INTEGRATED STRUCTURE/CONTROL DESIGN - PRESENT METHODOLOGY AND FUTURE OPPORTUNITIES

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Abstract

This paper introduces and reviews current methodology applied to integration of the optimal design process for structures and controls. This procedure is approached from both a practical and a mathematical viewpoint. A discussion of the formulation of performance indices or cost functions is presented, together with typical results. Synergistic benefits of such a procedure are outlined. One method, multi-level, linear decomposition, appears particularly attractive, based upon limited evidence. The impending development of large orbiting space structures and actively controlled, high performance aircraft present important opportunities, if not necessities, for further exploitation of this concept.

Introduction

The past few years have witnessed the growth of many areas of aerospace technology. In particular, the advent of reliable automatic active control has had an important impact upon aircraft configuration design. Relaxed static stability, gust load alleviation, maneuver load control and flutter suppression have all been the positive results of this technology. Until recently little thought or effort has been given to the synergistic integration of active control design and the design of the aircraft structure. Very often the active control appears as an add-on or "fix" to some structural difficulty.

While current practice has dictated visible interfaces between structural design and active control design, this is not likely to be the case in future competitive aerospace designs. Unintentional, strong, often adverse, coupling between the active control system and the flexible structure has occurred with sufficient frequency to convince engineers that a wholistic or integrated approach to control and structural design is essential.

This paper examines the subject of integrated structures and control design or ISCD. An archival literature search was done to define and to survey the likely trends in this emerging area. The review is representative but, because of limited space, not all inclusive. ISCD trends in aircraft and spacecraft design are seen to be related, but with significant differences. Before surveying current work in ISCD, let us first digress to the subject of integrated design itself to gain perspective on the problem.

Background

In addition to sociological, psychological, and mathematical meanings, the term "integration" has found increased usage in technological applications, such as: integrated circuits; systems integration; and, integrated design. Despite the differing uses of "integration" there is a common thread of meaning running through each of them, namely, the combination of segregated parts into a unified, coherent whole. Integrated design seeks to combine a variety of components and subsystems, of differing form and function, into a single functional system, such as an aerospace vehicle, so as to achieve not only a harmonious balance, but an advantageous interplay of performance related design objectives.

A case for integrated aerospace design has been made by Tolson and Sobieski [1], among others, based upon reports contained in Reference 2, a Workshop report on the Aeronautical Technology Possibilities for the Year 2000. Tolson notes that six of the seven individual discipline panels of the Workshop indicate significant potential benefits from integration of their technology with other technologies.

However, to favor "design integration" is one thing; it is quite another to develop an implementable design methodology, or even a reasonable statement of system design objectives. The solution of large, multiple-variable design problems is a large computational and organizational task. A truly integrated design effort requires consideration of an enormous number of design variables, requirements, constraints, and objectives.

If optimization techniques are to be used for individual discipline designs, then questions concerning performance indices and the integration of these indices into the system solution will arise very quickly. At the outset, a decision must be made as to the relative importance or weight to be assigned to each design parameter. Otherwise, cruise range of an aircraft might be accorded equal importance with control surface deflection. Furthermore, the development of an analytical model with sufficient detail to allow the realistic consideration of every design variable is now, and probably always shall be, prohibitive.

Even if all concerned parties agree upon the "proper mix" of weighted performance indices, problems remain as to how to compute and when to compute such indices. Such considerations are very important because the design process can be viewed as being conducted in either: (1) a series or sequential approach; or, (2) a parallel or simultaneous information flow approach. Let us consider and contrast these two alternatives.

With a series/sequential approach, the design aspects and performance index (for example, weight) associated with each individual discipline remain associated exclusively with that particular discipline. Each disciplinary design effort occurs at a specific point in a predefined sequence of events. At the end of the design sequence, overall system performance is compared to the initial overall design objectives to determine the adequacy of the design. If the design is in some way inadequate, parts of the process are chosen to be repeated, with the option of providing some form of design sensitivity information (design feedback) so that the design result provided by the second sequence is better than the first.

The final design obtained using the series approach is highly dependent upon the operational sequence. For example, a final design, with the control design considered first followed by structural design, may be very different from that obtained when structural design is done first, followed by control design. In fact, the design tends to be dominated by the first design discipline unless the system design requirements are so stringent that numerous design iterations are performed. In short, with a series/sequential approach, what is perceived to be integrated design is really iterated design, the enforced result of repetitive iteration.

On the other hand, consider the parallel or simultaneous design information approach in which individual disciplines retain unique identities, but with each individual design effort occurring at approximately the same time. This approach requires a high level of coordination between the various disciplinary design groups. Such coordination must be done at a higher level so that performance requirements of the individual disciplines can be weighed against the requirements of the whole system before a final design appears. This approach requires the construction of data base information to be shared by the individual design teams and, most importantly, the presence of someone with authority to choose a less than desirable solution in any one discipline for the good of the whole. Among the information provided to the coordinator is some form of design sensitivity data to help assess how changes in one area affect others.

