of mode shape vectors
ω	= natural frequency

Subscripts

c	= control surface degrees of freedom
cont	= controller
e	= excitation caused by sources other than structural, control, or gust effects
G	= gust
h	= associated with vertical deflection
s	= structural degrees of freedom

Superscript

F	= full order

Introduction

THE interactions of lightweight flexible airframe structures, steady and unsteady aerodynamics, and wide-bandwidth active controls on modern airplanes lead to considerable multidisciplinary design challenges. More than 25 years of mathematical and numerical methods' development, numerous basic research studies, simulations and wind-tunnel tests of simple models, wind-tunnel tests of complex models of real airplanes, as well as flight tests of actively controlled airplanes, have all contributed to the accumulation of a substantial body of knowledge in the area of aeroservoelasticity.[1-5] A number of analysis codes, with the capabilities to model real airplane systems under the assumptions of linearity, have been developed.[6-12] Many tests have been conducted, and results were correlated with analytical predictions.

A selective sample of references covering aeroservoelastic testing programs from the 1960s to the early 1980s,[13] as well as more recent wind-tunnel test programs[14-19] of real or realistic configurations, are included in the References section of this paper. An examination of Refs. 20–29 will reveal that in the course of development (or later modification), of almost every modern airplane with a high authority active control system, there arose a need to face aeroservoelastic problems and aeroservoelastic design challenges.

It has become evident that aeroservoelastic analysis and synthesis are not just endeavors or tasks of choice, which the designer is free to adopt or reject, depending on whether he wants to pursue technologies such as active flutter suppression or gust load alleviation. Even if the designer chooses, as part of his design approach, not to create *desirable* interactions and not to try to harness these multidisciplinary interactions to his benefit, still, as long as there are onboard high-power active control systems for flight mechanics, he has to face some multidisciplinary problems in the form of *undesirable* interactions. Aeroservoelasticity, thus, must be addressed in the course of modern airplane design. And whether benefits of aeroservoelastic interactions are to be pursued, or problems avoided in a cost-effective way, aeroservoelastic analysis and synthesis should be included in as early a stage of the airplane design process as possible, and not be postponed until the design is almost complete.

This paper aims at examining the integrated aeroservoelastic design challenge in the context of the evolving field of multidisciplinary design optimization (MDO), and at reviewing the status of the effort to make aeroservoelasticity an integral part of airplane conceptual and preliminary design.[30] Emphasis is not on aeroservoelastic *analysis*, where aeroservoelastic behavior is evaluated for given configurations and control systems. The drive discussed here is to develop integrated aeroservoelastic *synthesis*, the capability to simultaneously, and in an integrated way, synthesize aeroservoelastic systems across their contributing disciplines, quickly, efficiently, and reliably.

The work discussed here is limited to airframes and control systems of fixed-wing airplanes operating without significant aerodynamic heating. Selected references, which can serve as starting points for the review of developments in aeroservoelasticity and multidisciplinary interactions on panels, hypersonic vehicles, rotary wing aircraft, and also addressing the problem of whirl flutter, can be found in Refs. 31–38.

In the following sections, the integrated aeroservoelastic synthesis problem is defined, and different levels of complexity and difficulty identified. Mathematical modeling for design, behavior response analysis, behavior sensitivity analysis, and approximation concepts is discussed. The status of research and development efforts aimed at capturing the complexity of real actively controlled airplanes is surveyed, and the lessons learned will lead to the identification of problems and difficulties as well as to recommended directions for future work. A selective list of references is included, to provide a solid starting point for any interested reader, who seeks to study the many aspects of the interesting and complex problems at hand.

Analysis Problems: General Classification

The array of computational tasks needed during the design evaluation of a modern airframe can be sorted and categorized according to disciplines involved, the type of behavior in space and time captured by analysis, or according to the type of mathematical problems addressed. In general, for most fixed-wing aircaft, the disciplines affecting the design evolution of the airframe include 1) external aerodynamics (including propulsion integration), 2) structures (including materials), 3) control, 4) flight mechanics (including point performance and flight path analysis), and 5) economics. Electromagnetics for airplanes where radar cross section is important, integrated powerplant design on some air-breathing hypersonic vehicles, or heating problems in certain supersonic airplanes can be important in some design problems, but these are beyond the scope of the technology covered here. Space–time behavior classification leads to the distinguishing between 1) linear and nonlinear problems; 2) steady and unsteady (dynamic) problems; and 3) between problems of global nature (associated with the complete airframe or large sections of it) and problems of local nature (such as panel buckling and panel flutter problems, the failure modes of brackets and fittings, etc.).

The computational effort supporting modern airframe design must cover the following mathematical problems.

1) The utilization of explicit algebraic formulae (including numerical integration) for the generation of system matrices of structural and structural dynamic models (including the important *as-built* weight estimates[39,40]), system matrices for aerodynamic models, state-space dynamic system and control-system models, and mathematical models for flight mechanics and flight-path analysis. Airplane point performance analysis as well as cost analysis are also included in this category.

2) The solution of linear and nonlinear systems of algebraic equations, obtained from discretization of the relevant field problems, such as fixed-shape steady aerodynamic analysis; fixed-loads static structural analysis; solution-dependent-loads static aeroelastic analysis; and steady-state gust response covariance analysis.

3) The solution of eigenvalue problems such as static aeroelastic stability analysis and aileron reversal analysis (if needed); aeroservoelastic stability analysis in the Laplace domain, or bifurcation buckling stability analysis.

4) The solution of time-dependent linear and nonlinear problems modeled by systems of ordinary differential equations (after discretization of time-dependent field problems). Stability, control, and aeroservoelastic flight mechanics of the deformable airplane (including large motions as well as small-perturbation motion); flight-trajectory analysis; aeroservoelastic response to discrete gusts; and aeroservoelastic response to transient loads.

Some problems of mesh generation for either aerodynamic or structural models can belong mathematically to categories 1 or 2 (or even 3), depending on the mesh generation method and methods of computer-aided geometry used.

The classifications listed in the preceding list, while admittedly quite general, provide a standard against which the state of the art in airplane modeling for analysis and modeling for design optimization can be evaluated. There have been major developments in recent years in applied computational fluid dynamics (CFD), computational structural mechanics, computer graphics, and dynamic system simulation, as well as significant improvements in computational hardware. The aerodynamic analysis and shape synthesis of realistic airplane configurations[41-47] is becoming increasingly practical. Structural analysis and sizing optimization of complete airframes are already widely practiced.[48-58] So are the development and simulation of multi-input multi-output (MIMO) nonlinear control systems for the maneuvering airplane, with their variable gains and different limiters.

However, the generation of detailed mathematical models, and the detailed integrated analyses of the maneuvering airplane in all flight regimes constitute a monumental task. In some areas, accurate and reliable modeling and analysis are still beyond the capability of current technology. It takes months to complete just a very limited number of detailed analyses, and while this might be acceptable when one focuses on the results of one thorough, definitive cycle of detailed analyses, this is unacceptable when early design optimization of the whole vehicle is concerned. During design optimization, many configurations, alternative shapes, structural arrangements, control systems, and flight trajectories must be considered. Any optimization algorithm solving an optimization problem involving many design variables and constraints will change and evaluate the design numerous times. The challenge of design-oriented modeling is to construct quickly an array of reliable and efficient mathematical models covering all relevant disciplines. Accompanying fast analysis and solution techniques must make it possible to carry out a large number of complete behavior evaluations of the airplane, subject to a large number of variations of design variables in all relevant disciplines.

Aeroservoelastic Analysis: Coupled Nonlinear Behavior Models

If computers were fast enough, and limitations on the size of computer memory posed no problem if user-friendly robust algorithms were available for meshing and discretization of the relevant field problems in structures and aerodynamics, and if numerical solutions of large-scale nonlinear coupled-field problems for steady-state and time-domain behavior were practical, if simulation of the motion of a deformable airplane along a flight path, and the dynamic behavior of sensors and actuators in the presence of an active control computer could be done in an integrated manner, then, ideally, in the course of design optimization of an actively controlled vehicle, the following problems could be coupled and solved repetitively.

1) Steady-state (static) structural analysis subject to nonlinear loads, taking into account the possibility of large overall motions (in six rigid degrees of freedom), with small or large elastic deformations, allowing for buckling and postbuckling behavior.

2) Steady-state nonlinear aerodynamic analysis, covering the operational range of angles of attack (including high angles of attack) and flight conditions (including transonic speeds), and capable of capturing shock waves, separation, vortex generation, and vortex motion.

3) Steady-state aeroelastic analysis, e.g., Ref. 42.

4) Time-dependent nonlinear structural, aerodynamic, and aeroelastic[59,60] analyses, coupled with nonlinear control-system simulation, taking the nonlinearities of the control system (such as the presence of limiters, switches, gain schedules, etc.) into account.

The capability to carry out a whole array of aeroservoelastic behavior analyses of such scope is, of course, still beyond reach. Realistic design-oriented analysis models, to be used repetitively in the course of practical aeroservoelastic design optimization with current computational technology, must be more limited in size and in scope.

Aeroservoelastic Synthesis: Contributing Analyses

A practical and realistic aeroservoelastic synthesis problem, which is believed to be ready for inclusion in airplane MDO using current computational technology and modeling practices, can be supported by the following analyses, covering steady and dynamic behavior of the maneuvering, flexible, actively controlled airplane.[61-64]

1) Static *given loads* structural analysis, in which the airplane is constrained against rigid body motion in some manner, and is subject to predetermined load distributions that do not change throughout the design. The elastic displacements are obtained from a solution of the linear system of equations

$$[K]\{\boldsymbol{u}\} = \{\boldsymbol{P}\} \tag{1}$$

where $[K]$ is the stiffness matrix, $\{\boldsymbol{u}\}$ is the vector of displacements, and $\{\boldsymbol{P}\}$ is the load vector (or a set of load vectors).

2) Static aeroelastic *maneuver loads* linear analysis, in which the deformable airplane is free, and the loads depend on the flight conditions and take aeroelastic load redistribution into account. Motion in the rigid-body degrees of freedom and elastic motions, as well as control-surface rotations needed for trim, are obtained from a solution of the linear system of equations[62,65-69]

$$[\bar{K}]\{\bar{\boldsymbol{u}}\} = \{\bar{\boldsymbol{P}}\} \tag{2}$$

where the modified $[\bar{K}]$ now contains structural and aerodynamic contributions, and the loads $\{\bar{\boldsymbol{P}}\}$ depend on the maneuver parameters (load factor, roll rate, Mach number, altitude), aerodynamic design variables (initial camber distribution, or *jig shape*), and the structural design variables (through inertial loads).

It should be noted here that progress in CFD-based steady aeroelastic analysis has reached a stage where it is believed that it will become ready for inclusion in early integrated aeroservoelastic design optimization in the next few years. This will cover static aeroelastic nonlinear maneuver loads analysis, in which allowance for large rotations in the three *rigid body* rotational degrees of freedom is coupled with linear structural analysis and nonlinear aerodynamic analysis.[41,42,45]

3) Global and local bifurcation buckling [calculated for the internal loads obtained from Eqs. (1) and (2)[70–76]], or the nonlinear analysis in 2, where a panel or a group of panels can buckle, depending on the eigenvalues of

$$[[K] + \lambda[K_G]]\{\boldsymbol{\phi}\} = \{\mathbf{0}\} \tag{3}$$

or by using simpler interaction formulas.[77]

4) Natural frequency and mode-shape analysis

$$[-\omega^2[M] + [K]]\{\boldsymbol{\phi}\} = \{\mathbf{0}\} \tag{4}$$

where $[M]$ is the mass matrix.

5) Aeroservoelastic linear stability analysis[61,62,64,78–80]

$$\lambda[U]\{\boldsymbol{\eta}\} = [V]\{\boldsymbol{\eta}\} \tag{5}$$

where $[U]$ and $[V]$ include structural, unsteady aerodynamic, and control-system effects,[61,62,64] and λ is an aeroservoelastic pole.

6) Dynamic response analysis[81–84] for calculating time histories, and determining peak values of rigid-body motions, elastic deformations, and stresses resulting from dynamic excitation by transient control surface inputs, discrete gusts, landing impact, external store ejection, etc. The free-response equations [Eq. (5)] are transformed from the Laplace domain to the time domain, and the right-hand side (RHS) is modified to include forcing functions, and can be solved in the time domain by direct time integration. Alternatively, they can be solved in the frequency domain and then, selected responses can be transformed to the time domain using inverse fast Fourier transform (FFT) techniques.[85]

7) A gust response analysis for the state covariance matrix $[X]$[61,62,86,87]

$$[\bar{A}][X] + [X][\bar{A}]^T = -[\bar{B}][\hat{Q}_w][\bar{B}]^T \tag{6}$$

where $[\bar{A}]$ and $[\bar{B}]$ depend on structural and control system design variables, and $[\hat{Q}_w]$ is the intensity matrix of a Gaussian white noise driving a gust filter that generates either Dryden or approximate von Kármán[62] gust-excitation power spectral density. Root mean square (rms) values of accelerations, measurements, and control-surface activity in terms of rotation and rotation rate are calculated based on $[X]$.

