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Integrated Aeroservoelastic Wing Synthesis by Nonlinear Programming/Approximation Concepts

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Nonlinear programming/approximation concepts optimization techniques developed for structural synthesis are adapted to the integrated aeroservoelastic wing synthesis problem, in which constraints from several disciplines are taken into account simultaneously and the design space includes structural and control system design variables. Structural, aerodynamic, and control system mathematical models that are suitable for the preliminary design of airplanes are used in an integrated synthesis of wings and their active control systems. The effectiveness and efficiency of the new capability are studied using mathematical models of a remotely piloted vehicle as well as a more complex YF16-type airplane model. Simplified handling quality constraints are added to the set of design requirements. The performance of several complex eigenvalue approximations is examined. Effects of control law structure on the weight and robustness of the resulting aeroservoelastic designs provide new insights into the complex multidisciplinary interactions involved.

Introduction

THE application of composite materials technology and high authority control systems to the design of actively controlled, light weight, flexible wings[1,2] has made the interactions among the various disciplines in airplane design more complex and important. Failure to take these interactions into account can lead to potentially disastrous consequences.[3] On the other hand, taking advantage of them early in the design process offers greater design flexibility.[4,5] The integrated treatment of structures, control systems, flight mechanics, performance, and dynamic aeroelasticity has thus become a necessity.[6-9]

The synthesis of active control systems for elastic airplanes to guarantee flight mechanics and aeroelastic stability while providing desirable handling qualities and acceptable dynamic stresses is still considered to be a challenge to control systems designers.[10-13] The simultaneous synthesis of active control systems and the flexible structures that they control is even more complex. Many types of constraints on the behavior of the combined system have to be met. Stresses due to loads in different maneuvers have to be below an allowed level to prevent structural failure in yielding, buckling, or fatigue. Aeroservoelastic stability must be guaranteed. Control system power requirements must be within the power limits of actuators if the actuators are preassigned. If the actuators are designed as a part of the overall system, their required power may be minimized or limited to some desirable value. The mass of the structure may be minimized or limited to be below some desirable target value. The aeroelastic deformation of a wing has to be tailored so as to minimize drag or prevent a drag increase. From a control systems point of view, this is a problem of designing the controls and the plant simultaneously. At the outset the plant, the controls, and which constraints will drive the design are unknown. Intuition provides little help and actually can be misleading in these circumstances.

Optimization has always been a part of aerospace systems design[14-18] at all levels and each phase of the design process. Yet in many cases, its usefulness has been limited to component design and to relatively simple problems with a small number of constraints and design variables. In the structures area, it was an integration of numerical optimization and finite element techniques that has brought structural synthesis to maturity[18-22] so that it can deal with complex realistic problems. The most general approach to structural synthesis is based on the integration of nonlinear programming and approximation concepts (NLP/AC). Nonlinear programming algorithms will find local minima of general constrained optimization problems starting from feasible or infeasible initial designs. No intuition is therefore needed to identify active constraints in advance. Approximation concepts are used to save computation resources by replacing the computationally intensive detailed analysis by an approximate, computationally cheap analysis and gradient calculation. General structures modeled by thousands of finite elements can be sized with NLP/AC using current computing capabilities to meet stress, deflection, buckling, and natural frequency constraints while reducing weight to a minimum. Lacking the elegance and rigor of classical analytical optimization methods (see Ref. 18, Chap. 2), the mathematical programming based techniques are more suited for fully automated digital computation involving complex models and large numbers of design variables and constraints. These techniques have been used for aeronautical applications of control system design[23,24] and have been recognized by the control systems community as well.[25,26] It is recognized that a major change in control systems design over the next years will be the increasing use of parameter optimization.[25-38] Numerical optimization has been used for quite some time for the integrated synthesis of control augmented space structures.[39-47] The computationally intensive multidisciplinary control/aeroelastic design problem with its different types of design variables and constraints and its large scale is a natural candidate for NLP/AC.

In a recent series of publications,[48-53] a new synthesis capability for actively controlled fiber composite wings has been described. It is based on balanced design and analysis models that capture essential behavior characteristics, without making

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the integrated multidisciplinary design optimization task intractable. This balanced approach combines high-quality, approximate, but computationally efficient, analyses for the structural, aerodynamic, and aeroservoelastic behavior of composite wings at the preliminary design stage. The entire optimization problem may be treated at one level without the need for multilevel decomposition.

Exploratory studies in actively controlled wing multidisciplinary optimization were presented in Ref. 50. They focused on the interaction between the aluminum structure of a remotely piloted vehicle (RPV) wing and the active flutter suppression/gust alleviation system and on the integration of controls and structure in aeroservoelastic design optimization. Structural and control system sizing-type design variables[49,51] were included in the design space. Tradeoffs between structural mass and required control system power were studied. The results of more comprehensive multidisciplinary wing synthesis studies made possible by the new synthesis capability were reported in Ref. 52. Structural design freedom was increased by introducing fiber composite materials for wing skin construction. The design space was opened up by adding aerodynamic design variables to determine the jig shape (initial camber) of the wing. Drag constraints were added to the set of constraints. Thus, the design space spanned three disciplines, namely, structures, control, and aerodynamics, and the blend of behavior constraints covered strength, minimum gauge, flutter, gust response, and performance (induced drag). The same RPV model as used in Ref. 50 served as a test case.

The design studies in Refs. 50–53 contribute to the state of the art in design optimization by developing and gaining experience with synthesis techniques for multidisciplinary complex problems involving a very rich blend of constraints. They also offer better understanding and a fresh insight into the interactions between the various disciplines in wing design as well as numerical results that may serve as a basis for design tradeoffs.

The present paper adds to the growing experience in aeroservoelastic wing optimization by focusing on active control aspects of the design problem. The design space for the numerical examples reported here is made up of sizing-type structural and control system design variables.[49] The present capability can handle aerodynamic design variables as well but they are not used in the present studies. The RPV[50–53] is used to study locally optimal designs achieved with different control law structures and the resulting gain and phase margins of these optimized control augmented composite wings. The performance of different complex eigenvalue approximations in the context of NLP/AC technology is also examined. The new multidisciplinary wing synthesis capability is then applied to the aeroservoelastic synthesis of a realistic fighter-type airplane in order to demonstrate its power and generality and assess computational efficiency in dealing with more complex aeroelastic and control system configurations. Simplified handling qualities requirements are also added to the set of constraints.