The origin of integrated structures and control design synthesis can be traced to the birth of powered flight itself. Among the most challenging problems solved by the Wright Brothers before their first powered flight in 1903 was that of providing for three-axis stability and control, especially lateral control, of the aircraft. Their ingeneous solution to the necessity to generate rolling power involved differential torsional warping of the biplane wings. Roll control was effected by the movement of the pilot's hips as he lay prone within a cradle resting upon the lower wing surface. Movement of this cradle moved cables that in turn twisted or "warped" the wings; this action generated additional lift on one side of the aircraft, while reducing it on the other. Had it not been for the torsional flexibility of the biplane wing structure, maneuvering powered flight would not have taken place when it did.

While ailerons rapidly replaced wing warping as a roll controller, the advent of the high speed monoplane led to aileron roll "effectiveness" difficulties caused by excessive torsional flexibility of monoplane wings at high speeds. These difficulties spawned a number of analytical and experimental assessments, particularly in Great Britain, of the effects of flexibility on roll control. Control effectiveness, defined as the ability to generate roll moments (per unit of aileron deflection), became particularly important to the success of high speed fighter aircraft design before World War II.

The introduction of high aspect ratio, highly flexible, sweptback wings after World War II further exacerbated the problem of roll or "lateral" control effectiveness. Torsional flexibility reduces the effectiveness of both swept and unswept wing control surfaces. Swept wing bending flexibility is highly important, since added lift due to aileron rotation lessens the streamwise angle of attack of wing cross-sections. The result is reduced lift that in turn produces a smaller rolling moment than anticipated. The XB-47 and B-52 bomber aircraft encountered roll effectiveness difficulties sufficient to lead to the adoption of spoilers to replace ailerons as lateral control surfaces. Despite the mutual interaction between control surface and wing flexibility, control ineffectiveness is still perceived to be a structural problem.

Until the early 1970's the only engineering measures available to counter control induced aeroelastic difficulties, be they static or dynamic were: reduced airspeed; limited maneuverability; or, "beefed-up" structure. The late 1960's and 1970's witnessed the development of two major technologies applicable to solve aeroelastic difficulties: Active Controls Technology (ACT) and Aeroelastic Tailoring. Let us first consider ACT.

Active controls have been in use for over sixty years, starting with simple forms of autopilots and progressing to systems used to control "rigid body" aircraft dynamics. However, only in the last twenty years have active controls seriously been considered for controlling aircraft "elastic modes." When active controls are used to control both rigid body and elastic modes, aircraft performance can be increased both through improved aerodynamic performance and reduced structural weight. Structural weight can be reduced by activating control surfaces to reduce maneuver and gust loads, reduce fatigue loads due to turbulence, and to dampen structural modes that contribute to flutter. There have been many analytical and some experimental studies of the feasibility and potential benefits of many of the active control concepts. Reference 3 describes the development of analytical methods required to perform many of the analytical studies. Reference 4 gives an excellent review of both wind-tunnel and flight tests with active controls.

To complement active controls, the extreme strength of advanced composite laminated materials provides substantial latitude for changing or "tailoring" individual plies to couple together characteristic modes of deformation, such as spanwise bending and twist, without adversely affecting strength. The result is an "educated structure" that automatically (and passively) redistributes (rather than eliminates) aerodynamic loads in response to input loads such as those due to aileron deflection. In the context of "structural control" the structure itself is both sensor and actuator, accepting initial aerodynamic load inputs (aileron, rudder, pitch angle) and providing aerodynamic load outputs (roll moment, yaw moment, maneuver load).

Tailoring the structure to enhance aeroelastic performance has received a substantial amount of attention in recent years. A comprehensive review of these efforts is contained in Reference 5. Such structural design potential is important to ISCD efforts because many different advanced composite designs may exist to fulfill a mission. However, while each design might have approximately the same strength and weight, each can have radically different aeroelastic capabilities, some of which are more compatible with control surfaces.

A Static ISCD Problem - Control Effectiveness

Let us examine a simple ISCD problem, the interactive design of lifting surface stiffness and aileron controls to produce effective lateral control for a conventional, symmetrical planform aircraft. Consider a simple textbook idealization for which aileron deflection, δ_o, creates lift on a wing by producing an effective airfoil streamwise angle of attack over a portion of a wing such as that shown in Figure 1.

When the unswept wing rolls at a steady rate, p, an expression for the effective angle of attack along with the wing (written as $\alpha(y)$) may be found by adding three distinct effects together, as follows:

$$\alpha(y) = \frac{\partial\alpha}{\partial\delta}\delta_o - \frac{py}{V} + \theta(y) \tag{1}$$

The term $\partial\alpha/\partial\delta$ is due to added effective camber that repositions the zero-lift line to create additional lift. The term py/V represents the effect of roll velocity py, combined with forward speed, to create the so-called "damping-in-roll" effect. The term $\theta(y)$ reflects the flexibility of the wing and the tendency of streamwise sections to rotate, either through twisting or, in the case of swept wings, through a combination of bending and twisting. The amount of twist depends upon the flight dynamic pressure and sectional aerodynamic coefficients such as c_{1_α}, c_{1_δ} and c_{m_δ}. The value of steady-state roll rate p cannot be determined from Eqn. 1, since $\theta(y)$ depends upon p, δ_o and dynamic pressure. Equation 1, or its equivalent, can be input into an aeroelastic analysis to find $\theta(y)$ as a function of p, $\partial\alpha/\partial\delta$, $c_{m\delta}$, q, together with structural and wing planform parameters. This information is then used to determine the steady state roll rate, p.