8) Drag analysis based on linearized aerodynamics and small rotations, where induced drag for the deformed configuration in flight is calculated by integrating pressures over the exposed surfaces (taking leading-edge thrust into account), or by integration in the Treffetz plane.[88–95] If friction and form drag are included by buildup from components and by the integration of a two-dimensional airfoil drag along the span of the wing, and if the airfoil drag is parabolic in terms of airfoil lift, then the drag on the configuration can be approximated for small angles of attack by

$$c_D = c_0 + \{\boldsymbol{c}_1\}^T\{\bar{\boldsymbol{u}}\} + \{\bar{\boldsymbol{u}}\}^T[c_2]\{\bar{\boldsymbol{u}}\} \tag{7}$$

where c_0, $\{\boldsymbol{c}_1\}$, and $[c_2]$, respectively, are planform-dependent constant, vector, and matrix, and the vector $\{\bar{\boldsymbol{u}}\}$ contains jig-shape (initial shape) coefficients $\{\boldsymbol{u}_0\}$, rigid body and elastic displacements $\{\boldsymbol{u}\}$, as well as control surface rotations $\{\boldsymbol{q}_c\}$ and pitch rate q_W (in a symmetric pull-up maneuver)

$$\{\bar{\boldsymbol{u}}\} = \begin{Bmatrix} \{\boldsymbol{u}\} \\ \{\boldsymbol{q}_c\} \\ 0 \end{Bmatrix} + \begin{Bmatrix} \{\boldsymbol{u}_0\} \\ \{\mathbf{0}\} \\ q_W \end{Bmatrix} \tag{8}$$

With a relatively small modification of the drag analysis described earlier, additional nonlinear effects can be included, such as semiempirical corrections for attainable leading-edge thrust,[65,95] or corrections for drag resulting from flow behavior over flap hinge lines. The emphasis here is on corrections of airplane drag estimates because of angle of attack, trim, and shape variation effects of airframe flexibility. More comprehensive drag-prediction techniques, based on CFD analysis of the complete configuration, are becoming more powerful and more practical.[47,96,97] Integration of such capabilities into the framework of aeroservoelastic synthesis is a challenge calling for further research and development in the years ahead.

Analytical derivatives of all behavior functions with respect to all design variables can be obtained by implicit differentiation of the analysis equations.[98] This can be done analytically[62,98] or by using automatic differentiation.[99] Alternatively, finite difference (FD) and semianalytic (SA) differentiation techniques[98] can be used, as required. Of course, the development and computational challenges of obtaining behavior sensitivities of nonlinear structural and CFD calculations is still considerable,[100–106] but significant progress has been made in this area. More on obtaining sensitivities will be discussed later in this paper.

Aeroservoelastic System Characteristics and Behavior: Design Constraints and Candidate Objective Functions

The goal of the array of analyses outlined earlier is to predict the characteristics of an aeroservoelastic system as well as its response to controlled and uncontrolled excitations throughout the flight envelope and the operational life of an airplane. These predictions must be used throughout the design process to make sure that the resulting design is safe, behaves in a desirable manner, its characteristics meet design specifications, and that the resources required are acceptable. It is important to note that many behavior measures, while extremely important, might not be of particular interest from the overall airplane system point of view (as the aeroservoelastic design problem is just one part of the overall design problem), while other behavior measures translate into characteristics that are observed at the highest level of airplane system design. For example, particular stresses in specific parts of maneuvers are not visible from an overall system perspective as long as safety of the structure is guaranteed. Vibration levels during a flight in turbulence, affecting the ride comfort of the air crew and passengers, translate immediately into ease of operation and customer satisfaction. It is convenient, then, to distinguish between primary behavior measures, which are monitored and observed at the highest system level, and affect economics and operator/customer satisfaction, and secondary (internal) behavior measures, which can be transparent at the customer/operator level of evaluation.

In the structures area, elastic deformations, strains, and stresses (both static and dynamic) should be evaluated, as well as buckling instabilities, to guarantee structural integrity.[107,108] Based on the resulting structural model at every step of the design process, *as-built* weights[39,40] must be evaluated, and, depending on the topology and philosophy of design, the cost and manufacturing time can be estimated.

In the aerodynamics area, drag or drag-to-lift ratios for the flexible airplane can be evaluated for a variety of flight conditions.[91–95] Constraints on pressure distributions to guarantee flow smoothness, or to protect against seperation or buffett[65] can also be included.

Assuming a tightly coupled structural/flight-control system, dynamic aeroservoelastic stability (covering both rigid-body and elastic motions) must be ensured.[61–64] Handling qualities must be within recommended envelopes.[109–112] Handling quality constraints can be imposed on the locations of system poles, or by using frequency- and time-response performance measures.[29] Vibration and noise levels felt by the passengers and flight crew should be within recommended comfort levels.[113,114]

On the control system's side, if given actuators and sensors are used, and if predetermined hydraulic and electric systems are imposed, then limitations on actuator power, rate, and stroke, as well as limitations on overall hydraulic and electric power systems, must be met. If, however, actuators and their supporting power systems are to be designed as part of the aeroservoelastic synthesis task, then, of course, actuator and support system power requirements can be used to formulate constraints or objective functions, and these evaluations can be linked to cost and weight estimates for the active control system.

The consideration of robustness measures[115–117] has become an integral part of any practical control-system design synthesis. However, this is just one aspect of the important problem of how to carry out design optimization in the face of uncertainty; more on this problem will be discussed later in this paper.

Behavior measures such as weight, cost, flight performance (as influenced by lift, drag, and weight), ride comfort, or ease of handling are clearly primary, in that they have a direct impact on airplane operators, pilots, and passengers. At a lower level from an overall system's perspective is a host of other constraints mentioned earlier, which protect against failure mechanisms such as structural disintegration and instability, or ensure feasibility of the design within the limitations on materials, control-system power, and actuator performance. These constraints can be transparent at the systems level.

It is interesting to note that, with the developments in active control technology, some of these *transparent* constraints can even become unnecessary, and be dropped from the set of behavior constraints altogether. A case in point involves the aileron effectiveness constraint.

In addition to divergence, one of the most important static aeroelastic constraints in high-performance aircraft has been aileron effectiveness.[118–122] Airplane deformation, through the static aeroelastic action, tends to modify the stability derivatives[28,123–126] as well as unsteady aerodynamic forces used to couple flight mechanics and control-system behavior. In the case of thin, high-speed wings, wing twist resulting from aileron rotation can lead to aileron reversal, in which the twisting of the wing cancels any rolling moment resulting from the aileron rotation. In the case of typical fighter airplanes flying at low altitudes and at transonic speeds, the effectiveness of the ailerons can be reduced to 10–15% of what could have been achieved if the wing was rigid. In many formulations of the aeroelastic optimization problem, the constraint that limits the reduction of aileron effectiveness leads to considerable stiffening of the wing, and to added weight.

A different design approach, the active flexible wing (AFW), can, however, be adopted, if several leading- and trailing-edge control surfaces are available.[127–129] Using the control system to rotate each of the control surfaces at any given flight condition (rotation angles, which serve as aerodynamic camber design variables), enough rolling moment can be produced by the control surfaces even if one of them becomes reversed. Thus, it is feasible to ignore the constraints on individual aileron effectiveness[61,62,129] and to focus on meeting the desired performance of the airplane in terms of roll rate, pitch rate, or any time response to pilot commands.

As in the selection of design variables, which will be discussed next, constraints from all participating disciplines should be included in a balanced way. Results of any synthesis effort will be misleading, if failure modes in one discipline are included in the set of constraints in great detail, while other important constraints, representing a different discipline, are ignored.

Design Variables

Borrowing from the terminology developed for structural optimization,[61] a hierarchy of design variable types can be identified, in which the complexity of the design task and the associated computational challenges grow, as design variables change from sizing type, to shape design variables, and finally, at the highest level of complexity, to topology design variables.

Topology Design Variables

Topology changes involve layout variations in the form of number and relative positions of bodies and lifting surfaces, changes in the number of spars and ribs, and their pattern, changes in the number and location of control surfaces, the order of control-law transfer functions, and the identity of sensors and actuators they connect, i.e., which actuator responds to inputs from which sensors. The resulting optimization problem can be global in nature, with multiple minima over disjoint design spaces, with both discrete and continuous design variables. Practical topological optimization of realistic aeroservoelastic systems is still well beyond the capability of any current aeroservoelastic synthesis technique.

Sizing-Type Design Variables

When sizing-type design variables are used, preassigned parameters for the optimization include both topology and shape. Wing planform and depth (airfoil shape) distribution, control surface size and location, material properties, and structural layout of the wing (number of spars and ribs and their locations) and fuselage are preassigned. Control system structure is also preassigned. Thus, the number of sensors and actuators and their locations are given along with the number of control laws transforming given combinations of sensor outputs into control commands. It is also assumed that the general form of the transfer functions of sensors and actuators are given and cannot be changed during optimization (alternative approaches to the parametrization of the control system will, of course, lead to different choices for control system design variables).

To take advantage of multidisciplinary interactions, the design space is opened up to include structural design variables, control system (both hardware and software), and aerodynamic design variables simultaneously.

Structural design variables include thicknesses of panels, cross-sectional dimensions of beams and rods, mass and inertia of concentrated masses, as well as spring coefficients representing actuators and hinge stiffness. Usually, design variables associated with groups of individual finite elements are linked to guarantee smoothness of the resulting design and to reduce the number of design variables.[130,131] This linking may be obtained by assuming constant thickness (or constant cross section) for a structural region, or by using a series of spatial functions to determine the structural variation in a given region. In the polynomial-based equivalent plate approach,[132–134] structural design variables include polynomial coefficients, T_i, in the polynomial series describing skin-layer thickness distribution over the wing. In the case of composite skins, a separate series is assigned to the thickness in each fiber direction, as follows:

$$t(x, y) = \sum_{i=1}^{I} T_i x^{mi} y^{ni} = \sum_{i=1}^{I} DV_i x^{mi} y^{ni} \tag{9}$$

When a typical stressed skin aeronautical wing structure is considered, a finite element model of the structure suitable for predicting global behavior can be constructed using truss, shear web, and plane-stress membrane elements. Plane stress elements are used for the skins. Shear webs are used for the spar and rib webs, and truss elements are used for the spar and rib caps. The stiffness and mass matrices are, in this case, linear in the sizing-type structural design variables DV_i

$$[K] = \sum_i [K_i] \cdot DV_i \tag{10}$$

where a typical DV_i can be the cross-sectional area of spar/rib cap, or the thickness of a skin or web element, and the matrices $[K_i]$ are evaluated once and depend on element geometry and material and element position in the global structure. Thus, sensitivity of the stiffness matrix with respect to truss and plane-stress element design variables, has to be evaluated only once, and will not change throughout the design cycle. Equation (10) can actually be used to re-evaluate the stiffness matrix whenever sizing design variables change, and there is no need to go back to element stiffness computations and their transformation to global coordinates.

When beam, plate, and shell elements are used, their stiffness matrices depend on their sizing design variables (such as thickness or cross-sectional geometric properties) in a nonlinear manner.[135,136] Still, it is simple to obtain sensitivities with respect to these design variables because the global mesh of the finite element model does not change, and nodes stay in their original places during the optimization.

Control-system design variables can include polynomial coefficients, b_i and d_j, in the transfer functions representing control laws.[61,62]

$$\frac{y(p)}{r(p)} = \frac{b_n p^n + \cdots + b_1 p + b_0}{p^n + d_{n-1} p^{n-1} + \cdots d_1 p + d_0} \tag{11}$$

In the case of a second-order transfer function, e.g.,

$$\frac{y(p)}{r(p)} = \frac{b_2 p^2 + b_1 p + b_0}{p^2 + d_1 p + d_0} \tag{12}$$

where $r(p)$ is the Laplace transformed input, $y(p)$ is the Laplace transformed output, and p is the Laplace variable. An equivalent state-space representation consists of a state equation

$$p \begin{Bmatrix} \boldsymbol{x}_1 \\ \boldsymbol{x}_2 \end{Bmatrix} = \begin{bmatrix} 0 & -d_0 \\ 1 & -d_1 \end{bmatrix} \begin{Bmatrix} \boldsymbol{x}_1 \\ \boldsymbol{x}_2 \end{Bmatrix} + \begin{Bmatrix} \boldsymbol{b}_2\boldsymbol{d}_0 - \boldsymbol{b}_0 \\ \boldsymbol{b}_2\boldsymbol{d}_1 - \boldsymbol{b}_1 \end{Bmatrix} r \tag{13}$$

and an observation equation

$$y = \begin{Bmatrix} \boldsymbol{0} \\ -1 \end{Bmatrix}^T \begin{Bmatrix} \boldsymbol{x}_1 \\ \boldsymbol{x}_2 \end{Bmatrix} + [b_2] r \tag{14}$$

which in conventional state-space notation are written as

$$\begin{aligned} p\{\boldsymbol{x}\} &= [A]\{\boldsymbol{x}\} + \{\boldsymbol{B}\} r \\ y &= \{\boldsymbol{c}^T\}\{\boldsymbol{x}\} + [D] r \end{aligned} \tag{15}$$

The state-space matrices $[A]$, $[B]$, $[C]$, and $[D]$ are explicitly expressed in terms of the control system design variables in this case, and evaluation of them and their sensitivities with respect to these design variables is fast and straightforward. In the case of a strictly proper transfer function ($b_2 = 0$), the state-space matrices of a control element are linear in the design variables defined earlier. Their sensitivity with respect to these design variables has to be evaluated only once, and does not change throughout the design.