Analytical Modeling Techniques

A unique integration of analytical modeling techniques makes it possible to bridge the gap between those that are oversimplified (like beam/aerodynamic strip models) and the detailed techniques that require too much computer time (like detailed finite element/computational fluid dynamics). In the structures area, an equivalent plate analysis is used.[54,55] It is integrated with the piecewise continuous kernel function method for lifting surface unsteady aerodynamics.[56] The method of Roger[57] is used to generate finite-dimensional state-space approximations for the unsteady aerodynamic loads. The integrated aeroservoelastic system is modeled as a linear time invariant (LTI) system. Thus, any automated modern control system design methodology can be integrated and used. At the present stage of development, however, the control system is completely described by the location of sensors and control surfaces and by the transfer functions of the sensors, control laws, and actuators (Fig. 1). Realistic fiber composite wings and flight/flutter suppression control systems can be modeled with accuracy that is sufficient for preliminary design of airplanes. Several types of analysis can be carried out simultaneously:

1) Static aeroelastic maneuver loads analysis in which the wing is attached to a free-free airplane and the loads depend on the flight conditions and take aeroelastic load redistribution into account. The rigid-body and elastic displacements as well as control surface deflections needed for trim are obtained from a solution of the linear system of equations

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

where the generalized stiffness matrix $[\bar{K}]$ contains structural and aerodynamic contributions and the loads $\{\bar{P}\}$ depend on the maneuver parameters (load factor, roll rate, Mach number, altitude), aerodynamic design variables (initial camber), and the structural design variables (through inertial loads).

2) Natural frequency and mode shape analysis

$$\left[-\omega^2 [M] + [K]\right]\{\phi\} = \{0\} \tag{2}$$

where K and M are the stiffness and mass matrices, respectively.

3) Aeroservoelastic stability analysis

$$\lambda[U]\{\eta\} = [V]\{\eta\} \tag{3}$$

where $[U]$ and $[V]$ depend on structural and control system design variables and λ is an aeroservoelastic pole.

4) A gust response analysis for the state covariance matrix $[X]$[16,58]

$$[\bar{A}][X] + [X][\bar{A}]^T = -[\bar{B}][Q_w][\bar{B}]^T \tag{4}$$

where $[\bar{A}]$ and $[\bar{B}]$ depend on structural and control system design variables, and $[Q_w]$ is the intensity matrix of a Gaussian white noise driving a gust filter that generates either Dryden or approximate von Karman 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 $[X]$.

Static given-loads structural analysis (in which the wing is cantilevered and subject to predetermined load distributions) and induced drag analysis[51] are also available, but are not used in the studies reported here.

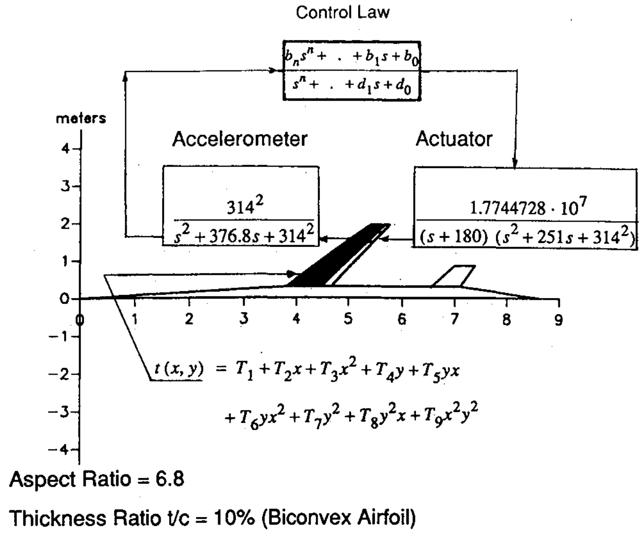


Fig. 1 Actively controlled remotely piloted vehicle.

Analytical derivatives of all behavior functions with respect to all design variables are obtained by implicit differentiation of the analysis equations.[18,51]

Multidisciplinary Synthesis Methodology

Approach to Optimization

Combining nonlinear programming with approximation concepts has proven to be successful in solving structural optimization problems.[19-22] NLP is general. No a priori knowledge of the active constraints that drive a certain design is needed. The behavior function approximations are used in order to overcome the computationally intensive nature of the problem. Only a small number of detailed analyses are carried out during optimization. Each detailed analysis and the associated behavior sensitivity analysis serve as a basis for constructing explicit approximations to the objective and constraint functions in terms of the design variables. Then a series of approximate optimization problems is solved until convergence to an optimal solution is achieved. Each step, consisting of a detailed analysis, behavior sensitivity analysis, approximate problem generation and a solution of the optimization problem (using approximate objective and constraints), is considered one optimization cycle. Experience in structural synthesis shows that for problems involving stress, deformation, and natural frequency constraints, convergence of the synthesis process is achieved in 10–20 optimization cycles. The optimizer, of course, needs many more function evaluations, but these are based on the approximations and are cheap computationally. In order to prevent the approximate problem from becoming too inaccurate as the design wanders away from the point in design space where detailed analysis was carried out, additional constraints are added to the approximate optimization problem in the form of move limits on the design variables. For the NLP/AC approach to be practical, it is crucial to avoid too many detailed analyses for function evaluations and sensitivity calculations. This depends on making the approximations accurate yet simple enough for efficient solution.

Intuition and experience with structural systems led to the development of successful approximations for displacement, stress, and natural frequency constraints in terms of the structural design variables.[18] No similar experience exists for aeroservoelastic system design. It is thus necessary to study alternative approximations of aeroservoelastic poles and gust response and evaluate their effectiveness.

Behavior sensitivities of objective and constraint functions are needed throughout the optimization for gradient calculation and the construction of approximations. If finite differences are used for behavior sensitivities, optimization of the large multidisciplinary system can become extremely costly. In the presence of design variables from different disciplines with different effects on the overall behavior of the system, step size selection for the finite differences can also pose a problem. In the present work, behavior sensitivity analysis is based on analytic derivatives of all behavior functions with respect to all design variables.[51] The nonlinear programming algorithm used for constrained function minimization throughout this work was the method of feasible directions as implemented in the CONMIN code.[59]

Design Variables

Preassigned parameters for the optimization include wing planform and depth (airfoil thickness) distribution, material properties, and structural layout of the wing (number of spars and ribs and their locations). 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. To take advantage of multidisciplinary interactions, the design space includes structural, control system, and aerodynamic design variables simultaneously. Structural design variables include polynomial coefficients in the 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:

$$t(x,y) = \sum_{i=1}^{l} T_i x^{mi} y^{ni} \tag{5}$$

Additional structural design variables include spar/rib cap areas, concentrated masses, and spring constants (for the springs representing stiffness of actuator and backup structure connecting control surfaces to the wing box or canard to the fuselage). Control system design variables include polynomial coefficients in the transfer functions representing control laws:

$$\frac{y(s)}{r(s)} = \frac{b_n s^n + \cdots + b_1 s + b_0}{s^n + d_{n-1} s^{n-1} + \cdots + d_1 s + d_0} \tag{6}$$

Aerodynamic design variables include coefficients in the polynomial series for wing initial (jig) shape

$$w_0(x,y) = \sum_{i=1}^{l} W_i x^{ri} y^{si} \tag{7}$$

Reference 49 describes a hierarchy of design variables (DVs) that includes sizing-type, shape-type and topological-type DVs in an increasing level of complexity. Because of the exploratory nature of the present work, only sizing-type DVs are used at the present stage across the disciplines. The control augmented structural synthesis problem formulated in this work is a sizing problem for the three disciplines. Thus, the balanced treatment of these disciplines (controls, aerodynamics, and structures) is also retained in formulating the optimization problem as in the analysis modeling.