Conceptually, the relationship defining the total roll moment about the aircraft centerline, M_R, created by aileron rotation δ_o may be written as follows:

$$M_R = \frac{\partial M}{\partial(\frac{pL}{V})}\left(\frac{pL}{V}\right) + \frac{\partial M}{\partial(\frac{\partial\alpha}{\partial\delta})}\left(\frac{\partial\alpha}{\partial\delta}\right)\delta_o + \frac{\partial M}{\partial c_{m\delta}} c_{m\delta}\,\delta_o \tag{2}$$

In Eqn. 2, L is the semi-span dimension of the wing, measured perpendicular from the roll axis to the wing tip. As the aircraft rolls, the wing tip traces out a helix in space, with an angle given by pL/V. The magnitude of pL/V per δ_o is a measure of "aileron effectiveness." The larger the value of pL/V, the more effective the controls are said to be.

The derivatives appearing in Eqn. 2 may be written symbolically as

$$\frac{\partial M}{\partial(\frac{\partial\alpha}{\partial\delta})} = M_{\alpha\delta} \tag{3}$$

$$\frac{\partial M}{\partial c_{m\delta}} = M_{m\delta} \tag{4}$$

$$\frac{\partial M}{\partial(\frac{pL}{V})} = M_p \tag{5}$$

These derivatives are functions of structural stiffness, flight dynamic pressure and Mach number. In the limiting case of infinite structural stiffness, $M_{m\delta}$ will be zero. These derivatives are found from an aeroelastic analysis in which each of the three parameters $\partial\alpha/\partial\delta$, $c_{m\delta}$ and pL/V, is set to equal unity (one at a time); the resulting roll moment M_R is then computed to determine the derivatives. When p is constant, M_R is zero; pL/V is found to be:

$$\frac{pL}{V} = \frac{-(M_{\alpha\delta}(\frac{\partial\alpha}{\partial\delta}) + M_{m\delta}\,c_{m\delta})\delta_o}{M_p} \tag{6}$$

The negative sign in Eqn. 6 belongs with the denominator term since this latter term is associated with "damping in roll" opposing the roll motion. The numerator (without the minus sign) in Eqn. 6 is sometimes referred to as the "rolling power." Note that, although both $M_{\alpha\delta}$ and $M_{m\delta}$ are generally positive, the term $\partial\alpha/\partial\delta$ is always positive while $c_{m\delta}$ is negative. As a result, the terms in the numerator work against one another to reduce lateral control effectiveness.

If structural flexibility is ignored, the design of the control surface for maximum "effectiveness" reduces to maximizing the derivative $M_{\alpha\delta}$. This derivative depends upon aileron location and spanwise and chordwise dimensions. The derivative M_p is independent of aileron parameters such as spanwise location and chord size.

With structural flexibility included, the lateral control design problem becomes more interesting. To maximize the value of pL/V (per unit aileron displacement, δ_o) at a fixed value of q, we can differentiate Eqn. 6 with respect to a structural parameter (denoted as x_i) and set the result equal to zero.

$$\frac{\partial(\frac{pL}{V})}{\partial x_i} = 0 = \frac{\frac{\partial M_{\alpha\delta}}{\partial x_i}\left(\frac{\partial\alpha}{\partial\delta}\right) + \frac{\partial M_{m\delta}}{\partial x_i} c_{m\delta}}{-M_p} + \frac{(M_{\alpha\delta}(\frac{\partial\alpha}{\partial\delta}) + M_{m\delta}c_{m\delta})}{M_p^2}\frac{\partial M_p}{\partial x_i} \tag{7}$$

Note that we have excluded any dependence of the aileron parameters $\frac{\partial \alpha}{\partial \delta}$ and $c_{m\delta}$ upon x_i.

Maximum roll effectiveness may be obtained by gathering like terms in Eqn. 7 to obtain the following:

$$\left[\frac{M_{\alpha\delta}}{M_p} - \frac{\partial M_{\alpha\delta}}{\partial x_i}\right] \frac{\partial \alpha}{\partial \delta} + \left[\frac{M_{m\delta}}{M_p} - \frac{\partial M_{m\delta}}{\partial x_i}\right] c_{m\delta} = 0 \quad (8)$$

or

$$D_1 \frac{\partial \alpha}{\partial \delta} + D_2 c_{m\delta} = 0 \quad (9)$$

The definition of terms in Eqn. 9 follows from Eqn. 8. In this case, a harmonious integrated design requires that

$$\frac{\partial \alpha}{\partial \delta} = \frac{c_{1\delta}}{c_{1\alpha}} = - \left[\frac{D_2}{D_1}\right] c_{m\delta} \quad (10)$$

Substitution into Eqn. 6 gives

$$\left(\frac{pL}{V}\right)_{OPTIMAL} = \frac{\left[-M_{\alpha\delta} + \frac{D_1}{D_2} M_{m\delta}\right] \frac{\partial \alpha}{\partial \delta} \delta_o}{M_p} \quad (11)$$

Unfortunately, the aileron terms $\partial\alpha/\partial\delta$ and $c_{m\delta}$ are not independent, but are functions of, at least, the aileron flap-to-chord ratio. Still, equations such as 10 and 11 are illustrative of desirable, if not attainable, relationships between two distinct, but interrelated disciplinary areas.