This parametrization, while simple, and directly related to the practical implementation of the resulting design, leads to disjoint design spaces[140] and to serious difficulties in gradient-based optimization. It is used here just as an example. If other control systems parametrizations are used, control system design variables will be determined accordingly.[137–143] Note that the stability constraints in the problem must ensure stability of the closed-loop complete system, as well as (if actuators are synthesized) the open-loop stability of these actuators. The poles of actuator transfer functions, such as in Eq. (11), must then be always stable.

Aerodynamic sizing-type design variables include coefficients in any parametrization of the jig shape.[61,62,89,124] For a preassigned planform, this is the camber shape of the manufactured unloaded wing, which needs to be determined so that in flight, while it is deformed under the action of loads [Eq. (2)], it leads to desirable performance. The jig shape can be defined by the vertical distance of the center plane of the wing from the reference $x-y$ plane using a series of polynomials

$$w_0(x, y) = \sum_{i=1}^{I} W_i x^{r_i} y^{si} \tag{16}$$

and the coefficients Wi can serve as jig shape design variables. Steady angles of the rotation of flaps and ailerons can be added to the set of aerodynamic design variables[61,62,129,144,145] to make it possible to change effective wing camber during different flight conditions. Variable camber (on a mission adaptive wing), can then be designed, by assigning design variables to the rotation of control surfaces to change the effective camber of the wing, or by assigning design variables to smooth functions of the form

$$w_0(x, y) = \sum_{i=1}^{I} DV_i fi(x, y) \tag{17}$$

where the shape functions $f_i(x, y)$ represent a smooth change in the camber obtained using flexible skin to cover flap mechanisms[146] or by using strain actuators.[147,148]

A control-surface rotation design variable can be allocated for each maneuver desired (Ref. 62). Similarly, control system parameters (Eq. 11) can be assigned for each maneuver point independently, and some form of *gain scheduling* may be used to switch control-system gains from flight condition to flight condition.[29]

Actually, changes in jig shape and camber design variables (categorized as aerodynamic *sizing* design variables) lead to changes in the camber shape of the wing. Nevertheless, these design variables are different from the other aerodynamic *shape* design variables, those that define the planform shape (sweep, aspect ratio, taper ratio, size and location of control surfaces, etc.) and airfoil thickness. When linearized lifting-surface aerodynamic theories are used (and small perturbation motion is assumed), the variation of aerodynamic sizing design variables does not change the aerodynamic mesh required, nor does it change the matrix of aerodynamic influence coefficients $[A]$ in the equation for pressures

$$[A(k, M_\infty)]\{\Delta \boldsymbol{p}\} = \{\boldsymbol{w}\} \tag{18}$$

where $\Delta \boldsymbol{p}$ and $\boldsymbol{w}$ are the pressure differences and downwash, respectively. Only the RHS, the downwash, is affected, and its dependence on jig shape and camber design variables is explicit and easy to compute.[62]

All sizing-type design variables, then, do not lead, during the optimization, to changes in mesh (whether structural or aerodynamic), or to changes in the location of nodes, or variation in the order (dimension) of any of the linear models used across the disciplines. They are, thus, much easier to handle than the shape design variables (which are discussed next), and of course, the toplogy design variables.

Shape-Design Variables

In a structural sizing problem, the matrices $[K_i]$ [Eq. (10)] are fixed. But they are nonlinear functions of the location of nodes in a finite element model of given topology. When shape-design variables are added to the problem, they determine the shape of the structure through any one of many possible shape parametrizations. The resulting variation of node locations leads to complex nonlinear dependence of the structural matrices on the shape-design variables and to a more expensive updating of these matrices.[148–155] Shape-design variables for a wing can include (as already discussed) aspect ratio, taper ratio, span and sweep, or, alternatively, the location of the vertices defining the planform shape of the wing. Fuselage shapes can be parametrized using polynomial or spline shape functions.[149,156,157] Locations of wings, canards and tail surfaces, and their shapes, are also included in the set of shape design variables.

In the aerodynamics area, with linearized, small-perturbation aerodynamics, as long as planform shape and control-surface size and location are fixed, the aerodynamic influence coefficient matrices [Eq. (18)] are fixed. When the overall planform shape of the wing is to be determined, as well as its airfoil depth distribution, then the aerodynamic influence coefficient matrices (both steady and unsteady) have to be generated anew with every change in shape-design variables.[158–164]

When the topology of the control system is fixed, then the number and type of sensors and active control surfaces, the connectivity and structure of control laws, and the order of the associated transfer functions are all fixed. Control-system "shape"-design variables are assigned to determine the positions of sensors, as well as size and location of control surfaces.[122,154] As can be seen, structural and aerodynamic effects are coupled in this case with control-system variation. Variation of shape-design variables in all disciplines, then, leads to variation of structural and aerodynamic meshes, and to changes in the location of structural and aerodynamic nodes as well as points of response measurement and system actuation.

The changes in node locations and overall mesh lead in certain cases to deterioration of accuracy of the analysis prediction because most finite elements perform well only within certain limits on aspect ratio and angular distortion.[153] Using the semianalytic method[98] to obtain structural sensitivities with respect to shape-design variables must be done carefully to avoid errors.[165] In the aerodynamic area, shape changes, leading to mesh changes, can also lead to errors in analysis and to noisy sensitivity evaluation. The *wiggly* behavior of analysis predictions[166] is especially severe when, in the course of shape variations, computational cells or aerodynamic panels get distorted and stretched in areas of high gradients of flow variables (such as subsonic leading edges or control-surface hinge lines).

Design-Oriented Modeling

For MDO to make an impact on the design in its early stages, careful consideration must be given to the creation of adequate mathematical models in all disciplines involved. Here it is important to distinguish between analysis models and design models,[167–169] design models being crafted for the special requirements posed by an MDO environment. The main issues distinguishing design models from analysis models revolve around 1) degree of detail and level of accuracy, 2) cost and time required for model generation, 3) availability of sensitivity information, 4) efficiency of interfaces and data transfer, and 5) cost of design-oriented analyses (given that a design oriented analysis has to be carried out repeatedly in the course of optimization).

It has long been the practice in airplane design, that simple approximate mathematical models serve successfully during the very early stages of design, and that more refined models are brought in as the design progresses from conceptual, to preliminary and, finally, to detail design. However, when the challenge is to design a new type of airplane, and when there is not enough engineering experience and data to support such a design, it is important to bring detailed, accurate analysis techniques to the cutting edge of the design effort. This is even more important when aeroservoelastic interactions are to be harnessed as *assets* rather than dealt with as *troubles* in a new integrated control augmented flight vehicle.

A list of questions that should be asked regarding model simplification include the following. Do we need all of the fine detail in the structural models, including local effects (which are accounted for in detail design), or is it sufficient to construct a structural model with a coarser finite element or aerodynamic mesh and less attention to local detail? Do we have to comply with the precise geometric definition of the outer shape of the airframe (including complex curves that are used locally in areas of component attachments and interfaces), or is it sufficient to generate an approximated geometry that captures the overall shape with acceptable accuracy and ignores localized inaccuracies? This last question will, of course, have different answers when structures or aerodynamic simplifications are discussed.

As to accuracy of point predictions (analysis) or trend predictions (design sensitivities). Do we accept less accurate stress, deformation, mode shape, natural frequency, aerodynamic load, and drag predictions if we can capture their sensitivities (trends) accurately? And, if accuracy of the design-oriented analysis is to be pursued, then how accurate should a design model be to be acceptable, compared with the accuracy of an analysis model?

Model detail and preciseness of geometric definition translate directly into time and effort required to create a structural finite element model or a CFD mesh for an airplane. There are powerful computer-aided graphics tools today, as well as developments in preprocessing and postprocessing for common commercial finite element and CFD codes. However, it is still a major problem in the airplane industry to create reliable structural and aerodynamic models with a short enough cycle time to be acceptable for early design stages, when many alternative configurations must be evaluated and compared quickly and efficiently.[170,171] In aeroservoelasticity, the problem is particularly serious because both structural and aerodynamic models must be created in a balanced way, and any weakness in modeling in any of the disciplines will affect the results of the whole design optimization effort.[156]

Discussion of the hierarchy of structural analysis techniques (from equivalent beam to equivalent plate to simplified finite element and to detailed finite element models), and aerodynamic analysis techniques (from linearized lifting surface to linearized panel methods to full potential and Euler and up to Navier–Stokes CFD methods), and the corresponding accuracies and effects on optimization can be found in Refs. 61, 172–177. Discussion of automated model generation and updating can be found in Refs. 47, 156, 171, and 178–182. In the following sections we address issues that are unique to the aeroservoelastic design-oriented analysis task.

Aspects of Design-Oriented Aeroservoelastic Mathematical Model Generation

Aeroelastic Equations of Motion

The Laplace transformed equations for the small perturbation motion for an elastic airplane with control surfaces, can be partitioned as follows:

$$\begin{aligned}&[p^2[M_{ss}] + p[C_{ss}] + [K_{ss}] - q_D[Q_{ss}(p)]]\{\boldsymbol{q}_s(p)\}\\&\quad + [p^2[M_{sc}] - q_D[Q_{sc}(p)]]\{\boldsymbol{q}_c(p)\}\\&= \frac{q_D}{U}\{\boldsymbol{Q}_{sG}(p)\}w_G(p) + \{\boldsymbol{Q}_{se}(p)\}\end{aligned} \tag{19}$$

$$\begin{aligned}&[p^2[M_{cs}] - q_D[Q_{cs}(p)]]\{\boldsymbol{q}_s(p)\} + [p^2[M_{cc}]\\&\quad - q_D[Q_{cc}(p)]]\{\boldsymbol{q}_c(p)\}\\&= \frac{q_D}{U}\{\boldsymbol{Q}_{cG}(p)\}w_G(p) + \{\boldsymbol{Q}_{ce}(p)\}\end{aligned} \tag{20}$$

where p is the Laplace variable, and $[M_{ss}]$, $[C_{ss}]$, and $[K_{ss}]$ are structural mass, damping, and stiffness matrices, respectively. The generalized unsteady aerodynamic matrix associated with structural degrees of freedom is $[Q_{ss}(p)]$. Motion in structural degrees of freedom is described by the vector $\{\boldsymbol{q}_s(p)\}$, and active control surface rotations (actuator outputs) are contained in $\{\boldsymbol{q}_c(p)\}$. The inertial and aerodynamic coupling between structural and active control surface motions is modeled by the matrices $[M_{sc}]$ and $[Q_{sc}(p)]$. Laplace-transformed gust velocity and associated generalized force vector are given by $w_G(p)$ and $\{\boldsymbol{Q}_{sG}(p)\}$, respectively. Corresponding terms indexed cc and cs account for actuated control surface motion and its coupling with the structural degrees of freedom. Generalized excitation forces caused by other sources are given by $\{\boldsymbol{Q}_{se}(p)\}$, $\{\boldsymbol{Q}_{ce}(p)\}$ (including hinge moments), and the equations are written for flight at airspeed U and dynamic pressure q_D.

These aeroelastic equations of motion are the basis for static aeroelastic analysis (no time dependence, but inertia relief included), flutter analysis (no active controls and no excitations), aeroservoelastic stability analysis (no excitations), or dynamic response to excitations.[62] They apply to cases where linear structural modeling and linear unsteady aerodynamics provide adequate representation of the aeroelastic behavior of deformable aircraft, and have been used successfully for the aeroelastic analysis of airplanes flying in the subsonic and supersonic flight regimes.