Objective Functions and Behavior Constraints

The wing can be synthesized to minimize mass or gust response or maximize performance with constraints on stresses, aeroservoelastic stability, aircraft performance in terms of roll rate, drag, or drag polar specification, and control system performance in terms of activity in gusts and limits on control surface travel and hinge moment. The objective function can be chosen to be mass, drag, rms value of any response to atmospheric turbulence (to be minimized), or steady roll rate or lift to drag ratio (to be maximized) or a combination of these. Constraints are imposed to meet a combined stress criterion for composite skin layers and a unidirectional stress criterion for spar/rib caps. The aeroservoelastic system poles are forced to reside in the left half of the complex plane to guarantee dynamic stability.[60] If not included as part of the objective function, the drag, lift/drag, mass, or roll rate can be constrained to ensure acceptable performance.

Test Cases and Results: Remotely Piloted Vehicle Wing

Description

Optimization studies presented here deal first with a small RPV similar to the NASA DAST research vehicle.[61,62] Its planform geometry is shown in Fig. 1. The wing control surfaces are used only for active flutter control. An accelerometer is placed on the wing strip containing the control surface. It is located in the middle (spanwise) and at the 0.65-chord point of the strip. Its measurement y_{SE} serves as an input to a control law that, in turn, generates an input command δ to the actuator of the wing control surface. The RPV structure is modeled as an assembly of four equivalent plates. A flexible wing is attached to a rigid fuselage and rigid control surfaces. The main wing box structure, extending from root to tip spanwise and to 80% chordwise, is the structure to be synthesized. A pair of 2.5-kg concentrated masses is attached to the wingtip to simulate a wingtip pod. The weight of fuselage, control surfaces, and nonstructural wing mass is 308 kg for a half airplane. A Dryden gust model with a scale length of 518.16 m and a vertical gust rms velocity of 1.06 m/s is used. The set of three load conditions for wing stress calculations consists of 3-g symmetric pullups at sea level, 10,000, and 20,000 ft. In the maneuver load calculations, the airplane is trimmed using the elevator. All stress constraints reflect a 1.5 safety factor. Flutter, gust, and aeroservoelastic stability calculations, though, are carried out at sea level, Mach 0.9 for the cantilevered wing. This is done in order to first examine flutter suppression/ structural optimization using a realistic but simple example without flight mechanics interactions. The RPV wing box skins are made of glass/epoxy laminates.[62] Fiber directions are 0, 90, +45, and −45 deg relative to a line passing through the midchord points of the wing box. The skin is then modeled as made of four unidirectional lamina. The thickness distribution of each of these lamina is described by a nine-term polynomial in x and y as in Fig. 1. Thus, there are 36 structural design variables.

Structural Designs

Mimimum weight designs with structural design variables only subject to minimum gauge and stress constraints (stress design) or gauge, stress, and flutter constraints (flutter design) are synthesized first (Fig. 2). The stress design is unstable. The flutter constraints are in the form of a 2% lower bound on viscous damping in five modes corresponding to the lowest frequencies. Move limits of 40% were used, and convergence was achieved within 15 optimization cycles.

Structure/Control Designs

The control system is now incorporated, and wing mass is minimized subject to gauge, stress and flutter constraints while the design space includes both structural and control system design variables. Following its successful application to the all aluminum wing studied in Ref. 50, the first control law used for this study is the localized damping type transfer function (LDTTF).[24,63] This second-order control law provides damping locally in the range of frequencies where damping is needed. Its form is

$$\frac{\delta}{y_{SE}} = \frac{a_c}{s^2 + b_c s + c_c} \tag{8}$$

where y_{SE} is the accelerometer measurement and a_c, b_c, and c_c are control system design variables. The denominator coefficients can be associated with equivalent damping ζ_c and natural frequency ω_c of the control law. Thus, c_c and b_c determine the center frequency and gain peak width of the control law transfer function, whereas a_c determines the effective gain. The active control system is assumed to have no weight in the calculations performed in this study. In the case of the all aluminum wing,[50] when the second-order control system was added to the the problem and design synthesis started with the stress/gauge constrained (unstable) design, aeroservoelastic

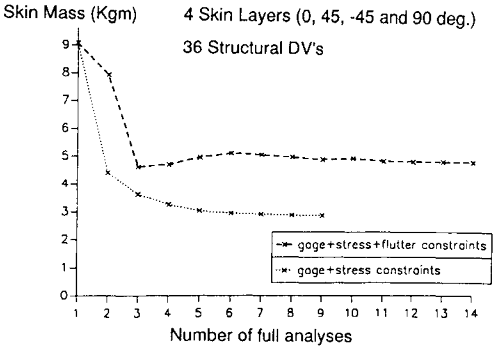


Fig. 2 Skin mass histories—stress and flutter designs—RPV composite wing.

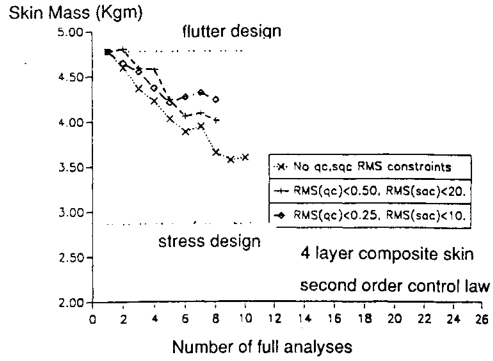


Fig. 3 Skin mass convergence histories for structure/control synthesis of the composite RPV wing (quadratic control law).

mass minimization made it possible to reduce the skin mass to its stress design value while the active control system prevented flutter. In the case of the composite wing, however, when the design space was opened up to include the three control system design variables as well as the 36 structural design variables, convergence could not be achieved when starting with the stress design. When synthesis starts with the feasible flutter design, convergence is achieved with 10% move limits, but only about 60% of the weight penalty needed for flutter prevention is recovered by the addition of the control system (Fig. 3). Limiting the control system power by including constraints on the aileron activity in atmospheric turbulence yields the same trend that was found for the aluminum wing: The more limited the control system is, the higher the structural weight penalty needed for aeroservoelastic stability. But the fact that, when the control system was unlimited in power it could not take care of the flutter problem called for further study.

Careful examination of the iteration histories starting with the stress design revealed complex eigenvalue approximations that were extremely sensitive to design changes. Linear[64]

$$\lambda = \lambda_0 + \sum_i \left.\frac{\partial \lambda}{\partial p_i}\right|_0 (p_i - p_{0i}) \tag{9}$$

or reciprocal

$$\lambda = \lambda_0 + \sum_i \left.\frac{\partial \lambda}{\partial (1/p_i)}\right|_0 \left(\frac{1}{p_i} - \frac{1}{p_{0i}}\right) \tag{10}$$

eigenvalue approximations were used first, where p_i is a typical design variable. The accuracy of these approximations is evaluated when constraint values obtained by a full analysis at a new design point are compared to approximations to these values constructed based on full analysis at the previous design. In the design synthesis cases that failed to converge, approximation accuracy for complex eigenvalues could change dramatically from iteration to iteration, yielding very good approximations in some instances and substantial errors in others. The Rayleigh quotient approximations (RQA),[46]

$$\lambda = \frac{\{\psi_0\}^T [V(p_i)] \{\phi_0\}}{\{\psi_0\}^T [U(p_i)] \{\phi_0\}} \tag{11}$$

[based on fixed direct ϕ_0 and adjoint ψ_0 eigenvectors of Eq. (3) evaluated at the reference point] improved approximation accuracy but did not solve the convergence problem. A closer look at the poles of the stress design composite wing revealed two flutter mechanisms. It appears that the second-order control law could not stabilize both simultaneously because of the narrow range of frequencies for which it is effective. Indeed, the design does not converge since it fluctuates between these two instabilities.