One recent example of this type of integrated design is presented in Reference 6. That reference describes a parameter study involving advanced composite material laminate tailoring and control surface position and characteristics to minimize control surface hinge moments with a prescribed roll effectiveness. Additionally Reference 7 discusses the effect of laminate tailoring upon roll effectiveness.

ISCD - Dynamic Applications

The discussion of integrated design of a structure and control system for a situation such as lateral control effectiveness is atypical because the choice of a performance index is relatively clear. On the other hand, the application of active control to aerospace design often has as its purpose the modification of some specific dynamic response characteristic. Applications include: increased damping of large orbiting space structures; augmented aircraft stability; gust load alleviation to reduce loads related to atmospheric turbulence; and, flutter suppression.

In most cases, an active control is added to enhance the structural design by reducing loads or performing a function that the structure is incapable of doing without modification, if at all. To accomplish this there is a cost. This cost may be measured in terms of weight of the additional actuators, power required, drag created or cost of installation. In some cases, the control laws must be carefully implemented to discourage unfavorable interaction between the controls and the dynamic response of the structure.

Let us first consider the case of a series/sequential design sequence during which an active control law has been formulated for an existing structural configuration. Let us also assume that the control is, in some sense, best or optimal for the existing set of structural parameters. It is of interest to ask whether or not a change in a design parameter (call it p instead of x_i to retain generality) will produce a situation in which the new optimal control is even "better" than before.

Consider Figure 2 which illustrates the multi-dimensional behavior of a cost function/performance index, J, that is a function of a control design variable u and the parameter p. Mathematically, J = J(u,p). At a fixed value of p, say p_o, the control optimization problem has a solution u_o^*, while at another value, $p = p_1$, the best control is $u = u_1^*$. Since the parameter p is held fixed during each control design, the optimal control costs $J^*(u_o,p_o)$ and $J^*(u_1,p_1)$ are not the same. In addition, the optimal control u^* is different in each case. Figure 2 indicates that gradients $\frac{\partial u^*}{\partial p}$ and $\partial J^*/\partial p$ exist to relate one curve to another.

In essence, ISCD seeks to determine the "best of the best" combination of structure and controls. An additional function measuring structural cost must also be considered, together with that shown in Figure 2. If the best optimal control occurs at a certain parameter value p, but a heavy structure results, the system is not optimal even though the control is. As mentioned before, a system performance index must be chosen to arbitrate such situations.

Literature related to ISCD has focused as much upon the definition of suitable optimization objective functions (performance indices or cost functions) as it has on the search for effective computational methods. The variety of proposed interdisciplinary objective functions and synthesis methods reflects the multi-disciplinary nature of the problem. Approaches to the problem generally can be grouped into the two categories described previously: (1) the control and structural designs are separate and largely independent; and, (2) the structural and control designs are simultaneous. Let us turn now to the dynamic design problem itself.

Equations of motion for a discretized, lumped parameter (finite element) model of a flexible structure with forced motion may be written in the following form:

$$M\ddot{x} + C\dot{x} + Kx = bu + F \quad (12)$$

M, C, and K are the mass, damping, and stiffness matrices, respectively, while x is a vector of system coordinates; b is a control input coefficient matrix, while u is the control input vector. F represents external loads which, for aeroelastic problems, include motion dependent forces that may be appended to M, C, and K. If only motion dependent loads are considered, Eqn. 12 may be written in state-space form,

$$\dot{X} = AX + Bu . \quad (13)$$

Here, $X = \begin{vmatrix} x \\ v \end{vmatrix}$, where $v = \dot{x}$. [A] contains system or plant dynamics (M, C, and K), actuator dynamics, and, in the case of aeroelastic systems, "aerodynamic states." A control is designed for an existing structure and the A matrix is fixed. With this introduction, let's turn to space-structures related work.

References 8, 9, 10 focus upon orbiting space structure-related ISCD. In each of these studies, optimal steady-state linear quadratic regulator (LQR) theory is used for design synthesis. References 8 and 9 use a series/sequential design approach. Reference 8 considers an actively controlled, cantilevered truss structure optimized to obtain a minimum mass design, given a constraint on fundamental natural frequency. Some manipulation of weighting matrices, Q and R, in the LQR cost function, J, defined as

$$J = \int_0^\infty (X^T Q X + u^T R u)dt \qquad (14)$$

is also performed. Reference 8 shows that increased active damping of structural response occurs at the expense of control effort. Also, the value of the cost function J for the controlled optimal (least weight) structure was modestly higher than that for the controlled baseline structure. This implies that the control cost function J is not a totally reliable <u>system</u> cost function.