When detailed finite element structural models are used, the order of the resulting equations is reduced by some form of modal-order reduction, where the displacement vector $\{\boldsymbol{u}_s(p)\}$ is approximated by a linear combination of a fewer number of modal vectors (mode shapes)

$$\{\boldsymbol{u}_s(p)\} = [\Phi]\{\boldsymbol{q}_s(p)\} \tag{21}$$

The matrix, $[\Phi]$, contains a subset of the normal modes of the structure, or normal modes of a modified structure, or a set of suitable Ritz vectors. Effective structural order reduction is crucial for design modeling, because common finite element models of airplanes are too big and intensive computationally, to be used in detail, repeatedly during the optimization process.[183–189] If the partitioned full-order mass and stiffness matrices are $[M_{ss}^F, M_{sc}^F]$, $[K_{ss}^F, 0]$, then they are replaced by reduced-order generalized mass and stiffness matrices

$$[K_{ss}] = [\Phi]^T[K_{ss}^F][\Phi] \tag{22}$$

$$[M_{ss}] = [\Phi]^T[M_{ss}^F][\Phi] \tag{23}$$

$$[M_{sc}] = [\Phi]^T[M_{sc}^F] \tag{24}$$

The selection of mode shapes or Ritz vectors for structural-order reduction is extremely important in the context of structural, aeroelastic, and aeroservoelastic synthesis. As the structure changes in composition and shape during the optimization process, the question is: should the modes used be updated to follow the changing structure, or can a set of fixed modes provide enough accuracy, even for large variations of the structure.[62,183] Another consideration involves the importance of local effects, and the capability of the reduced-modal coordinates to capture these local changes accurately. Local effects become important when behavior sensitivities are required with respect to design variables of localized nature (such as the thickness of a single skin finite element), when excitation forces or sensor measurements are concentrated at a few single points on the structure, and when stresses are required. The traditional practice has been to use detailed full-order finite element models for stresses and steady aeroelastic response, whereas modally reduced models have been used in dynamic aeroelasticity. As Refs. 184 and 187 show, however, modes can also be used for stress and static aeroelastic calculations, and can lead to a significant reduction in model order and computation time.

Unsteady Aerodynamics

The unsteady aerodynamic generalized forces are calculated directly for the modally reduced-order structure. Using any linearized aerodynamic panel or lattice method e.g., Refs. 190–197, the complex normalized unsteady pressures for simple harmonic motion, caused by structural motion in mode shape j, are found from the aerodynamic equations

$$[A(k, M_\infty)]\{\Delta \boldsymbol{p}^j\} = \left\{\frac{\partial h^j}{\partial x} + \hat{j}\,\frac{k}{b}\,h^j\right\} \tag{25}$$

In this equation, $\{\boldsymbol{h}^j\}$ and $\{\Delta \boldsymbol{p}^j\}$ are displacements in mode j, and the corresponding normalized vector of panel pressures, respectively. For each panel, the displacements and local slopes are usually defined at *downwash points*, whereas the pressures are defined at *pressure points*. That is, the boundary conditions and pressures may be applied at different points within each panel. The matrix of aerodynamic influence coefficients is $[A(k, M_\infty)]$, and it depends on the Mach number M_∞, and the reduced frequency (based on a representative semichord, b)

$$k = \omega b/U \tag{26}$$

Using the diagonal matrix of panel areas $[\Delta S]$, the generalized aerodynamic force associated with pressures caused by motion in mode j, and deformation in mode i (at the pressure points), is given by

$$Q_{i,j}(k, M_\infty) = \{\boldsymbol{h}^i\}^T[\Delta S]\{\Delta p^j\} \tag{27}$$

Because the structural and aerodynamic discretizations are usually different, there is a need to interpolate displacements and slopes of deformation from the structural mesh to the aerodynamic mesh. This is one of the classic problems of aeroelasticity.[198–201] It involves three interpolation operations. From structural finite element nodes to aerodynamic downwash points

$$\{\boldsymbol{h}^j\} = [T_{hd}]\{\boldsymbol{\phi}^j\} \tag{28}$$

$$\left\{\frac{\partial h^j}{\partial x}\right\} = [T_{\alpha d}]\{\boldsymbol{\phi}^j\} \tag{29}$$

and from structural nodes to pressure points

$$\{\boldsymbol{h}^i\} = [T_{hp}]\{\boldsymbol{\phi}^i\} \tag{30}$$

where the matrices $[T_{hd}]$, $[T_{\alpha d}]$, and $[T_{hp}]$ are interpolation matrices, and the vector $\{\boldsymbol{\phi}^j\}$ is a vector of finite element modal displacements. These interpolation matrices are fixed if the planform is fixed during optimization. If, however, configuration planform changes are allowed during optimization, then the finite element and aerodynamic meshes move and change, and the interpolation matrices have to change too. If an assumed pressure mode method is used for unsteady aerodynamics (Ref. 202), similar expressions are obtained.

Control-Surface Aerodynamics

For high-dynamic pressures, where aeroelastic instabilities, such as classical flutter and divergence, are likely to occur, linearized potential unsteady aerodynamic theory has proven to be quite accurate. Although limited to wing/body combinations operating in subsonic and supersonic flight conditions without flow separation, the associated numerical methods still serve in industry for the aeroelastic clearance of all new airplanes.

For aeroservoelastic analysis, where control surfaces are used to modify system dynamics, unsteady aerodynamic loads and the associated hinge moments caused by control-surface motions become important. In this area, linearized unsteady lifting-surface techniques are not as successful as in the case of complete wings.[203–211] Trailing-edge control surfaces (including tabs) operate, many times, in thick boundary layers and behind hinge lines, which introduce geometric discontinuities into the flowfield. Even on wings with smooth variable camber[23] there can be a considerable loss of effectiveness of trailing-edge control surfaces because of flow separation. The problem can become more severe when the same control surfaces are used for both variable camber (in a quasisteady manner) and for active flutter suppression or gust alleviation (dynamically oscillating about the steady-state positions). This might lead to situations in which the control-surface travel might be large enough to introduce significant flow separation. As to leading-edge control surfaces, the prediction of aerodynamic effects is challenging because of the large pressure gradients at the leading edge and along the hinge line.[203] In addition, gaps and slots can modify the flow over the control surface significantly, and in the transonic speed regime, oscillating shock waves might make unsteady control-surface aerodynamic derivatives highly nonlinear.

While experimental and numerical efforts are underway to improve the reliability of control-surface aerodynamic prediction,[212–215] linearized unsteady aerodynamic theory should be used with caution, and care must be taken to verify the accuracy of its predictions, and to use correction factor techniques as necessary.[216–218]

In a related development, which might be found to improve the situation, it was reported recently that periodic blowing over deflected flaps[219] can delay flow separation significantly using only relatively small blowing momentum (and, thus, small power of the blowing system required). The potential of this method in controlling separation over *oscillating* flaps has not been investigated yet. But if improvement in aerodynamic performance of trailing-edge devices can indeed be achieved, then not only will aerodynamic predictions become more reliable, but also this might lead to the re-evaluation of tab surfaces[220] for the aeroservoelastic control task.

State-Space Linear Aeroelasticity

Unsteady generalized aerodynamic forces are usually calculated for simple harmonic motion at a selected set of reduced frequencies [Eqs. (25–27)]. They are transcendental functions of the frequency. When the Laplace transform (rather than the Fourier transform) of the aerodynamic forces is calculated, it is also a transcendental function of the Laplace variable. To construct a linear time invariant (LTI) state-space model of the aeroservoelastic system, a model that will serve, in turn, for modern control-system design,[221,222] the unsteady aerodynamic forces must be rational functions of the Laplace variable. A rational function approximation (RFA) is fitted, usually, to the unsteady aerodynamic loads over the range of reduced frequencies k_1, k_2, k_3, ... for which these loads, $[Q(\hat{j}k_1)]$, $[Q(\hat{j}k_2)]$, ..., (called the tabulated matrices) are available from the solution of Eqs. (25–27). This approximation is then used in the LTI model.[223–232]

Such a simple and widely used approximation is the Roger approximation,[224,229] in which a matrix of generalized forces (at some Mach number M) is given as a function of reduced frequency in the form

$$[Q(\hat{j}k, M)] \approx [E_0(M)] + (\hat{j}k)[E_1(M)] + (\hat{j}k)^2\,[E_2(M)] + \sum_{l=1}^{mL} \frac{\hat{j}k}{(\hat{j}k + \beta_l)}\,[E_{l+2}(M)] \tag{31}$$

where the matrices $[E_i]$ and the lag roots β_l are real, while the generalized aerodynamic matrix $[Q(\hat{j}k)]$ is complex, and $\hat{j}$ is the pure imaginary unit $\sqrt{-1}$. Note that the lag roots β_l are the same for all elements i, j of the generalized force matrix. Replacing the Fourier transform by a Laplace transform through analytic continuation,[226] $\hat{j}k \rightarrow p(b/U)$, and partitioning into forces caused by structural motion and forces caused by active control-surface rotations

$$[Q_{ss} \quad Q_{sc}] \begin{Bmatrix} q_s \\ q_c \end{Bmatrix} = [E_{0ss} \quad E_{0sc}] \begin{Bmatrix} q_s \\ q_c \end{Bmatrix} + \frac{b}{U}[E_{1ss} \quad E_{1sc}] \begin{Bmatrix} pq_s \\ pq_c \end{Bmatrix} + \frac{b^2}{U^2}[E_{2ss} \quad E_{2sc}] \begin{Bmatrix} p^2q_s \\ p^2q_c \end{Bmatrix} + p\{r_{1s}\} + p\{r_{2s}\} + \cdots \tag{32}$$

$$[Q_{cs} \quad Q_{cc}] \begin{Bmatrix} q_s \\ q_c \end{Bmatrix} = [E_{0cs} \quad E_{0cc}] \begin{Bmatrix} q_s \\ q_c \end{Bmatrix} + \frac{b}{U}[E_{1cs} \quad E_{1cc}] \begin{Bmatrix} pq_s \\ pq_c \end{Bmatrix} + \frac{b^2}{U^2}[E_{2cs} \quad E_{2cc}] \begin{Bmatrix} p^2q_s \\ p^2q_c \end{Bmatrix} + p\{r_{1_c}\} + p\{r_{2_c}\} + \cdots \tag{33}$$

where new state variables are defined by

$$\begin{Bmatrix} r_{1s} \\ r_{1c} \end{Bmatrix} = \frac{1}{p + \beta_1(U/b)} \begin{bmatrix} E_{(1+2)ss} & E_{(1+2)sc} \\ E_{(1+2)cs} & E_{(1+2)cc} \end{bmatrix} \begin{Bmatrix} q_s \\ q_c \end{Bmatrix} \tag{34}$$

leading to additional Laplace-transformed differential equations for the vectors of state variables, $\{r_l\}$, $l = 1, 2, 3 \ldots$, where, if $[I]$ is the unit matrix

$$p \begin{Bmatrix} r_{is} \\ r_{ic} \end{Bmatrix} = -\beta_i \frac{U}{b}[I] \begin{Bmatrix} r_{is} \\ r_{ic} \end{Bmatrix} + \begin{bmatrix} E_{(1+2)ss} \\ E_{(1+2)cs} \end{bmatrix} \{q_s\} + \begin{bmatrix} E_{(1+2)sc} \\ E_{(1+2)cc} \end{bmatrix} \{q_c\} \tag{35}$$

Examination of Eqs. (19), (20), (32), and (33) shows that the aerodynamic terms combine with structural terms to modify the mass, damping, and stiffness matrices in Eqs. (19) and (20), whereas additional state variables are added to represent time-lag behavior of the unsteady aerodynamic forces. These are called *added states* or *aerodynamic states.* As Eq. (35) shows, the aerodynamic states are coupled with the structural states and are influenced by control-surface rotations.

Several alternative approximation equations for unsteady aerodynamic generalized forces have been developed in the past 25 years. They all add states to the LTI state-space model of the aeroelastic system. Because the order of the aeroservoelastic state-space model affects the computational effort required for eigenanalysis [Eq. (5)], gust response analysis [Eq. (6)], or other dynamic response computations, it is extremely important in the context of aeroservoelastic optimization to keep this order as low as possible. The need to minimize the number of added aerodynamic states is behind many of the other approximation techniques, usually at a cost of increased computational effort required to create the rational function approximation. In the classical Roger approximation,[224] the aerodynamic lag terms are preselected, and the $[E]$ matrices are obtained by least-squares fitting. To obtain more accurate approximations, mathematical optimization may be used to determine the lag terms to minimize (over the set of frequencies at which aerodynamic matrices are available) some measure of fitting error. Different forms of the approximation, such as in the minimum state (MS) method,[228,229] may lead to an iterative process for the determination of system matrices.

If the planform shape of the wing and its control surfaces is preassigned, and if the optimization problem is a sizing-type problem, then a rational function approximation of the aerodynamic generalized forces must be created only once, for a fixed set of modes used for structural-order reduction. If, however, the planform shape of the wing can be changed during optimization (shape-optimization problem), new aerodynamic matrices and new rational function approximations must be generated repeatedly. This adds an important consideration and affects the selection of the RFA technique used.