The control law was subsequently changed to a first-order low-pass filter of the form

$$\frac{\delta}{y_{SE}} = \frac{a_c}{s + b_c} \tag{12}$$

This control law is expected to have a wider bandwidth and, thus, be more effective in controlling the two instabilities. Indeed, the first-order control law makes it possible to regain most (85%) of the flutter weight penalty. The rms of control surface rotation and rotation rate, however, are much higher compared with the second-order control law.

A third control law was also studied. It is a fourth-order law made up from the sum of two second-order filters. This control law is expected to be more effective than the single second-order law in suppressing the flutter of the stress design. Its form allows tuning a second-order filter to each of the two instabilities:

$$\frac{\delta}{y_{SE}} = \frac{a_c}{s^2 + b_c s + c_c} + \frac{d_c}{s^2 + e_c s + f_c} \tag{13}$$

This control law has six design variables. The denominator coefficients can be associated with equivalent damping and natural frequency of the control law for each filter.

It should be re-emphasized at this point that the capability described here can be used to synthesize any control laws described by rational transfer functions. The selection of specific control laws in the present study was influenced by the aerodynamic energy approach.[24,63] The thrust of the work at the present stage, though, is not to identify preferable control laws but rather to examine the convergence characteristics and performance and gain experience with NLP/AC when applied to the multidisciplinary wing design problem.

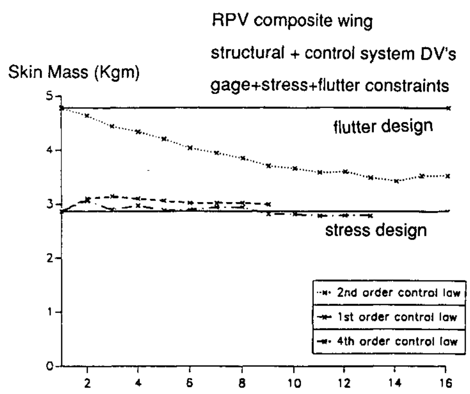


Fig. 4 Skin mass histories with different control laws (no gust response constraints).

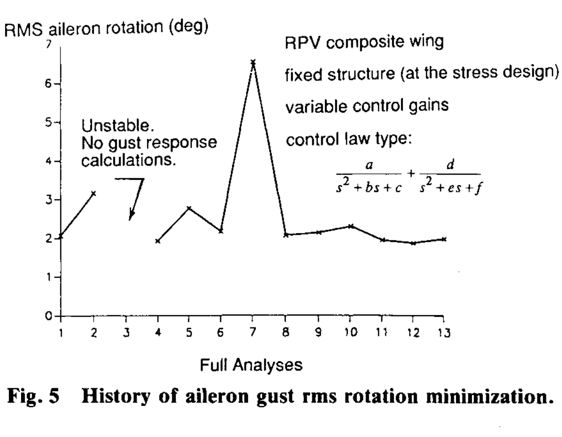


Fig. 5 History of aileron gust rms rotation minimization.

The performance of the three control laws is compared in Fig. 4 in terms of the minimum skin mass achieved when no gust response constraints are imposed on the control system. Indeed, the fourth-order control law makes it possible to stabilize the wing without any mass penalty over the stress design. Actually, it even reduces the mass slightly with respect to the stress design, but this is associated with the convergence criteria used. The stress design mass could be slightly reduced by tightening the percent change in objective function used in a diminishing return convergence criterion (see Ref. 59, pp. 100–101). A relative change in objective of less than 1% in three consecutive optimization cycles was used in the examples shown. The final fourth order law is

$$\frac{1421.7}{s^2 + 20.6s + 9596.8} + \frac{21{,}224.6}{s^2 + 120.1s + 20752.3}\ \text{deg/g} \tag{14}$$

The double quadratic control law is thus tuned to frequencies of 15.6 and 23.0 cps with equivalent damping ratios of 10.5 and 41.7% in these two frequencies, respectively.

Freezing the stress design of the composite RPV wing and looking for some "best" control system to stabilize it using a fourth-order control law leads to the design history in Fig. 5. Six control system design variables are now used in an effort to minimize the rms of aileron rotation due to atmospheric gusts. Move limits of 10% are used to converge to a control law

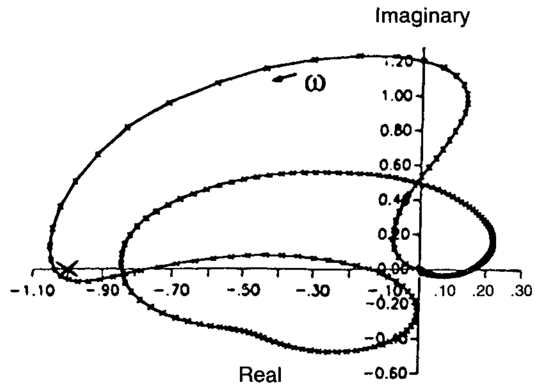
$$\frac{2289}{s^2 + 17.2s + 9209.7} + \frac{50{,}900}{s^2 + 305s + 23{,}380}\ \text{deg/g} \tag{15}$$

yielding a minimum rms rotation of 1.9 deg and associated rms of rotation rate of 249 deg/s. When, during the optimization, stability is lost, the gust response calculation is bypassed. This shows up as gaps in the design history of Fig. 5. If better performance in terms of rms of aileron activity is required, the design space has to include structural design variables in addition to the control system DVs. A feasible minimum skin weight design was found satisfying the gauge, stress, flutter, and additional constraints on the rms aileron activity (that limit it to half the values achieved in Fig. 5). Some structural weight, however, had to be traded in this case, and the resulting skin weight was about 22% heavier than the stress design.

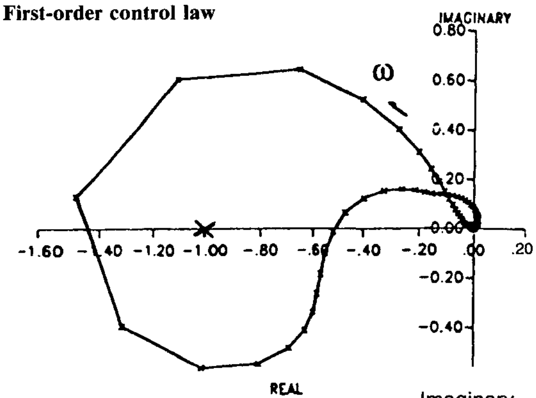
Of course, it might be argued that control system power translates in the end to added mass, and that for the tradeoff studies to be more realistic, one needs to include the weight of the control system in the objective function. The current capability can take this into account by linking the values of certain concentrated masses to the rms aileron rotation and rotation rate needed. This was not carried out, however, in the examples given here. In any case, as with the aluminum wing, the complex tradeoff between structural weight and control system power (or the resulting weight of the control system) is evident.