Khot, et al., [9] also consider a tetrahedral truss as an example of a feed tower for a class of large space antenna applications. The truss's apex models the antenna feed. Apex displacement, or line of sight (LOS) error, is to be minimized. The structure is optimized by two procedures. In the first case, apex deflections resulting from given loading are minimized, subject to the constraint that structural mass is fixed. In the second case, structural mass is minimized subject to a frequency separation constraint. Another case is considered in which the result of the second optimization is scaled so that its weight is the same as the unoptimized structure. Optimal steady-state LQR control is synthesized for each of the four configurations, considering two different weighting matrices in the LQR cost function. The structure optimized for minimum deflections showed least LOS error with control, but, in one case, showed the highest value of the LQR cost function. The structure optimized for minimum weight showed the opposite trend. Significantly, the minimum weight design does not necessarily produce a superior closed-loop system, at least in terms of LOS error. Again, there is the implication that the optimal controlled structure is not the sum of two optimal systems.

Reference 10 comes closest to simultaneous design by applying an iterative design approach in which an optimal steady-state LQR control is synthesized for a given structure. Closed-loop damping ratios are then determined. Gradients of these ratios with respect to structural design variables are computed, holding the control design constant. These gradients are then used for an optimization step to minimize mass, subject to constraints, until mass is minimized. While the structural and control designs are not simultaneous, they are <u>partially</u> integrated. The design method was applied to the ACOSS-FOUR truss with two different constraints on damping ratios. Results show that, like Ref. 9, increased system damping is obtained at the expense of a higher LQR cost function, but LOS error is improved

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The second category of space-structure related ISCD studies considers the problem of truly simultaneous, cooperative selection of structural and control design variables. The work of Hale, et al., [11, 12, 13] is particularly noteworthy. These studies consider design of a spacecraft that must perform a maneuver between two specified initial and final configurations within a finite time span. Optimal structural and control parameters are found to minimize a cost functional, defined as:

$$J(u,p) = J_s(p) + \int_0^{t_f} 1/2\{x^T Q_0 x + \dot{x}^T Q_1 \dot{x} + u^T R u\}dt \qquad (15)$$

$J_s(p)$ is a non-negative function (e.g. mass) of structural parameters, p, only. The second part of J is the control cost function from LQR theory, Q_0, Q_1, and R being arbitrary weighting matrices. The integrated design objective function is a simple sum of the objective functions of the segregated designs, although the control cost function is also a function of structural design parameters. The problem is converted into an unconstrained optimization problem by appending a set of constraints to Eqn. 15, as follows:

$$J_a(u,p) = J_s(p) + \int_0^{t_f} 1/2\{x^T Q_o x + v^T Q_1 v + u^T Ru\}dt + \int_0^{t_f} \{\lambda^T S (v-\dot{x}) + \tilde{x}^T (M\dot{v} + Cv + Kx-bu)\}dt \quad (16)$$

S is a weighting matrix (usually the identity matrix), λ is vector of Lagrange multipliers, and $\tilde{x}$ is a vector of adjoint displacements. Having found the first variation of J_a, the coefficients of the variations δx, δv, $\delta \tilde{x}$, $\delta\lambda$, and δp_i (i = 1, 2, ... N; N = the number of structural design parameters) are set to zero to establish the necessary conditions for the optimum. Equations 15 and 16 are basic to the approach of Refs. 11-13 although various refinements are also presented.

Salama, et al., [14], write the objective function as

$$J_{opt} = \min_p [\rho_1 J_s(p)+\rho_2 \min_u \int_0^\infty 1/2(X^* QX+u^* Ru)dt] \quad (17)$$

where ρ_1 and ρ_2 are scalars. The effect of this approach is to constrain the active control to be an optimal steady-state LQR for any structural parameter set. The computation of gradients of J with respect to the parameters, p_i, requires differentiation of the optimal control necessary conditions, the steady-state matrix Riccati equation. Thus, the gradients provide changes in the control design while maintaining its optimality.

These formulations are significant since they clearly unify structural and control syntheses into a single problem objective. However, this unification approach has an interpretive difficulty: what does minimization of a sum of vehicle mass and an LQR cost function really accomplish? Indeed, LQR synthesis itself has a similar problem: what does minimization of a sum (integral) of weighted squares of displacements, rates, and control variables mean? The addition of a mass penalty term has been demonstrated to eliminate many relative extrema in the objective function, making a global minimum more pronounced [11]. Like LQR synthesis, such additive cost methods represent at least a convenient parameterization of the problem wherein designs can be iteratively considered and improved through variation of the weighting matrices.