RFAs of gust response for the LTI model must also be generated for the gust input terms in Eq. (25). The dependence of gust input forces on reduced frequency is different from that of the generalized unsteady forces discussed earlier, and care must be taken to ensure good accuracy of fit with the particular RFA selected.[81,187,233]

In the context of generating unsteady aerodynamic forces and transforming them into LTI state-space form, additional issues must be considered. First, because coupling between rigid body and elastic degrees of freedom is expected in a highly integrated aeroservoelastic system,[234–236] the LTI state-space model should be capable of predicting rigid body as well as elastic motion. Its aerodynamics should be consistent with stability derivatives in the low-frequency range,[126] when these stability derivatives are estimated by other methods, such as the USAF DATCOM, advanced aerodynamic codes, or wind-tunnel results. When modal-order reduction is carried out, it is important to account for effects of residual flexibility on aeroelastically corrected derivatives, i.e., flexibility not modeled by the reduced basis used,[126] in addition to the flexibility effects modeled by the modal basis used.

It is important to use a consistent formulation of the equations of motion for flight stability and control simulation including large rigid body motions as well as elastic deformations.[237–240] This is an area in which different models and different approaches are still used in the flight control and in the flutter professional communities.

Finally, the range of reduced frequencies, at which Eq. (31) is solved for the subsequent RFA fitting, should well cover all frequencies of interest in the stability, response, and control-system design analyses. If a state-space model of a typical fighter airplane, e.g., is to be constructed to be valid over a range of frequencies from 0 to 50 Hz, and if the mean aerodynamic chord is 2.5 m, then using half the mean aerodynamic chord, the range of reduced frequencies used for the RFA fitting should cover reduced frequencies from 0 (steady) to

$$k_{\max} = \omega_{\max} b / U_{\min} \tag{36}$$

If at a given Mach number, say 0.85, the LTI model has to be valid at altitudes up to 9.9 km, then the minimum speed is calculated at the highest altitude, and the highest reduced frequency required is obtained from Eq. (22) as 3.08. The set of reduced frequencies used for constructing RFAs should cover this range with enough points to capture the variation of unsteady aerodynamic forces with frequency, and with special emphasis on areas where aeroelastic problems are expected. If flutter with external stores is expected at 4–7 Hz, e.g., care must be taken to have an accurate fit between reduced frequencies of 0.246 and 0.431. The low end of the frequency spectrum should be covered well too, for rigid-body stability and control. As can be seen, unsteady aerodynamic forces must be evaluated at many carefully selected reduced frequencies, before an acceptable rational function approximation can be constructed. When aeroservoelastic analysis predicts instabilities or considerable dynamic response at certain combinations of frequencies and flight conditions [Eqs. (5) and (6)], the analyst should go back to the RFA and make sure that enough reduced frequencies in the tabulated set cover the particular range of interest, and that the RFAs provide good quality of fit in this region.

Control

Structural response in the form of deformation, strain, or acceleration is measured by sensors, whose transfer functions are usually predetermined. In the case of a strictly proper transfer function, the measured response y_{meas}, and the actual structural response y_{str}, are related by a transfer function of a typical sensor as

$$\frac{y_{\text{meas}}}{y_{\text{str}}} = \frac{a_{n-1}p^{n-1} + \cdots + a_1 p + a_0}{p^n + b_{n-1}p^{n-1} + \cdots + b_1 p + b_0} \tag{37}$$

The actual structural responses are linear combinations of structural displacements, velocities, and accelerations

$$\{y_{\text{str}}\} = [\Phi_0]\{q_s\} + [\Phi_1]p\{q_s\} + [\Phi_2]p^2\{q_s\} \tag{38}$$

Elements of the $[\Phi_i]$ matrices depend on the type of sensor and its location on the structure.

Similar transfer functions describe the dynamics of actuators,[241–243] relating the actual response of the actuator (which serves to rotate an active control surface), to its input command. Those input commands to the actuators are, in turn, determined by an array of control-law transfer functions, transforming an array of measured responses into actuator input commands.[61,62]

The importance of accurate actuator modeling, even at the cost of using high-order models, is demonstrated in Ref. 242. The reader is also alerted to the fact that actuator models, as usually derived and tested in the lab, assume a given load against which the actuator has to work. If complete interaction with the aeroelastic system is to be accounted for, then equations for the actuator power mechanism and control mechanism must be integrated directly with Eqs. (25), which represent the hinge moment the actuator has to provide. In the case of irreversible actuators, with an actuator model based on realistic representative loads, the actuator transfer functions can be generated separately. Integration with the aeroelastic system is obtained through I/O relations representing actuator response (and control-surface rotation) to control-system command, where the control command is based (through some control law) on the sensor measurement of a structural response [Eqs. (37–38)].

A state-space model of the control system can then be constructed[62]

$$\begin{aligned} p\{x_{\text{con}}\} &= [A_{\text{con}}]\{x_{\text{con}}\} + [B_{\text{con}}]\{y_{\text{str}}\} \\ \{q_c\} &= [C_{\text{con}}]\{x_{\text{con}}\} + [D_{\text{con}}]\{y_{\text{str}}\} \end{aligned} \tag{39}$$

where the control-system state vector contains sensor, control law, and actuator states. The control-system state-space matrices, $[A_{\text{con}}]$, $[B_{\text{con}}]$, $[C_{\text{con}}]$, and $[D_{\text{con}}]$, contain elements determined by the numerator and denominator polynomial coefficients of all sensor, control law, and actuator transfer functions. The control-system equations can now be coupled with the equations of the structural/aerodynamic system to create the overall LTI state-space equations of the aeroservoelastic system.[62,79–81]

Parametrization of the control system in terms of transfer function polynomial coefficients leads to disjoint design spaces, as discussed earlier in the design variable section, and to a highly nonlinear dependence of response functions on control-system design variables. Experience with design by mathematical programming in the control-system field is growing continuously, and alternative approaches to control-system modeling and parametrization are now available.

For aeroservoelastic synthesis, formulating the aeroservoelastic equations as a set of second-order differential equations, rather than the standard first-order state-space LTI equations [Eq. (5)], has been suggested.[16,63] The resulting state equations can be viewed as a generalization of a structural dynamic model, with modified mass, damping, and stiffness matrices, determined by structural, unsteady aerodynamic, and control-system contributions. This may offer an advantage when approximations of behavior functions have to be created for an approximate problem optimization in nonlinear programming/approximation concepts approach (NLP/AC).[167]

Order Reduction

Control-system approaches to order reduction of LTI systems[244–251] start with detailed state-space models of the accurately modeled, high-order systems. For any given LTI system, defined by its $[A]$, $[B]$, $[C]$, and $[D]$ matrices, an equivalent, reduced-order model ($[\tilde{A}]$, $[\tilde{B}]$, $[\tilde{C}]$, $[\tilde{D}]$) is then constructed to capture the dominant dynamics of the system so that selected responses, as predicted by the reduced-order model, will closely approximate those responses in the high-order system, and so that the effect of inputs on both detailed and reduced-order models will be similar in some manner.

It is quite difficult, however, to automatically reduce the order of complex, high-order aeroservoelastic models of real airplanes. These models have thousands of structural degrees of freedom, transcendental unsteady aerodynamic forces, and many outputs that need to be monitored in the form of not only dominant poles but also dynamic stresses at many points on the structure. Order reduction in each of the disciplines, with methods that are tailored to the particular physics of each disciplines are, thus, usually used before system-level order-reduction attempts. Thus, as has already been discussed in previous sections, some form of modal-order reduction is usually used in the structural dynamics area (with special attention given to providing accurate stress information), as well as efforts to generate approximate rational unsteady aerodynamics models with the minimal number of added states.

While structural-order reduction using some modal basis is quite routine, and must be carried out if just for making it possible to generate unsteady aerodynamic generalized forces for a reasonable number of degrees of freedom, the picture is less clear in the unsteady aerodynamic area. To obtain comparable accuracy of fitting using RFA with a smaller number of added aerodynamic states, usually means an increased computational effort at the stage where the RFA is constructed. For example, compared with the cost of obtaining a Roger approximation,[224] the iterative process associated with the determination of an equivalent MS approximation[228,229] can be substantial. This increased computational cost will be compensated, however, by computational savings in subsequent aeroservoelastic analyses, carried out with the smaller number of added aerodynamic states.

An alternative approach, using the general state-space model-order reduction techniques[244–251] can be developed as follows. First, generate an unsteady aerodynamic RFA with as many added states as required (enjoying the computational advantage of a simple approach such as the Roger approach), and use it to construct a high-order LTI model of the aeroservoelastic system. Then, apply one of the general-order reduction techniques[251] to this model, enforcing the responses predicted by the resulting reduced-order model to match the dynamics of the full-order original in some optimal manner.

There has not been, to date, any systematic comparison of the two approaches for aeroservoelastic applications. It is not clear whether it is more efficient to pay the computational price up front and create a MS model, or to generate a high-order Roger model followed by order reduction of the resulting LTI system.

In the case of planform shape optimization, when aerodynamic influence coefficient matrices [Eq. (25)] and the resulting generalized aerodynamic loads [Eq. (27)] must be repeatedly generated, the more efficient approach to overall model-order reduction has yet to be determined. Note that there is a marked difference here between sizing-type and planform-shape optimization. In sizing-type optimization, even though structural mode shapes are changing during the course of optimization, still (with linear aerodynamics) it is sufficient to obtain a rational function approximation just once, for any good choice of base vectors.[62,79] In a set of modal coordinates, $\{\boldsymbol{q}\}$, let a MS RFA[79,228] be generated:

$$[Q(p)]\{\boldsymbol{q}\} = \langle [E_0] + p[E_1] + p^2[E_2] + p[E_3][p[I] - [\Delta]]^{-1}[E_4]\rangle\{\boldsymbol{q}\} \tag{40}$$

This RFA can then be used either in a fixed-mode approach, or, when modes are updated, the RFA can be updated by pre- and postmultiplication by the modal updating matrices.

If a new set of generalized coordinates are used, where

$$\{\boldsymbol{q}\} = [\Phi]\{\boldsymbol{\eta}\} \tag{41}$$

then the new MS rational function approximation can be obtained from the previous one

$$[\tilde{Q}(p)]\{\boldsymbol{\eta}\} = \langle [\tilde{E}_0] + p[\tilde{E}_1] + p^2[\tilde{E}_2] + p[\tilde{E}_3][p[I] - [\Delta]]^{-1}[\tilde{E}_4]\rangle\{\boldsymbol{\eta}\} \tag{42}$$

where

$$[\tilde{Q}] = [\Phi]^T[Q][\Phi] \tag{43}$$

$$[\tilde{E}_0] = [\Phi]^T[E_0][\Phi] \tag{44}$$

$$[\tilde{E}_1] = [\Phi]^T[E_1][\Phi] \tag{45}$$

$$[\tilde{E}_2] = [\Phi]^T[E_2][\Phi] \tag{46}$$

$$[\tilde{E}_3] = [\Phi]^T[E_3] \tag{47}$$

$$[\tilde{E}_4] = [E_4][\Phi] \tag{48}$$

If planform-shape optimization, however, is carried out, then changes in the generalized aerodynamic forces $[Q(p)]$ are not only a result of mode-shape variation [Eq. (41)], but also to changes in aerodynamic influence coefficients [Eq. (25)] as a result of changes in relative distances between sending and receiving points.[159,160] RFAs in this case must be generated more often, and the associated computational burden becomes more significant.

Nonlinear Programming/Approximation Concepts

The approach to engineering optimization, known as nonlinear programming/approximation concepts (NLP/AC), is the key to the success and growing power of structural synthesis today. It brought structural synthesis to the point where realistic, complex engineering structures can be optimized, subject to a multitude of static and dynamic load conditions, as well as constraints imposed to prevent a rich variety of structural and aeroelastic failure mechanisms.[48–58,167,168,252–255] The main idea in NLP/AC is to let an optimization algorithm communicate directly with *approximations* of the constraints and objective function of an engineering optimization problem, rather than with *exact* values of constraints and objectives obtained from detailed, computationally intensive analyses. (The word exact is used here, as distinguished from approximate, to describe the results of high-fidelity modeling and analysis, but with the understanding that no mathematical model is perfect in accuracy and fidelity.)