Another issue of extreme importance in control system synthesis is that of stability robustness.[25,37,65,66] Robustness requirements are not included directly in the set of behavior functions in this study. In light of the fact that control system synthesis here is carried out for a plant that is changing during the synthesis process, it is interesting to examine stability robustness of the resulting synthesized control systems.

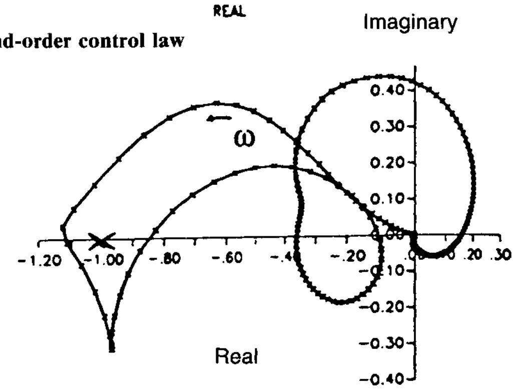
All of the examples up to this point involve a single-input single-output control system. Gain and phase margins of this control system can be studied by examining the Nyquist plots of the open-loop system. Figure 6 shows Nyquist plots for optimized control augmented wing designs subject to gauge, stress, and flutter constraints for the first-order quadratic and fourth-order control laws. In studying them, it should be remembered that they reflect control laws applied to different



a) **First-order control law**



b) **Second-order control law**



c) **Fourth-order control law**

Fig. 6 Nyquist plots for control augmented RPV minimum mass designs (no gust response constraints).

final plants (wing structure). The second-order control law has the highest gain and phase margins (with the highest penalty in terms of wing weight, see Fig. 4). Leading to smaller structural weight, the first- and fourth-order laws have small gain and phase margins. It was found that a considerable improvement in gain margin of the fourth-order control law design could be achieved by including (in addition to gauge, stress, and flutter constraints) gust response constraints on control surface activity. In the present case, this resulted in a higher weight and higher damping in the aeroservoelastic poles. Of course, other control laws may be more robust than the ones studied here.[66] In any case, it is clear that it is essential to include constraints that will guarantee robustness of the resulting design in the integrated optimization problem formulation.

YF16-Type Airplane Model

The studies presented thus far focused on a very simple airplane configuration (RPV) and a simple single-input, single-output control system. In order to demonstrate the power of the present capability in synthesizing more complex configurations with more complex control systems, a more realistic model is considered next. It is similar to a YF16 fighter airplane and is shown in Fig. 7. A flexible wing/flaperon combination is attached to a rigid fuselage/elevator combination. The wing box skin thickness distribution is to be synthesized. The airplane is initially statically stable and weighs 4234 kg per half airplane (not including the skin mass). Minimum gauge and stress constraints are imposed on an array of 5×5 grid points over the skin. The two maneuver conditions considered for stress calculations are a 7.33-g symmetric pullup and a steady 160-deg/s roll, both at sea level, $M = 0.9$. Stress (stress + gauge constraints) and flutter (stress + gauge + flutter) design histories converged in less than 14 optimization cycles for the composite graphite/epoxy wing with structural design variables only. Minimum gauge is 0.0127 mm (0.005 in.) for each laminate (0, 90, +45, −45 deg) in the graphite/epoxy skin. Aeroelastic stability is examined for symmetric and antisymmetric vibrations of the free-free airplane at sea level, $M = 0.9$. A minimum of 5% damping (ζ) is required in the first four symmetric and three antisymmetric poles (the first symmetric pole is a short-period pole). Damping of 1% is required for higher-frequency poles. When only structural design variables were considered, move limits of 40% were used. The stress design skin weight was 30.93 kg and the flutter design skin weight was 100.5 kg. The penalty in terms of weight paid for meeting the flutter constraints is clearly evident.

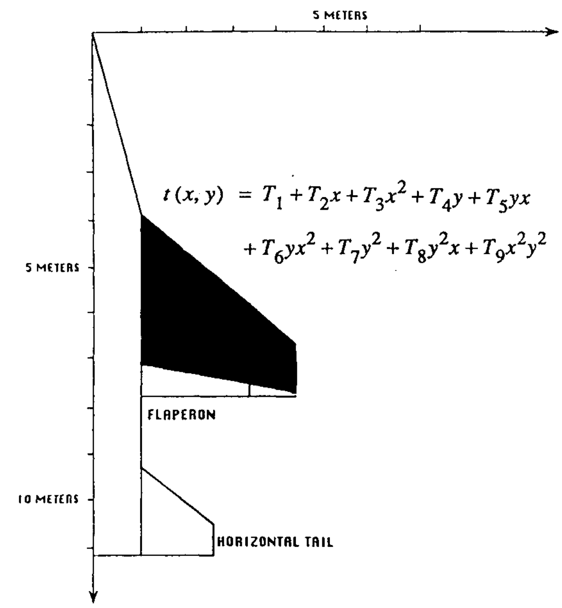


Fig. 7 Lightweight fighter model—no tip missiles (wing box skin thickness synthesized).

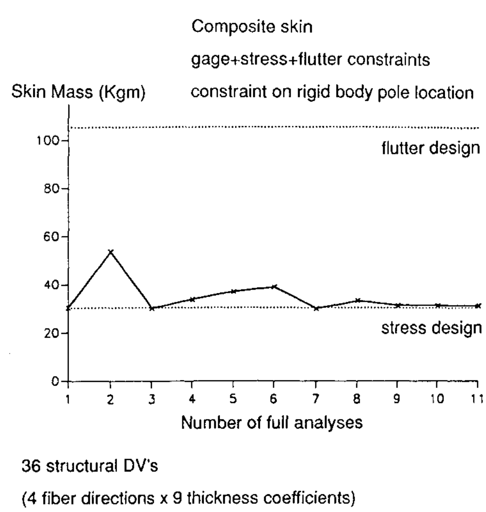


Fig. 8 Skin mass minimization history for the control augmented lightweight fighter model.

A multi-input, multi-output (MIMO) control system is now added to the model. It is structured after the actual YF16 control system[67] with an addition for flutter suppression. Angle of attack, pitch rate, and normal acceleration are measured at the center fuselage and used by control laws that take care of static stability and handling qualities of the airplane in symmetric motion. Roll rate measurement at the fuselage is used for the roll channel to control rolling performance. Wingtip accelerometers (at the tip leading edge) of each wing are used for flutter suppression in combination with the fuselage normal acceleration reading. The sum of the tip accelerations is used for flutter suppression in symmetric motion. Their difference is used for antisymmetric vibration stabilization. Assuming perfect sensors and using the transfer functions of the actual YF16 actuators,[67] six control laws are synthesized simultaneously to ensure 5% damping (ζ) in poles associated with elastic modes in symmetric and antisymmetric motion. A 35% minimum damping constraint and constraints on short-period frequency that limit it to the range of 0.25–1.00 cps[10] as well as a 35% minimum damping requirement on the control augmented roll pole are a simple way to introduce handling quality considerations. The interactions between a flight control system and an active flutter suppression system can thus be taken into acount in the early design stages.