Another interesting approach to ISCD for space structures is presented by Haftka, et al. [15], who use the magnitudes of a control variable as the objective function. For their problem, the damping matrix has only one non-zero, diagonal entry; this term is due to an actuator. The quantity to be minimized is called "control strength" and represents the actuator effort expended to control (in this case, damp out) a single degree-of-freedom of a beam structure suspended by cables in a laboratory. The objective of the design synthesis is to minimize, with respect to the structural design variables, the control effort required to satisfy constraints on minimum modal damping. This approach is formulated to use structural design for specific benefit to the control design.

Returning to earth, we now consider aeroservoelastic design. Zeiler and Weisshaar [16,17], provide an example of ISCD as applied to optimal aeroservoelastic systems. Their approach is based upon a technique known as multilevel linear decomposition [18-21]; their objective is to maximize the size of the flutter envelope. The aeroservoelastic system is subdivided into structural and control subsystems, as indicated conceptually in Figure 3. Their idealization is a three-degree-of-freedom airfoil with an active trailing edge control. The structural design parameter is the shear center position, while control design parameters include: a nondimensional design airspeed, at which the A matrix is computed; and, weighting matrices for the LQR control synthesis procedure.

Figure 4 shows a typical situation encountered for aeroservoelastic optimization. The horizontal parameter is shear center location, a_e, measured in semi-chords from the airfoil mid-chord. Negative values of a_e indicate that the shear center lies forward of the midchord. The variable $\overline{U}$ is a nondimensional airspeed. Both open-loop (control off) and closed-loop (control on) stability boundaries are shown in Figure 4.

Figure 4 was laboriously constructed by first choosing the design airspeed, $\overline{U}_{des}$, to be 6.0. Then, a value of shear center position, a_e, was chosen at which LQR control theory was used to compute a full-state, optimal control, feedback control law. This control law minimizes a control performance index J, given by Eqn. 14. As a result, as a_e changes, so too does the feedback control law. Three typical situations shown in Figure 4 are of interest and are shown as vertical lines through points 1, 2, and 3.

At point 1 the system is stable at $\overline{U}_{des}$ but subcritical instabilities appear. Given the design constraint that the system must be stable up to $\overline{U}_{des}$, this situation is clearly unsatisfactory. In addition, the closed-loop instability airspeed is not far removed from $\overline{U}_{des}$.

At point 2 the closed-loop instability airspeed is farther removed from $\overline{U}_{des}$, but subcritical instabilities, introduced by the optimal control at $\overline{U}_{des}$, remain. However, at point 3, not only is the closed-loop instability airspeed (flutter) large, but no subcritical instabilities appear. For this value of $\overline{U}_{des}$, point 3 represents a "best" combination of structural design and control design.

The value of $\overline{U}_{des}$ is arbitrary for the present control formulation. In fact, it is a control design variable. If $\overline{U}_{des}$ were chosen at 6.5 for instance, a new figure would replace those shown in Figure 4. The optimal combination of a_e and active control would be different, perhaps better, perhaps worse. In addition, the appearance of subcritical instability regions is sometimes due to the value of weighting matrices chosen for the LQR formulation. How to best choose $\overline{U}_{des}$, Q and R, and a_e to maximize the flutter free, closed-loop flight envelope is a laborious task if approached by a brute force method. However, Figure 4 indicates a potential worthwhile benefit for the effort.

Zeiler [16] has developed a procedure to use optimization theory to move the system parameters from an initial starting point, say point 1 in Figure 4, to the final point 3 without actually generating the entire group of costly curves shown in Figure 4. The essential parts of his procedure are:

1. choice of LQR theory to provide the control law

2. use of unsteady aerodynamic theory to represent motion dependent airloads

3. feedback of all system states (except aerodynamic states) at a design airspeed $\overline{U}_{des}$.

4. use of the multi-level, linear decomposition optimization procedure to decide upon system and subsystem design parameter changes while maintaining optimality of the control and structure.

5. use of control system optimal sensitivity derivatives to predict a new control law due to changes in $\overline{U}_{des}$, a_e, Q and R, but without actually recomputing the optimal control problem.

References 16,17 indicate that structural redesign can enhance the stabilizability (controllability of unstable modes) of the system by the control. It is also shown, as it was in Refs. 8, 9, 10, that the cost function for active control optimality is not necessarily a good indicator of system optimality, since global minima of the LQR cost function did not coincide with the best overall system design. Neither was the "best" open-loop structural design found to be "best" for the closed-loop design.

This latter approach to integrated structure/control is general in that different types of optimal design formulations may be used at various levels (system and subsystems). However, the method does require that the subsystems be optimal in some sense and that appropriate design parameter derivatives be available so that item (5) above can be accomplished efficiently. Efficient computation of these derivatives for structural and control optimization problems has been studied recently in Refs. 22-25 and is considered to be essential to ISCD efforts. It is to this subject that we now turn our attention.