Let an original optimization problem, supported by detailed analyses for constraints and objectives, be formulated as an inequality constrained nonlinear programming problem

$$\begin{aligned} &\min \quad f(\{\boldsymbol{x}\}) \\ &\text{subject to} \quad g_j(\{\boldsymbol{x}\}) \le 0, \qquad j = 1, m \\ &\{\boldsymbol{x}_L\} \le \{\boldsymbol{x}\} \le \{\boldsymbol{x}_U\} \end{aligned} \tag{49}$$

where $\{x\}$ is the vector of design variables, $f(\{x\})$ is the objective function, $g_j(\{x\})$ are m nonlinear inequality constraint functions, and $\{x_L\}$, $\{x_U\}$ are lower and upper side constraints, respectively. Using high-fidelity behavior analysis and sensitivity analyses results at some design point $\{x_0\}$, an approximate nonlinear programming problem is formulated

$$\begin{gathered} \min \quad \tilde{f}(\{x\}) \\ \text{subject to} \quad \tilde{g}_j(\{x\}) \leq 0, \qquad j = 1, m \\ \{x_L\} \leq \{x\} \leq \{x_U\} \\ \{x_0\} - \{ML\} \leq \{x\} \leq \{x_0\} + \{ML\} \end{gathered} \tag{50}$$

where $\tilde{f}$, $\tilde{g}_j$ are approximate objective function and constraint functions, respectively. The move limit constraints ($\{ML\}$) are added to the problem to prevent the design from wandering too far away from the point (or points) where the approximations were generated, thus, protecting the accuracy of the approximate problem.

When the approximations used are accurate enough within reasonable move limits and are cheap to evaluate, optimization of even large-scale problems becomes practical. A new design point is reached by optimization of an approximate problem. A new detailed analysis is carried out at the new design point. New approximations are created. Optimization of the new approximate problem is carried out, and so on until convergence is achieved. While many approximate analyses are required by the optimization routines during the solution of the approximate problem [Eq. (50)], only a few detailed analysis and sensitivity calculations are carried out in the process.

Selected Successful Approximation in Structural Synthesis

The effectiveness of NLP/AC depends on the availability of accurate approximations for all relevant constraints and objective functions. In the structural area, such effective approximations are available today for constraints on deformations, stresses (when full-order finite element models are used), natural frequencies, dynamic response, bifurcation buckling, involving either sizing-type design variables (where the shape and topology of a structure are predetermined, and panel thickness or element cross-sectional area serve as design variables), or overall shape design variables.[256,257]

Local approximations in the form of first-order Taylor series expansions, using intermediate design variables and intermediate response quantities, are very popular and computationally efficient, and are based on detailed analysis and behavior sensitivity analysis at a base (reference) point. In this case, if physical design variables are $\{x_i\}$, and a behavior response function is y, then intermediate design variables $\{\bar{x}_j\}$ are sought ($\bar{x}_j = \bar{x}_j(x_i)$) and an intermediate response function $\bar{y}$ is sought, ($y = y(\bar{y})$), so that the intermediate behavior function behaves more linearly in terms of the intermediate design variables.

A first-order Taylor series for the intermediate function in terms of the intermediate design variables is constructed

$$\bar{y} = \bar{y} + \left.\frac{\partial \bar{y}}{\partial \bar{x}_j}\right|_0 (\bar{x}_j - \bar{x}_{j0}) \tag{51}$$

The approximate $\bar{y}$ is then substituted into $y = y(\bar{y})$ to obtain an approximation for y.

The key is, then, to capture as much of the nonlinearity explicitly through the transformations between original and intermediate functions and variables, and then use first-order Taylor series, where the dependence of an intermediate response function on intermediate design variables is as linear as possible.

As an example, consider the stresses in truss finite elements representing spar caps or rib caps in a typical aeronautical wing structure. Suppose that all other structural-sizing design variables are held constant, and that the active design variables include only cap cross-sectional areas. The internal force in element i, with a cross-sectional area $A_i = x_i$, is found by finite element analysis to be F_i, and, thus, the stress in element i is given by

$$\sigma_i = F_i/x_i \tag{52}$$

In a statically determinate structure, the internal forces are independent of the cross-sectional areas and depend only on the configuration geometry of the structure. Of course, in any statically indeterminate structure, the internal forces depend on all structural-design variables, including cross-sectional areas. Thus, $F_i = F_i(x_j)$. Still, experience in structural analysis suggests that internal forces in many cases change in a less nonlinear way when the cross-sectional areas change, compared to the changes in stresses, which are influenced by the explicit division by the cross-sectional area, x_i in Eq. (52). This observation leads to two of the most powerful approximations for stresses in structural synthesis. In the case of elastic displacement and stress constraints in typical airplane structures, represented by truss and plane-stress finite elements, approximations in terms of reciprocal sizing design variables have been found to be very effective.[135,136] Each sizing-type design variable x_i is replaced by its reciprocal $\bar{x}_i = 1/x_i$. A first-order Taylor series in these reciprocal variables can be written in terms of the original design variables as follows (Ref. 98, Chapter 6):

$$\sigma \approx \sigma_0 + \left.\frac{\partial \sigma}{\partial(1/x_i)}\right|_0 \left(\frac{1}{x_i} - \frac{1}{x_{i0}}\right) = \sigma_0 + (x_i - x_{i0}) \frac{x_{i0}}{x_i} \left.\frac{\partial \sigma}{\partial x_i}\right|_0 \tag{53}$$

A direct Taylor series in the original design variables is

$$\sigma \approx \sigma_0 + (x_i - x_{i0}) \left.\frac{\partial \sigma}{\partial x_i}\right|_0 \tag{54}$$

However, we can also use a Taylor series approximation of the intermediate response function, the internal force F_i (in terms of either direct or reciprocal design variables)

$$\bar{F}_i \approx F_0 + (x_j - x_{j0}) \left.\frac{\partial F_i}{\partial xj}\right|_0 \approx F_0 + (x_j - x_{j0}) \frac{x_{j0}}{x_j} \left.\frac{\partial F}{\partial x_j}\right|_0 \tag{55}$$

and then substitute in the explicit expression [Eq. (52)]

$$\sigma_i = \bar{F}_i/x_i \tag{56}$$

This is known as the force approximation, and has been extended to structures containing more complex finite elements, such as beams and plates.[258]

Another example of the utilization of intermediate design variables and intermediate response quantities is the Rayleigh quotient approximation (RQA) used in eigenvalue problems [Eqs. (3) and (4)], for the computation of natural frequencies or bifurcation buckling loads for a structure.[259–261] In the case of free undamped vibration of a linear structure, each natural frequency ω_i [Eq. (4)] is the ratio of corresponding kinetic and potential energies associated with the corresponding mode shape $\{\phi_i\}$

$$\omega_i^2 = \frac{\{\phi_i\}^T[K]\{\phi_i\}}{\{\phi_i\}^T[M]\{\phi_i\}} = \frac{U_{\text{elastic}}}{T_{\text{kinetic}}} \tag{57}$$

In many structures with distinct natural frequencies, the variation of mode shapes is slower than the variation of natural frequencies, when the structure is subject to modification.

Mathematically, it is known that if approximate mode shapes are used in Eq. (57) (with a first-order error in the mode shapes), then the error in the square of the natural frequency is of second order.[262] A simple approximation for the natural frequency can be obtained, then, by using the fixed mode shapes as evaluated at the base design point $\{\phi_i\}_0$, together with approximated stiffness and mass matrices

$$\omega^2_{i,\text{approx}} = \frac{\{\phi_i\}_0^T[K_{\text{approx}}]\{\phi_i\}_0}{\{\phi_i\}_0^T[M_{\text{approx}}]\{\phi_i\}_0} \tag{58}$$

The approximation is constructed using approximate strain energy and kinetic energy, which serve as intermediate response quantities in this case. In typical airplane structures, when finite element models can be constructed using truss and plane-stress elements, the stiffness and mass matrices are linear in the sizing-design variables, and the approximated $[K]$ and $[M]$ obtained by direct first-order Taylor series, are, in fact, exact:

$$[K_{\text{approx}}] = [K_0] + \left.\frac{\partial[K]}{\partial x_i}\right|_0 (x_i - x_{i0}) \tag{59}$$

$$[M_{\text{approx}}] = [M_0] + \left.\frac{\partial[M]}{\partial x_i}\right|_0 (x_i - x_{i0}) \tag{60}$$

When other design variables are involved, direct or reciprocal, any other approximation of the modified stiffness and mass matrices can be used in the RQA.[260,261] Note that the derivatives of intermediate response functions in terms of intermediate design variables must be obtained at the base point, where an approximation is constructed. Indeed, behavior sensitivity analysis, as discussed in previous sections,[98] is one of the most important elements in NLP/AC synthesis technology.

Approximations for Aeroservoelastic Synthesis

Complex Poles

Successful approximations in the structures area owe their discovery to the deep understanding of both the physical nature and mathematical properties of engineering structures. Generalization of such approximation techniques to sizing-type aeroelastic optimization, including flutter constraints, has also proven to be very successful. In the rapidly evolving field of control/structure interaction,[263,264] and integrated control/structure optimization,[265–268] RQAs have been introduced to approximate the complex poles of the combined system. In that case, left and right eigensolutions of Eq. (5) are required, where the system matrices U and V contain structural and control terms, and are, in general, nonsymmetric.

The RQAs, as well as direct, reciprocal, or hybrid Taylor series approximations for natural frequencies, buckling loads, or structure/control and aeroservoelastic poles, lead to significant computational savings because they are simple and explicit in the design variables, and because the eigenvalue problems [Eqs. (3–5)] do not have to be solved repeatedly. Avoiding eigenvalue reanalysis is extremely important when large matrices are involved, as can be expected with detailed finite element models.

However, the highly nonlinear dependence of eigenvalues on elements of the system matrices is a challenge to any of the eigenvalue approximations described earlier, and usually makes it necessary to use tight move limits. The problem is especially severe when control-system design variables are used in the form of numerator and denominator coefficients of transfer functions [Eqs. (11–15)]. In the aeroservoelastic optimization studies reported in Ref. 62, there was almost no difference in optimization rate of convergence, between cases where RQA were used to approximate complex poles and cases when Taylor series in reciprocal variables were used. An effort to improve eigenvalue approximations for such dynamic systems is described in Ref. 269. The approach described in Refs. 16 and 63, when active control system elements are modeled as equivalent mass, stiffness, and damping contributions, may offer an advantage in this case.

Still, in the case of aeroservoelastic optimization, when structural and aerodynamic order-reduction techniques are used, and if system matrices [Eq. (5)] can typically be of order 50 to about 200,[62] then, using current super computer technology, it may be worthwhile to approximate the systems matrices $[U]$ and $[V]$ [Eq. (5)], and to then carry out complete eigenvalue analysis each time aeroservoelastic poles are required.[269]

Dynamic Response

While system's poles determine the stability and affect handling qualities of the aeroservoelastic system, dynamic response constraints take into account dynamic stresses, fatigue, vibration levels, handling qualities, and control effort. Approximations used for dynamic response constraints in aeroservoelasticity are based on generalizations of dynamic response approximations from structural synthesis.[84,85] One of the difficulties encountered in early studies of aeroservoelastic synthesis[61,62] was associated with the poor quality of direct and reciprocal approximations of the rms of dynamic response to atmospheric turbulence.[69,87]

It should be realized that when any of the complex poles of the coupled system [Eq. (5)] approaches instability, then the rms of the response to random excitation becomes infinite. Direct or reciprocal approximations of the rms in terms of structural or control-system design variables cannot capture this behavior. As Ref. 269 shows, however, expression of the covariance matrix [Eq. (6)], explicitly in terms of the right and left eigenvectors of Eq. (5) and the terms of the associated complex eigenvalues, makes it possible to develop an approximation of the gust response, which can capture the sharp rise in response when the damping of any pole becomes small. It is shown that any rms of structural response can be expressed in terms of a series containing terms of the form $1/(\lambda_i + \lambda_j)$, where λ_i, λ_j are combinations of all poles of the system [including all roots of Eq. (5), real or complex conjugate]. If these poles are then used as intermediate response functions, and if good approximations of these complex poles $(\bar{\lambda}_i, \bar{\lambda}_j)$ can be obtained using the Rayleigh quotient, or Taylor reciprocal approximate expressions, an approximation of the rms quantity can be constructed by replacing all $1/(\lambda_i + \lambda_j)$ terms by the approximate $1/(\bar{\lambda}_i + \bar{\lambda}_j)$ terms. Clearly, when any pole tends to become unstable, there will be a resulting marked increase in the rms response.

Another important comment regarding the rms response to gusts: when in the course of the optimization process any pole is found to be unstable, then the covariance analysis of Eq. (6) becomes meaningless, and the gust response evaluation is bypassed. That is, a gust response based on Eq. (6) is evaluated only for a stable system.[62] Viewed from another perspective, if the system is stable, and any pole migrates in the Laplace plane toward becoming very close to the imaginary axis, there will then be a sharp rise in resulting rms response, and this response will serve as a penalty function, keeping poles away from instability.

Design Optimization in the Presence of Model Variation and Modeling Uncertainties

Analytic expressions for sensitivities of gain and phase margins, in the case of aeroservoelastic synthesis, can be found in Ref. 270. Other measures of robustness, derived mainly from techniques in the control-systems area, are discussed in Refs. 115–117, 266, 268, and 271. As limited studies in Refs. 62 and 274 show, if robustness constraints are not included in the formulation of the problem, then resulting designs emerge that can be very sensitive to any change in a system's parameters.