Figure 8 shows a skin mass design iteration history for the control augmented YF16-type airplane model. Move limits of

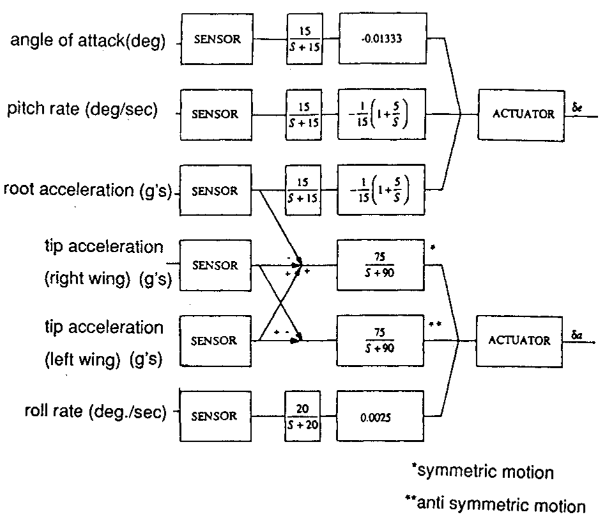


Fig. 9 Lightweight fighter model—control system at start of synthesis.

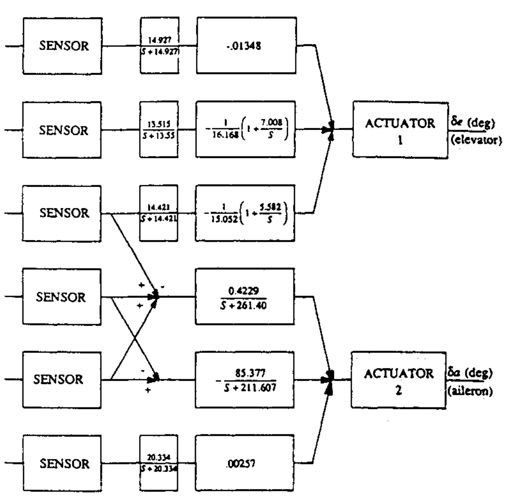


Fig. 10 Lightweight fighter model—control system at the end of synthesis.

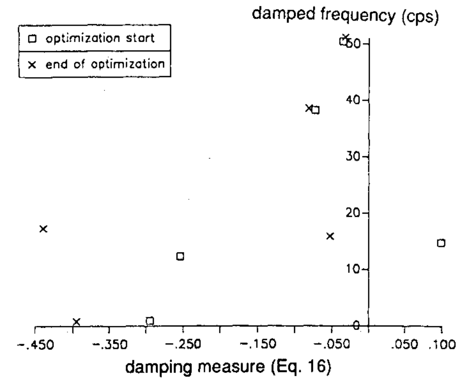


Fig. 11 Control augmented lightweight fighter poles—symmetric vibrations.

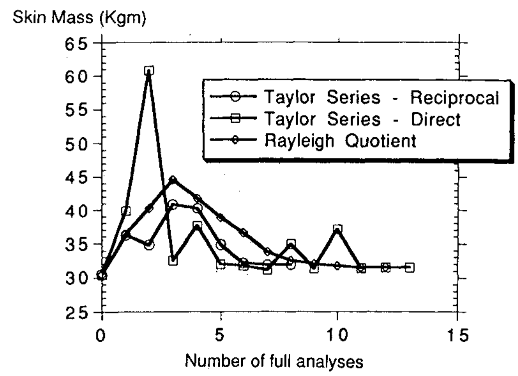


Fig. 12 Skin mass minimization histories with different aeroservoelastic pole approximations.

10% were used for all design variables. A total of 36 design variables are used for the thickness distribution of a wing box skin consisting of four composite laminates, and 14 design variables are used in the control system. Gauge, stress, flutter, and handling quality constraints are included. The design converges to the stress design weight in 11 full analysis/optimization cycles. The initial and final control systems are shown in Figs. 9 and 10.

It is interesting to notice the change in sign in the antisymmetric flutter suppression control law, the bandwidth increase in the two flutter suppression laws, and the practical elimination of the symmetric flutter suppression law in the final control system compared with the initial design. Locations of the complex poles of the symmetric control augmented YF16-type model are shown in Fig. 11 (actuator poles, aerodynamic poles, and integrator poles are not shown). The damping measure is defined as

$$\zeta = \frac{\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{16}$$

where σ and ω are the real and imaginary parts of the complex poles, respectively. Thus, a positive damping measure indicates instability.

The synthesis of the control augmented YF16-type model wing involved 820 constraints and 50 design variables. It took 18 min of CPU time on the UCLA IBM 3090 Model 600J.

Before concluding this section, it is interesting to examine the effect of different complex eigenvalue approximations on synthesis results. Composite wing skin mass histories for a structural/control design subject to stress, minimum gauge, and flutter constraints are shown in Fig. 12. Move limits of 40% were used for the structural design variables and 10% for the control design variables. Taylor series direct and Rayleigh quotient approximations lead to essentially the same result, and their performance in terms of the rate of convergence is similar. Taylor series reciprocal approximations lead to faster convergence but to a slightly higher final weight.

Conclusions

Using current supercomputers, unique integration of analysis techniques, analytic sensitivities, and optimization based on approximation concepts methodology, the single-level multidisciplinary synthesis of realistic actively controlled composite wings is both practical and feasible. However, the introduction of control system design variables in addition to structural design variables presents a challenge to current approximate optimization problem generation. Smaller move limits are necessary when constraints on pole location and gust response are included. This slows the convergence of the optimization process and makes it harder to find the feasible region when starting with infeasible designs.

The importance of NLP based synthesis technology is also evident because the multidisciplinary interactions and constraints that will drive the design are unknown at the outset and are very hard to predict. It has also been shown that an integrated approach to multidisciplinary wing synthesis can successfully generate designs that satisfy a rich blend of multidisciplinary constraints and possible objectives.

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References

[1]Newsom, J. R., Adams, W. M., Mukhopadhyay, V., Tiffany, S. H., and Abel, I., "Active Controls: A Look at Analytical Methods and Associated Tools," *Proceedings of the 14th Congress of the International Council of the Aeronautical Sciences,* Paper ICAS-84-4.2.3, Toulouse, France, 1984, pp. 230–242.

[2]Weisshaar, T. A., "Aeroelastic Tailoring—Creative Uses of Unusual Materials," *AIAA/ASME/ASCE/AHS 28th Structures, Structural Dynamics and Materials Conference,* AIAA, New York, 1987.

[3]Felt, L. R., Huttsell, J., Noll, T. E., and Cooley, D. E., "Aeroservoelastic Encounters," *Journal of Aircraft,* Vol. 16. No. 7, 1979, pp. 477–483.

[4]Lynch, R. W., and Rogers, W. A., "Aeroelastic Tailoring of Composite Materials to Improve Performance," *Proceedings of the 16th AIAA Structures, Structural Dynamics and Materials Conference,* AIAA, New York, 1975.