Multidisciplinary Optimal Sensitivity Derivatives

As seen previously, the development and use of a parallel or simultaneous integrated multidisciplinary design methodology, along the lines of Ref. 18, benefits from the use of: (1) linear, hieararchal, problem decomposition; (2) formal or numerical optimization techniques; and, (3) design sensitivity methods. In the formulation of Ref. 18, the required sensitivity data must be in the form of the sensitivity of an optimum solution (including a disciplinary performance index, design variables, and active constraints) of an optimization problem for which some system design parameters (such as wing aspect ratio) are held fixed during the actual optimization. These "sensitivity of optimum solution" derivatives or optimal sensitivity derivatives are in contrast to the usual concept of sensitivity, particularly in automatic control theory usage, that is concerned with predicting the change in a narrow disciplinary performance objective due to parameter variations rather than the change in the actual design.

One approach to the calculation of the optimum sensitivity derivatives is the straightforward, laborious solution of an optimization problem for a number of different values of design parameters; finite difference derivative calculations then can be used. This approach is not only inefficient and expensive, but it is subject to numerical error. The alternative, due to Sobieski, Barthelemy and Riley [22], is to differentiate the necessary conditions of optimality from the optimization problem, with respect to the parameters held fixed during optimization (e.g. wing aspect ratio), and to evaluate the resulting expressions at an optimum solution. These derivative expressions then can be used to extrapolate to other optimum solutions with different values of the design parameters using first-order Taylor series expansions [23,24], but without actually resolving the problem. The optimal sensitivity derivative concept as applied to controls has been interpreted geometrically previously, as shown in Figure 2.

However, to date, the development of analytical expressions for optimal sensitivity derivatives has been limited primarily to numerical nonlinear programming problems. Applications of the methodology of Ref. 18 to structural optimization using optimal sensitivity derivatives in two and three level decomposed problems have been illustrated by Sobieski, James and Dovi [19] and Sobieski, James, and Riley [20]. An example of multidisciplinary applications of the methodology for the case of static structural design and increased aircraft range has been given by Sobieski, Barthelemy, and Giles [21] for the L-1011 aircraft.

The primary use of design parameter sensitivity (as opposed to optimal sensitivity) in optimal control law analysis has been the determination of the change in the optimal control cost due to changes in nominal parameter values. But, unlike the optimal sensitivity concept just described, parameter sensitivity information has not been used to select a new optimal solution for a new design parameter. Thus, such approaches do not lend themselves to true integrated design methodologies since there is no opportunity to select changes in the control law. An example of design parameter sensitivity is given by Hood and Montgomery [26] who use derivatives of the optimum cost function with respect to aircraft stability parameters to design an optimal gust load alleviation system.

Analytical expressions for optimal sensitivity derivatives for the steady-state, linear, quadratic cost, Gaussian (LQG) optimal control law problem have been developed recently by Gilbert [25]. These developments were essential to the ISCD control law design results for aeroservoelastic systems described previously in Refs. 16,17, although only the optimal regulator gain portion of the results were used.

Optimal sensitivity derivatives for the LQG optimal control law problem are developed by differentiating the necessary conditions for optimality for the problem with respect to fixed design parameters with nominal values. These expressions are then evaluated at the optimal control law solution to obtain the desired expressions. With the linear state-space system, we deal with matrix equations of the following type:

$$x = A(p)x + B(p)u + Dw \tag{18}$$

$$y = C(p)x \tag{19}$$

$$z = M(p)x + v \tag{20}$$

where w and v are zero-mean, Gaussian distributed, "white" noise processes with intensity matrices w and v respectively. The LQG problem consists of solving for the control u to cause the performance index

$$J = E\{y^TQ(p)y + u^TR(p)u\} \tag{21}$$

to be a minimum; E{ } denotes the expected value operator. The scalar design parameter p is assumed to have a fixed value during the solution of the problem.

The optimal control law solution to the LQG problem is given by the interconnection of the optimal steady-state linear, quadratic cost regulator (LQR) and the steady-state optimal Kalman filter solutions. The necessary conditions of optimality for these two optimization problems are given in terms of nonlinear matrix Riccati equations that in turn determine the optimal regulator and Kalman filter gain matrices.

Differentiation of the matrix Riccati equations (necessary conditions of optimality) with respect to p results in two linear Lyapunov equations with unique solutions. Solution of these latter equations leads to expressions for the sensitivities of the optimal regulator and Kalman filter gain matrices that, in turn, allow the sensitivity of the optimally controlled system and optimized performance index to be determined as well. This process must be repeated for each scâlar parameter of interest. The structure of the Lyapunov equations leads to some significant reductions in the required computational burden since the coefficient matrices of the Riccati sensitivities are identical for every parameter.

Once the sensitivity of the optimally controlled system to the design parameters is determined, the sensitivity of many common controlled system performance measures, such as time and frequency responses, covariance responses, and closed-loop eigenvalues and eigenvectors can be calculated using well-known expressions. Choosing structural design parameters, such as mass distribution, structural element areas and inertias, or natural vibration frequencies as the fixed design parameters and calculating LQG sensitivity of optimum derivatives with respect to those parameters contributes greatly to the efficiency of the integrated structure/control law design procedure.