The problem can be addressed by using controllers to stabilize the system over many flight conditions and design weights simultaneously. Stability constraints in this case (with proper bounds on frequency and damping) will be calculated for all flight conditions covered, and will actively influence the resulting design.[62,139,142] How conservative the integrated system will turn out to be when robustness constraints are added, and what the tradeoff is between robustness and efficiency of the resulting designs, are questions whose answers have yet to be found.

Also, the potential of adaptive controllers has been investigated for active flutter suppression with the hope that such controllers can be made to adapt to varying flight conditions, varying configurations (such as in the case of fighter airplanes with external stores), and uncertainties in modeling.[15,207] But even if, indeed, adaptive controllers can be made flexible and robust enough to successfully control systems with multitudes of dynamic properties, there will still be limitations on power, control-surface travel, and the rate of rotations of actuators. Investigation of tradeoffs between power and weight of adaptive control systems and wing structural weight in the context of integrated aeroservoelastic optimization has yet to be reported.

Other approaches for addressing uncertainty in the design optimization of structural systems are still in various stages of study and evaluation.[275–278] Ranging from statistical methods, in which the statistical characteristics of uncertainties are known or assumed, or methods based on fuzzy logic, as well as methods that use bounds on the system uncertainties to optimize for a worst-case combination of preassigned parameters and modeling errors, all these methods have not been applied yet to aeroelasticity and aeroservoelasticity of fixed-wing airplanes.

Approximations and Shape-Design Variables

There has been limited experience and success with alternative approximations in NLP/AC-integrated aeroservoelastic optimization to date, in only a few integrated studies involving sizing type design variables. Much less is known in the area of aeroservoelastic approximations, when shape-design variables are added to the sizing-type design variables discussed earlier. Even when the structures discipline alone is considered, significant difficulties still exit when shape synthesis is attempted. It is not always clear how to parameterize the shape, or how to select intermediate design variables and intermediate response functions. The calculation of behavior sensitivities becomes more expensive and more difficult,[151–155] because the finite element mesh has to deform, and stiffness terms are highly nonlinear as functions of node location.

When control system and aerodynamic design variables are added to the design space, effective approximations become more elusive. Compared with the vast body of knowledge regarding approximation concepts in the structures area, approximation theory, and practice for NLP/AC in the areas of control and aerodynamics are in their infancy. Most often used are direct, reciprocal or hybrid Taylor-series-based approximations for the response quantities in terms of the actual design variables. How to find intermediate design variables and response quantities, which will lead to highly accurate approximations over large move limits, is still the subject of active research.

Regarding aerodynamic design variables, effective approximation of the induced drag in terms of jig shape and flap rotation design variables has been used in Ref. 62, taking advantage of the quadratic nature of the induced drag in terms of these design variables.

When planform shape is changing during optimization, steady and unsteady aerodynamic forces have to be regenerated repeatedly. In the context of dynamic aeroelasticity and aeroservoelasticity, the unsteady aerodynamic forces [Eqs. (25–27)] are changing with variation of planform shape or control-surface size and location.

Downwash [on the RHS of Eq. (25)] is changing because of the change in structural mode shapes [as a result of the changing mass and stiffness of the wing, Eq. (4)]. When a rigid-control surface rotation mode is considered, then, with changes in the shape of the control surface, downwash caused by motion in this mode will also change. The influence coefficient matrix is changing with the wing geometry and the resulting change in distances between receiving and sending points. The interpolation matrices in Eqs. (28–30) must reflect new positions of grid or collocation points on the wing. In the integration for generalized force in Eq. (27), the panel areas and the interpolation matrix also change with variations of the planform shape. Moreover, for each new planform shape, the unsteady aerodynamic forces must be calculated at many reduced frequencies, before a rational function approximation can be constructed [Eqs. (31) and (40)]. The coupling between the aerodynamic problem and the structural-order reduction problem is also evident. In the context of planform-shape optimization, there is still very little experience with the kind of modes to be used, and whether to allow them to vary or to keep them fixed as the structure evolves during optimization.[159,160,183]

Weak and Strong Aerodynamics/Structures/Controls Coupling and Associated Design Approaches

Aeroservoelastic interactions in modern airplanes with wideband active control systems can affect not only six-degrees-of-freedom stability, control and handling qualities, or aeroelastic stability (flutter) and ride comfort (vibration levels). Actually, internal stresses in the airframe can be increased or reduced when control surfaces are activated both statically (in a variable camber mode to improve drag and reduce wing loads) and dynamically (for dynamic loads and gust alleviation). Interdisciplinary coupling can, thus, become quite tight, when controls participate not only in shaping the overall dynamic response of the complete flight vehicle (both flight mechanics and elastic motions), but also in making an impact on detailed structural design and structural integrity of the airframe.[279,280]

The need to address adverse interactions (such as aeroservoelastic instability) and the benefits of favorably harnessing aeroservoelastic interactions have been known and discussed for years. Active controls on variable camber (mission adaptive) wings to reduce stresses in maneuvering flight were tested and implemented.[144–147] Gust-alleviation systems for both ride comfort and dynamic stress reduction have been devised.[281–285] Maneuver loads spectra for the fatigue-life evaluation of fighter airplanes had been developed using flight simulations that take into account both aircraft dynamics and active-flight control-system design. The importance of dynamic stresses because of atmospheric gusts, as participants in determining the structural design of both civil and military airplanes, is now well established.[286–291]

Still, to date, published studies of applications of aeroservoelastic optimization to realistic airplane systems, have been quite limited in scope and in degree of multidisciplinary integration. Usually, active control systems have been designed for given airframes after these airframes had been optimized structurally subject to structural and aeroelastic constraints. If the effect of the structural design on the coupled structure/control aeroservoelastic system was to be evaluated, then it was usually done in a parametric way; i.e., a few structures with different planforms were optimized structurally and aeroelastically. Then control systems were designed for these structures in some optimal way, and finally, the overall resulting control/structural systems were evaluated and compared.

In a different scenario, when a flight-control system is designed separately, then its sensors, actuators, and control laws can be included as preassigned parameters in the aeroservoelastic model of an airframe when this airframe is optimized structurally, with constraints on aeroservoelastic stability added to the usual constraints on stresses, strains, deformations, etc.

Actually, the problem mentioned first in the preceding text, that of designing a control system for a given optimized airframe, has become quite important with the appearance of easily programmable digital flight controls. Active control laws play an important role in flight mechanic dynamic maneuver simulations, and such simulations are used to determine critical loading conditions for the establishment of extreme loads and fatigue loading spectra. As can often happen, the flight-control system can be modified (for any number of reasons) after fatigue life of the airframe (using these original loads spectra) had been demonstrated.[284] This change in active controls might make it necessary to re-evaluate fatigue life and to check for the possibility of internal loads that are now larger than the original ones, for which the airframe was designed.

Of course, a requirement on any flight-control system modification might be that it will not allow increases in critical stresses in the structure. However, the design of a flight-control system (including aeroservoelastic controls) using any of the MIMO control-system synthesis methods available today[117,139–142] is quite challenging, if only for the need to observe or estimate a large number of outputs (such as stresses in many points throughout the airframe, in addition to accelerations, velocities, and angular rates), and to keep them within bounds. There can be cases where available control surfaces are ineffective in controlling a particular response. The topology and geometry of control surfaces and sensor arrays must then be improved to make the airframe more *control friendly*,[292,293] with better controllability and observability characteristics for all structural responses of interest. In any case, with variable camber and wide-bandwidth active controls, modern airframe design has arrived at a stage where the control system, and not only the aeroelastic system alone, affects stresses and, thus, structural design.[281–285]

It is important to mention here the still-existing reluctance, in design and certification circles, to rely on active controls for flutter suppression in civil aviation, the main reason being the perceived lower reliability of such systems compared with passive design. This makes it impossible at this stage to reap the complete rewards (in terms of structural weight savings) that active controls might offer. In the gust-alleviation area (as Ref. 281 shows), a careful approach will rely on the partial relief of gust stresses, the possibility of reducing speed (in turbulence) if there is system failure, and on highly redundant control mechanisms involving many control surfaces, including spoilers.[294] If flutter within the flight envelope is eliminated using passive means, while active controls are used to provide the margins of safety outside of the flight envelope, structural weight savings can still be significant.

As to structure/aerodynamic coupling, it has been pointed out[295] that interdisciplinary coupling can be relatively weak and one-sided in this case, and that aeroelastic optimization for minimum weight can be carried out separately, as a second step, with added constraints and jig shape-design variables to force the airframe to deform in maneuver into a desired aerodynamic shape, which was optimized as a first step in the aerodynamics discipline. This uncoupling (or asymmetry) between disciplines seems to apply even in cases where a multitude of aerodynamic shapes, for different maneuvers, is needed, because, in addition to the jig shape, the designer can utilize leading- and trailing-edge control surfaces in a variable camber (mission-adaptive wing, Refs. 144–147) concept. Yet, as the experience with mission-adaptive wings shows,[147] rotation of control surfaces beyond certain angles at certain angles of attack leads to severe buffeting and loss of control effectiveness caused by flow separation. If the same control surfaces are used for variable camber and flutter or gust alleviation, the combined total rotations (static plus dynamic) must be within bounds, and tradeoffs between control rotations for camber variation and control rotations for dynamic control (and their resulting effect on the structure) should be determined through an integrated approach. Moreover, if airfoil-thickness design variables are introduced, then the aerodynamics and structures disciplines are more strongly coupled and the tradeoff between drag (aerodynamic) and weight (structural), as they affect overall performance, should be determined by an integrated approach.

Integrated Aeroservoelastic Synthesis Capabilities

Experience with integrated simultaneous optimization of aerodynamics, airframe, and flight controls, subject to constraints on stresses, fatigue life, deformations, dynamic stability, ride comfort, handling qualities, robustness, power limitations of control system and elements, as well as consideration of drag, load factor, and roll rate in maneuvers, is nonexistent. Reported results of tradeoff studies, examining effects of active control technology on structural weight, performance, flight comfort, and safety are mostly based on parametric studies, in which optimization was done one discipline at a time. A number of aeroservoelastic optimization studies have been published in the last 10 years, reporting results for highly simplified beam or plate structures and control systems. There has been no reported development of a truly integrated aeroservoelastic optimization capability within the aerospace industry, and only a few academic efforts were reported with the capability to model and optimize realistic airplane configurations.

The aircraft integrated design–Ingegneria Aerospaziale (AIDIA) computer code,[63] and the lifting surface control augmented structural synthesis, (LS–CLASS) computer code[61,62,272–274] were developed in the late 1980s for the integrated synthesis of aeroservoelastic systems. LS–CLASS is aimed at actively controlled wings, and its structural modeling is based on equivalent plate techniques. AIDIA is more general in its structural modeling, and can be interfaced with different structural modules, such as MSC/NASTRAN. It can, thus, be used for integrated structure/control synthesis of general structures, as well as for aeroservoelastic synthesis. Both capabilities are based on modeling techniques that can represent real airplanes and practical control systems. This realism is very important. Beyond the development of modeling, sensitivities, approximations, and optimization strategies for real applications, the integrated multidisciplinary synthesis capabilities, once operational, must be used for extensive numerical studies. These numerical experiments in MDO are needed to help identify problem areas and weaknesses in the MDO technology used. They also help build experience and insight in an area where very little experience is available, and where, because of the complexity of multidisciplinary interactions, intuition can be, many times, misleading. Following a similar philosophy and emphasizing realistic modeling, important elements of aeroservoelastic model-order reduction for optimization technology were brought together and used for aeroservoelastic synthesis in Ref. 64. The optimization procedures reported in Ref. 64 were not based on NLP/AC, but the reduced-order approximations used for structural dynamics and unsteady aerodynamics, as well as the reduced-order approximations for stress analysis presented in Refs. 184 and 187 and for aileron effectiveness[119] all fit very well into the framework of aeroservoelastic NLP/AC.

Structural-order reduction is used in the three capabilities mentioned earlier. In LS–CLASS, full-order structural models can also be used throughout the optimization process. Approximation concepts/nonlinear programming, as an optimization strategy, is the basis for AIDIA and LS–CLASS. AIDIA uses convex linearization,[254] whereas LS–CLASS allows a variety of approximations, depending on the behavior function being approximated. In LS–CLASS, direct, reciprocal, hybrid, or RQAs can be used for natural frequencies and aeroservoelastic poles. Intermediate response functions are used in the evaluation of damping coefficients and induced drag.[62,272–274] The method of feasible directions[130] is used for solving the approximate optimization problems. In addition, in both LS–CLASS and AIDIA, a control system and structure can be designed to cover many load cases at many flight conditions simultaneously, as a way to ensure robustness of the resulting integrated system. While AIDIA is reported to use the *p-k* method[223] for stability analysis, LS–CLASS uses aeroservoelastic poles obtained by solution of the linear eigenvalue problem [Eq. (5)]. With both capabilities, any behavior function can be used as a constraint or an objective.