[5] Haftka, R. T., "Optimization of Flexible Wing Structures Subject to Strength and Induced Drag Constraints," *AIAA Journal,* Vol. 15, 1977, pp. 1101–1106.

[6]Tolson, R. H., and Sobieszczanski-Sobieski, J., "Multidisciplinary Analysis and Synthesis: Needs and Opportunities," AIAA Paper 85-0584, April 1985.

[7]Grossman, B., Gurdal, Z., Strauch, G.J., Eppard, W. M., and Haftka, R. T., "Integrated Aerodynamic/Structural Design of a Sailplane Wing," *Journal of Aircraft,* Vol. 25, No. 9, 1988, pp. 855–860.

[8]Zeiler, T. A., and Weisshaar, T. A., "Integrated Aeroservoelasic Tailoring of Lifting Surfaces," *Journal of Aircraft,* Vol. 25, No. 1, Jan. 1988, pp. 76–83.

[9]Morris, S., and Kroo, I., "Aircraft Design Optimization with Multidisciplinary Performance Criteria," *Proceedings of the AIAA/ASME/ASCE/AHS/ASC 30th Structures, Structural Dynamics and Materials Conference,* AIAA, Washington, DC, April 1989.

[10]Rimer, M., Chipman, R., and Muniz, B., "Control of a Forward Swept Wing Configuration Dominated by Flight Dynamics/Aeroelastic Interactions," *Journal of Guidance, Control, and Dynamics,* Vol. 9, No. 1, 1986, pp.72–79.

[11]Beaufrere, H., "Limitations of Statically Unstable Aircraft due to the Effects of Sensor Noise, Turbulence, and Structural Dynamics," AIAA Paper 86-2203, Aug. 1986.

[12]Yamamoto, T., "Impact of Aircraft Structural Dynamics on Integrated Control Design," AIAA Paper 83-2216, Aug. 1983.

[13]Becker, J., Weiss, F., and Sensburg, O., "Compatibility Aspects of Active Control Technologies with Aircraft Structural Design," *Structural Control,* edited by H. H. E. Leipholz, Matrinus Nijhoff, Dordrecht, 1987.

[14]Ashley, H., "On Making Things the Best—The Aeronautical Uses of Optimization," *Journal of Aircraft,* Vol. 19, No. 1, 1982, pp. 5–28.

[15]Sobieszczanski-Sobieski, J., and Chopra, I., "Introduction to Special Section," Special Section on the Multidisciplinary Optimization of Aeronautical Systems, *Journal of Aircraft,* Vol. 27, No. 12, 1990.

[16]Bryson, A. E., and Ho, Y. C., *Applied Optimal Control,* Hemisphere, Washington, D.C., Revised Printing, 1975.

[17]Miele, A., *Theory of Optimum Aerodynamic Shapes,* Academic, New York, 1965.

[18]Haftka, R. T., Gurdal, Z., and Kamat, M. P., *Elements of Structural Optimization,* 2nd ed., Kluwer, Dordrecht, 1990.

[19]Schmit, L. A., "Structural Synthesis—Its Genesis and Development," *AIAA Journal,* Vol. 10, No. 10, 1981, pp. 1249–1263.

[20]Schmit, L. A., "Structural Analysis—Precursor and Catalyst," *Recent Experiences in Multidisciplinary Analysis and Optimization,* NASA CP-2327, Pt. 1, 1984, pp. 1–17.

[21]Schmit, L. A., "Structural Optimization—Some Key Ideas and Insights," *New Directions in Optimum Structural Design,* edited by E. Atrek, R. H. Gallagher, K. M. Ragsdell, and O. C. Zienkiewicz, Wiley, New York, 1984.

[22]Hornlein, H. R. E. M., "Takeoff in Optimum Structural Design," *Computer Aided Optimal Design: Structural and Mechanical Systems,* edited by C. A. Mota Soares, Springer-Verlag, Berlin, 1987.

[23]Schy, A. A., Adams, W. M., and Johnson, K. G., "Computer Aided Design of Control Systems to Meet Many Requirements," 17th Meeting of AGARD Guidance and Control Panel, Ceilo, Norway, Sept. 1973.

[24]Nissim, E., and Abel, I., "Development and Application of an Optimization Procedure for Flutter Suppression Using the Aerodynamic Energy Concept," NASA TP-1137, Feb. 1987.

[25]Maciejowski, J. M., *Multivariable Feedback Design,* Addison-Wesley, Reading, MA, 1989, Chap. 7.

[26]Boyd, S. P., and Barratt, C. H., *Linear Controller Design—Limits of Performance,* Prentice-Hall, Englewood Cliffs, NJ, 1991.

[27]Mayne, D. Q., Polak, E., and Sangiovanni-Vincentelli, A., "Computer-aided Design via Optimization: A Review," *Automatica,* Vol. 18, 1982, pp. 147–154.

[28]Polak, E., Mayne, D. Q., and Stimler, D. M., "Control System Design via Semi-infinite Optimization: A Review," *Proceedings of the IEEE,* Vol. 72, 1984, pp. 1777–1794.

[29]Ly, U. L., "A Design Algorithm for Robust Low-Order Controllers," Ph.D. Dissertation, Stanford Univ., Stanford, CA, 1983 (available from Univ. Microfilm International, order no. 8307181).

[30]Wuu, T. L., "DELIGHT.MIMO: An Interactive System for Optimization-based Multivariable Control System Design," Ph.D. Dissertation, Univ. of California, Berkeley, CA, 1986 (available from Univ. Microfilm International, order no. 8718215).

[31]Rauch, H. E. (ed.), "Application of Nonlinear Programming to Optimization and Control," *Proceedings of the 4th IFAC Workshop,* San Francisco, CA, June 1983.

[32]Di Pillo, G. (ed.), "Application of Nonlinear Programming to Optimization and Control," *Proceedings of the 5th IFAC Workshop,* Capri, Italy, June 1985.

[33]Stimler, D. M., and Polak, E., "Nondifferentiable Optimization in Worst Case Control System Design: A Computational Example," *Proceedings of the IEEE Third Symposium on Computer-Aided Control System Design,* IEEE, Piscataway, NJ, Sept. 1986, pp. 102–109.

[34]Adams, W. M., and Tiffany, S. H., "Application of Optimization Techniques to the Design of a Flutter Suppression Control Law for the DAST ARW-2," *Recent Experiences in Multidisciplinary Analysis and Optimization,* NASA CP-2327, Pt. 1, 1984, pp. 279–295.

[35]Gangsaas, D., Bruce, K. R., Blight, J. D., and Ly, U. L., "Application of Modern Synthesis to Aircraft Control: Three Case Studies," *IEEE Transactions on Automatic Control,* Vol. AC-31, No. 11, 1986, pp. 995–1013.

[36]Gordon, V. C., and Collins, D. J., "Multi-Input Multi-Output Automatic Design Synthesis for Performance and Robustness," *Journal of Guidance, Control, and Dynamics,* Vol. 9, No. 3, 1986, pp. 281–287.