Conclusion

This paper has explored the philosophy and methodology related to integrated structures and control design. From the representative literature reviewed it is apparent that the potential for the development of a reliable methodology for accomplishing this objective exists. Equally important, limited results of such application provide strong indications that, given the increasing importance of coupling introduced into new designs, simultaneous design of such coupled systems is necessary to produce adequate performance let alone optimal performance. Multi-level linear decomposition techniques have been found to offer a promising technique for organizing the computational efforts necessary to accomplish ISCD efforts. The companion development of optimal sensitivity derivatives to discern efficient changes in structural design and control design to produce an effective, harmonious system are at an advanced stage of development. Missing from the literature is the large-scale application of ISCD efforts directed to a real aerospace design. The real value of this literature survey and discussion can only be realized when such a successful rewarding effort occurs.

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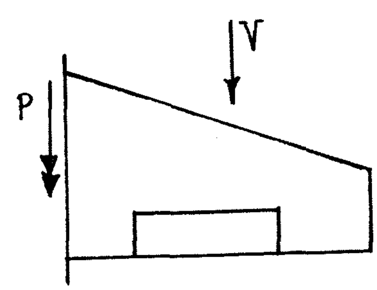

Figure 1 - Wing planform with control surface

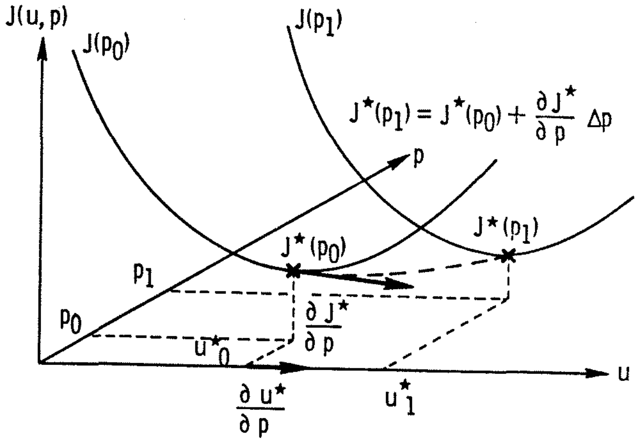

Figure 2 - Geometrical interpretation of optimal sensitivity

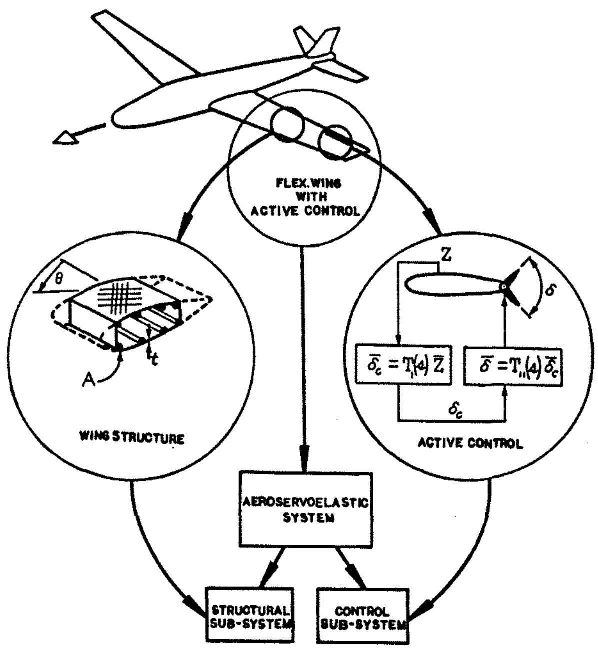

Figure 3 - Multi-disciplinary decomposition of a structural and control system

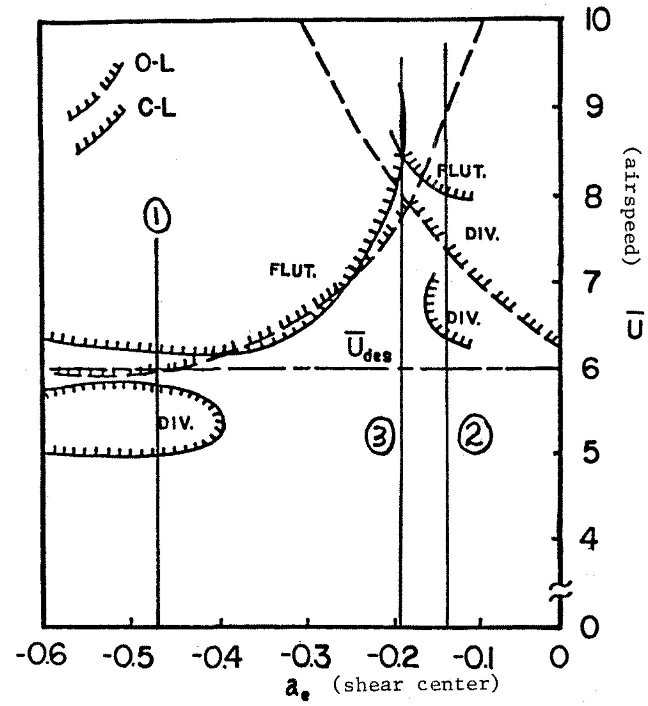

Figure 4 - Closed-loop stability boundaries for an optimal actively controlled airfoil