In addition to constraints on element gauges, stresses, displacements, natural frequencies, aeroservoelastic poles, and flutter envelope, LS–CLASS has the capability to calculate rms values of dynamic response to atmospheric turbulence, so that constraints on control surface activity (in terms of rms rotation and rms rate of rotation) can be imposed at a variety of flight conditions. This is a more realistic way of including control-system power and performance limits in the optimization, than the minimization of some weighted control-system gains, as reported in many studies of controls/structures optimization. In the aerodynamics area, LS–CLASS can use jig-shape design variables and steady (maneuver-dependent) control-surface rotations to affect drag and internal loads by optimizing a variable camber. In an implementation of an AFW approach, LS–CLASS can impose requirements on performance in pullup and rolling maneuvers, relying on the variable camber optimization and aeroelastic tailoring to meet these requirements even if a control surface becomes reversed.[61,62,274] LS–CLASS can also impose constraints on handling qualities in the form of constrains on frequency and damping of flight mechanics poles, such as short period, etc. It should be emphasized again here, that all these design variables and constraints are integrated, and that the optimization problems are solved across all participating disciplines with all design variables changing simultaneously.

Reported Results

Results reported in Refs. 61–63 and 272–274 have demonstrated that the effectiveness of NLP/AC can be extended beyond structural synthesis to integrated aeroservoelastic optimization, including structural, control, and aerodynamic design variables and constraints. Convergence of the sequence of approximate optimization problems has been achieved with a few, and up to about 30 detailed analyses/sensitivity calculations. A typical structural synthesis problem with deformation and stress constraints converged within 10–15 approximate optimizations. When control-system design variables were introduced, move limits had to be tightened, and convergence of the NLP/AC optimization process took up to about 25–30 approximate optimizations in some cases.

The need to reduce move limits for control-system design variables (5 and 10%, compared with 40 and 50% in the purely structural case) is because of the limited accuracy of the approximations used for aeroservoelastic poles and for rms responses to atmospheric turbulence. It was found that neither Taylor-series-based nor RQAs had any clear advantage when control-system design variables were present. Moreover, as has already been discussed, gust-response constraints cannot be approximated effectively with direct or reciprocal Taylor series because of the sharp rise in response when any of the poles approaches instability (the gust response approximations of Ref. 269 have not yet been incorporated into LS–CLASS). This was one of the major reasons for the need to reduce move limits to protect the accuracy of the approximate problem.

Interestingly, optimizations carried out with AIDIA, in the case of structure/control-design variables, converged faster. An example of an actively controlled swept wing, reported in Ref. 63, converged within seven approximate optimization cycles. In the control-system parametrization in AIDIA, the controller is modeled as a second-order system and is used to directly modify structural matrices. Approximations that have been successful for structures, may, thus, be equally successful for the augmented aeroelastic/control model obtained this way.

Extensive numerical experimentation using LS–CLASS revealed intricate interactions among the participating disciplines. *Stress designs*, in which wing composite structures were tailored for minimum weight to meet stress and manufacturing constraints, were usually unstable at high dynamic pressures resulting from flutter. *Flutter designs*, in which the structures were optimized to meet both stress and flutter constraints, were heavier. When an active control system was added, and the actively controlled structures were optimized for minimum weight, with structural- and control-design variables, and subject to stress and flutter constraints, it was possible to reduce the structural weight back to the stress design weights. In that case, the control system was, in fact, synthesized to stabilize against flutter. With no control-system limitations or cost in the problem formulation, the active controls could take care of flutter, while leaving the structure to meet the steady stress design maneuver loads.

However, this resulted, many times, in high rates of activity of the control surfaces caused by gusts, affecting the power required for control-system operation. When this power was limited in subsequent problems, as an added constraint, then structural weight could not be brought down to its stress weight. Thus, the studies indicated the existence of a tradeoff between control system power and structural weight saved.

Application to an F16-type fighter-control system/wing, with additional simple handling qualities constraints (in the form of limitations on frequency and damping in the short-period mode), demonstrated convergence of the NLP/AC approach in a very realistic case, and found a minimum weight solution that met all constraints. Typical problems, with up to 50 design variables and 3000 constraints, and covering structures, aerodynamics, and controls simultaneously, took up to 1 h of CPU time in an IBM 3090 in the late 1980s.

The introduction of induced drag constraints complicated the picture somewhat. Minimizing the weight of a wing, with stress, flutter, and drag constraints, using structural, control, and aerodynamic camber (jig shape) design variables, revealed interesting interdisciplinary interactions and tradeoffs. Results of integrated optimizations from both AIDIA and LS–CLASS indicated that when an active control system was synthesized as part of the integrated design at one flight condition only, robustness of the resulting design was poor. Synthesizing structure and controls at several flight conditions simultaneously was required to produce a robust design.

Results of structure/controls aeroservoelastic optimization with robustness constraints are reported in Ref. 64. With 22 thickness design variables for the composite skin of an active flexible wing wind-tunnel model, plus three simple gain design variables Gi relating sensor outputs $\{y\}$ to actuator command inputs $\{\boldsymbol{u}\}$, integrated optimization was carried out using reduced-order models based on finite element structural modeling and MS rational function approximation of unsteady aerodynamic forces. Constraints included gauge constraints on skin-layer thicknesses and side constraints on control-system gains, plus constraints on flutter dynamic pressure and gain margins as well as a rolling moment constraint. No stress constraints were included, and the optimization was assumed to start from a stress design, with zero lower bounds on all structural gauge design variables, so that no thickness is reduced below its starting value. While the multidisciplinary nature of interactions included in this example was quite limited, and constraints on control system power requirement were imposed in only a simplified manner, the result did demonstrate the feasibility of aeroservoelastic optimization based on industry-type structural finite element models. It also demonstrated the importance of optimizing structures and controls simultaneously.

Lessons

The integrated optimization studies discussed earlier revealed the limitations of existing approximation techniques used for aeroservoelastic systems. To allow larger move limits in the integrated aeroservoelastic case, better approximations for aerodynamic, aeroelastic, and aeroservoelastic behavior functions must be developed.

For planform shape optimization, where the consideration of interdisciplinary interactions affects a design in the conceptual and preliminary design stages, no integrated aeroservoelastic synthesis capability exists today. An intensive research effort, reported in Refs. 156 and 161–163, has been focusing on the problem of integrated airplane shape optimization. However, most efforts have been devoted to the static aeroelastic problem, including divergence constraints, aileron static control, and aileron effectiveness. Integration of aeroelasticity with the airplane performance problem, with an effort to develop design-oriented aerodynamics for drag/lift estimation up to supersonic speeds, are important steps on the way toward the practical integrated MDO of airplanes. The considerable computational cost of aerodynamic analysis and sensitivity computations, as well as interpolation between structural and aerodynamic meshes, were found to be major challenges.

Other problems that were discovered included the nonsmooth behavior of some aerodynamic predictions with respect to changes in the configuration's shape.[159,160,163,166] This problem makes it necessary to re-examine analysis techniques used, and develop design-oriented techniques that eliminate superfluous nonsmooth behavior. Alternatively, if existing computer codes are to be used for aerodynamic predictions, methods for estimating sensitivity and for optimization in the presence of numerical *noise* must be developed.

Only very limited experience exists in the area of planform shape optimization with dynamic aeroservoelastic constraints. Most of the research effort has been aimed at developing approximation concepts and effective sensitivity analysis[71,159,160] and at preparing the tools required for NLP/AC synthesis. It is quite difficult to find intermediate design variables and intermediate response quantities in aerodynamics that will lead to the same accuracy of approximation as had been achieved in the structures area. However, a continuing research effort in this direction should strive to create such approximations, guided by the understanding of the physical nature of the problem, and by taking advantage of its mathematical structure. Without such approximations, NLP/AC has to rely on formal Taylor-series-type approximations (direct, reciprocal, or hybrid). When behavior functions are highly nonlinear, the move limits necessary will be small, and convergence rate of the NLP/AC process will be slow.

Additional Necessary Developments

A considerable amount of research has yet to be conducted to develop an integrated aeroservoelastic synthesis capability that covers all important constraints, affecting the design of a modern, highly integrated airplane. To be accepted by the aerospace industry, mathematical models used in each of the contributing disciplines must be accurate and robust to industry standards. This requires major improvements in the automation and cycle time of the processes used to create aerodynamic and structure meshes and corresponding structural and aerodynamic models, as well as practical, realistic control systems for new configurations. Because the MDO problem requires massive amounts of data transfer and storage, as well as evaluation of overall system response under many loading conditions at a multitude of maneuver points, developments in information communication, storage, and parallel processing are needed. A cultural change within the industry, in which designers are encouraged to become fluent in all relevant disciplines, and in which teams of experts work in a coordinated manner, has already begun to some extent.

In aeroservoelasticity, to model interactions between flight-control and structural dynamics, a consistent design-oriented aeroelastic formulation is required, integrating rigid body and elastic motions, stability derivatives, and unsteady aerodynamic forces. A comparative study of control-system parametrization and associated approximations should be conducted to determine the most effective ones in the context of NLP/AC.

Following the fast developments in applications-ready CFD aerodynamic tools and parallel computation,[47] methods for sensitivity analysis and approximations for advanced aerodynamic analysis techniques are required, so that more realism is brought into the aerodynamic part of the aeroelastic synthesis formulations.[46,105,106] The computational effort required to include finite difference CFD in large-scale MDO is still considerable. But the need to include realistic drag and load predictions in the transonic speed regime and in cases where aerodynamic loads are nonlinear, provides a strong motivation for developing methods to include such predictions in the integrated design formulation.

As has already been argued earlier in this paper, research efforts aimed at developing automated model generation, fast analysis, fast sensitivity analysis, robust approximation concepts and efficient data management are all required to make realistic NLP/AC aeroservoelastic synthesis feasible. However, this is just one facet of the problem. In a design environment so complex and so tightly coupled and integrated, design intuition is almost nonexistent (actually, it might be misleading), and design experience is quite rare. Questions such as how to make good design decisions, how do disciplines interact when optimal designs are pursued, what are the resulting tradeoffs, how does modeling uncertainty affect results, must all be answered. A practical integrated MDO capability can provide the necessary answers, and once it is developed, it should be used for numerical experimentation to educate the designers and build a body of design experience. In aeroservoelasticity, studies of integrated optimization of strongly coupled airplane systems are already underway, as an extension of the work reported in Refs. 61, 62, and 272–274, and will be reported in the near future.

Finally, another important role of MDO should be recognized: its usefulness in evaluating overall value of new technologies. A new technology is being developed currently for the active control of structures, using strain actuators and smart sensors.[296-300] One of the goals of this smart-structures technology is the development of structures and aeroelastic systems that will be more efficient than the ones available today. However, new phenomena, interactions, failure modes, and design considerations must be addressed when the effects of the new technology on the integrated airplane are examined. It is believed that only through systematic optimization studies, addressing the integrated system in as a complete manner as possible, can design experience be gained and clear trends identified. Thus, after the accuracy of analysis methods is established, methods for sensitivity analysis, approximation concepts, and optimization strategies must be developed for the new technology to be assessed using MDO.

Integrated aeroservoelastic synthesis, then, is necessary for the improvement of designs based on current technology, and for directing the development of future technologies for maximum effectiveness and economy.[301]

Conclusions

A broad view of aeroservoelastic synthesis has been presented in this paper. The key elements of aeroservoelastic analysis have been examined from a design-oriented perspective, including methods that are ready for MDO applications, and emerging nonlinear analysis methods that offer to add accuracy and generality. Application of the engineering optimization method known as NLP/AC for integrated aeroservoelastic synthesis has been shown to be a natural extension of its successful utilization in structural synthesis. Aeroservoelastic sensitivities and approximation concepts have been discussed, and strengths and weaknesses were identified. A survey of the limited experience in integrated aeroservoelastic synthesis existing today, covered the main lessons learned, and the required directions for further research. The importance of intensive research efforts to develop efficient techniques for aeroservoelastic MDO in compliance with industry accuracy standards and to prepare the computational and data management infrastructures required have been emphasized. It was then argued that, as a step following the creation of practical, realistic aeroservoelastic MDO capabilities, such capabilities should be used for extensive numerical design studies to build an experience base for designers of tightly coupled aeroservoelastic systems, as well as for assessing overall benefits of new technologies in a thorough manner. The importance of the shape-synthesis problem was emphasized, addressing interdisciplinary interactions early in the design stage, when airplane shape is still evolving. Finally, a rich reference section is provided, listing key publications in all areas related to aeroservoelastic analysis and synthesis.

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