[37]Mukhopadhyay, V., "Stability Robustness Improvement Using Constrained Optimization Techniques," *Journal of Guidance, Control, and Dynamics,* Vol. 10, No. 2, 1987, pp. 172–177.

[38]Mukhopadhyay, V., "Digital Robust Control Law Synthesis Using Constrained Optimization," *Journal of Guidance, Navigation, and Control,* Vol. 12, No. 2, 1989, pp. 175–181.

[39]Bodden, D. S., and Junkins, J. L., "Eigenvalue Optimization Algorithms for Structure/Controller Design Iterations," *Journal of Guidance, Control, and Dynamics,* Vol. 8, No. 6, 1985, pp. 697–706.

[40]Onoda, J., and Haftka, R. T., "An Approach to Structure/Control Simultaneous Optimization for Large Flexible Spacecraft," *AIAA Journal,* Vol. 25, No. 8, 1987, pp. 1133–1138.

[41]Haftka, R. T., "Optimum Control of Structures," *Computer Aided Optimal Design: Structural and Mechanical Systems,* edited by C. A. Mota Soares, Springer-Verlag, Berlin, 1987.

[42]Khot, N. S., "Minimum Weight and Optimal Control Design of Space Structures," *Computer Aided Optimal Design: Structural and Mechanical Systems,* edited by C. A. Mota Soares, Springer-Verlag, Berlin, 1987.

[43]Gilbert, M. G., and Schmidt, D. K., "Integrated Structure/Control Law Design by Multilevel Optimization," AIAA Paper 89-3470, 1989.

[44]Junkins, J. L., and Rew, D. W., "Unified Optimization of Structures and Controllers," *Large Space Structures Dynamics and Control,* edited by S. N. Atluri and A.K. Amos, Springer-Verlag, Berlin, 1988.

[45]Thomas, H. L., and Schmit, L. A., "Control Augmented Structural Synthesis with Dynamic Stability Constraints," *AIAA Journal*, Vol. 29, No. 4, 1991, pp. 619–626.

[46]Thomas, H. L., Sepulveda, A. E., and Schmit, L. A., "Improved Approximations for Control Augmented Structural Synthesis," *AIAA Journal,* Vol. 30, No. 1, 1992, pp. 171–179.

[47]Haftka,. R. T. "Integrated Structure-Control Optimization of Space Structures," *Mechanics and Control of Large Flexible Structures,* edited by J. L. Junkins, Vol. 129, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1990.

[48]Livne, E., "An Integrated Approach to the Optimum Design of Actively Controlled Composite Wings," Second NASA/Air Force Symposium on Recent Advances in Multidisciplinary Optimization, Hampton, VA, Sept. 1988.

[49]Livne, E., Schmit, L. A., and Friedmann, P. P., "Towards an Integrated Approach to the Optimum Design of Actively Controlled Composite Wings," *Journal of Aircraft,* Vol. 27, No. 12, Dec. 1990, pp. 979–992.

[50]Livne, E., Schmit, L. A., and Friedmann, P. P., "Exploratory Design Studies Using an Integrated Multidisciplinary Synthesis Capability for Actively Controlled Composite Wings," 31st Structures, Structural Dynamics and Materials Conference, AIAA Paper 90-0953, Long Beach, CA, 1990.

[51]Livne, E., "Integrated Multidisciplinary Optimization of Actively Controlled Fiber Composite Wings," Ph.D. Dissertation, Dept. of Mechanical, Aerospace, and Nuclear Engineering, Univ. of California, Los Angeles, CA, Aug. 1990.

[52]Livne, E., Schmit, L. A., and Friedmann, P. P., "Further Design Experimentation with an Integrated Multidisciplinary Synthesis Capability for Actively Controlled Composite Wings," Third Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization, San Francisco, CA, Sept. 1990.

[53]Livne, E., Friedmann, P. P., and Schmit, L. A., "Studies in Integrated Aeroservoelastic Optimization of Actively Controlled Composite Wings," 32nd Structures, Structural Dynamics and Materials Conference, AIAA Paper 91-1098, Baltimore, MD, April 1991.

[54]Giles, G. L., "Equivalent Plate Analysis of Aircraft Wing Box Structures with General Planform Geometry," *Journal of Aircraft,* Vol. 23, No. 11, 1986, pp. 859–864.

[55]Livne, E., Schmit, L. A., and Friedmann, P. P, "Design Oriented Structural Analysis for Fiber Composite Wings," Univ. of California at Los Angeles, UCLA-ENG-88-36, Los Angeles, CA, 1988.

[56]Lottati, I., and Nissim, E., "Three Dimensional Oscillatory Piecewise Continuous Kernel Function Method," *Journal of Aircraft,* Vol. 18, No. 5, 1981, pp. 346–363.

[57]Roger, K. L., "Airplane Math Modeling Methods for Active Control Design," Structural Aspects of Active Controls, AGARD CP-228, Aug. 1977, pp. 4–11.

[58]Golub, G. H., Nash, S., and Van Loan, C., "A Hessenberg-Schur Method for the Problem $AX + XB = C$," *IEEE Transactions on Automatic Control,* Vol. AC-24, No. 6, 1979, pp. 909–913.

[59]Vanderplaats, G. N., *Numerical Optimization Techniques for Engineering Design,* McGraw-Hill, New York, 1984, pp. 163–177, 283.

[60]Hajela, P., "A Root Locus-Based Flutter Synthesis Procedure," *Journal of Aircraft,* Vol. 20, No. 12, 1983, pp. 1021–1027.

[61]Liebst, B. S., Garrard, W. L., and Adams, W. M., "Design of an Active Flutter Suppression System," *Journal of Guidance, Control, and Dynamics,* Vol. 9, No. 1, 1986, pp. 64–71.

[62]Eckstrom, C. V. and Spain, C. V., "Design Considerations and Experiences in the Use of Composite Material for an Aeroelastic Research Wing," *AIAA/ASME/ASCE 23rd Structures, Structural Dynamics and Materials Conference,* AIAA, New York, Aug. 1982, pp. 157–165; also AIAA Paper 82-0678, 1982.

[63]Nissim, E., "Design of Control Laws for Flutter Suppression Based on the Aerodynamic Energy Concept and Comparisons with Other Design Methods," AIAA Paper 89-1212, April 1989.

[64]Murthy, D. V., and Haftka, R. T., "Approximations to Eigenvalues of Modified General Matrices," *Computers and Structures,* Vol. 29, No. 5, 1988, pp. 903–917.

[65]Karpel, M., "Sensitivity Derivatives of Flutter Characteristics and Stability Margins for Aeroservoelastic Design," *Journal of Aircraft,* Vol. 27, No. 4, 1990, pp. 368–375.

[66]Schmidt, D. K., and Chen, T. K., "Frequency Domain Synthesis of a Robust Flutter Suppression Control Law," *Journal of Guidance, Control, and Dynamics,* Vol. 9, No. 3, 1986, pp. 346–351.

[67]Moore, R. L., "Aeroservoelastic Stability Analysis of an Airplane with a Control Augmentation System," Ph.D. Dissertation, Ohio State Univ., Columbus, OH, 1978 (available from Univ. Microfilms International, order no. 7902191).