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Aeroelastic Tailoring of Composite Structures

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A wing-design optimization study is conducted on a composite wing. The objective is to evaluate the effect of the composite layup orientation on the optimized weight while satisfying constraints on strength, roll-reversal velocity, and flutter velocity. The wing optimization studies are presented with the composite layups oriented at 5-deg increments up to ± 20 deg from the midspar of the wing. The multidisciplinary optimization system, ASTROS, was used in the design study. This study, although not conclusive, indicates that optimal designs when subjected to multiple structural constraints are relatively insensitive to the orientation of the laminate layup.

I. Introduction

MULTIDISCIPLINARY design optimization (MDO) has been the subject of numerous investigations in recent years. This technology push is primarily attributed to the rapid growth in speed, data transfer, and storage capabilities of modern computers. It is anticipated that in a few years the speed of computation may surpass the Gflops/s range with similar improvements in memory devices. The computer's capabilities are doubling or tripling in a relatively short time, while the cost of computation and information processing is reducing by similar factors. These far-reaching developments in computers are the propelling force behind the rapid evolution of the so-called *information highway*. The information explosion is already affecting almost every facet of life in industrialized countries while pushing industrialization of the remaining countries. The world is a very competitive market place for products. It is expected to be even better for the consumer. Cost, quality, and innovation are the key ingredients for success in such an environment. A well-orchestrated MDO strategy is the best means for improvement in all three areas. It is often the mistakes made in early design that haunt the bad performance of the products. MDO systems on modern computers allow the rapid evaluation of the operation scenarios of the products.

The rapid strides in computers are the catalyst in promoting sophisticated computer architectures, database technology, and numerical methods. These developments, in turn, are providing the necessary infrastructure for integration of both disciplines and the design stages. For example, in airframe development, aerodynamics, structures, and controls are the main disciplines; whereas in design, manufacture, operation, and maintenance are the stages of development. Each of these stages is further divided into manageable tasks that are appropriate to available resources. For example, the design task is traditionally conducted in conceptual, preliminary, and detail design stages. If we couple this view of design with the task of integration of the disciplines (such as aerodynamics, structures, and controls), we have an almost intractable optimization problem, where the overall minimum cost is the primary driver. It is understood, however, that the product development time (from concept to market) is a significant cost factor and needs to be minimized as well. The promotion of smooth design interfaces and data transfers is the key to overall cost reduction.

Structural optimization is rapidly transitioning from an interesting topic of academic research to an effective interdisciplinary design tool to achieve the objective of improved performance, reduced design time, and minimized weight and/or cost. It is also emerging as an excellent communicator between disciplinary groups such as aerodynamics, structures, and controls. With success comes the demand for expanding the envelope of opportunities to bring in more complex performance constraints and variables that affect the configuration. For example, the current emphasis in preliminary design is optimization with sizing variables such as thickness of the plates, cross-sectional areas, moment of inertias of rods and beams, laminate thicknesses and directions of composite layers, and concentrated masses and their offsets (mass balancing). The next step is to bring in the structural concept variables such as the number and location of the spars, ribs, stiffeners, etc. These are all basically structural variables, and their effect on the final result is not expected to be significant over the sizing variables alone. However, there is strong speculation that configuration variables such as wing sweep, aspect ratio, surface area, taper ratio, arrangement of control surfaces, and hinge lines may produce significantly better designs when they are included in the preliminary design. Nevertheless, changes in a configuration can significantly alter the aerodynamic behavior and present numerous difficulties for optimization because the analytical derivatives are not easy to obtain from the aerodynamic computations. The finite difference derivatives on the other hand are too expensive in a preliminary design setting. The conceptual design can accommodate these variables much more effectively, because of fewer variables and constraints and a generally simplified analysis.

The object of this paper is to explore the benefits of defining ply orientation as a variable in the design of composite structures. The implication being that at any given point in the structure all of the fibers are oriented in the same direction, and the angle of this orientation and the total thickness of the fibers are the two variables. In contrast, the general practice in the design of composite structures is to assign a fixed layup consisting of a number of fiber directions (four or more), and the optimization selects the percentages of fibers in each direction. For example, in a layup consisting of 0-, 90-, and ±45-deg ply directions, the design can start with equal percentages (25%) for each direction, and the optimizer selects the actual percentages to minimize or maximize the objective function subject to the specified constraints. For example, in an extreme case of a high-aspect-ratio rectangular wing subject to bending only, the final layup will consist of 100% 0-deg fibers. This is on the assumption that the 0-deg fibers are specified in the spanwise direction. Similarly, if the

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wing is subjected to pure twist, only +45 and −45 deg fibers will be in the final design. However, this is true only when there are no minimum size limits. The variables in the optimization problem are the thicknesses of the plies in each direction and in each element. This is a well-accepted procedure, but, nevertheless, it is interesting to consider allowing the same layup (0, 90, and ±45 deg) to orient differently with reference to a fixed axis. The present study addresses this issue by optimizing a structure for static loads with constraints on strength, roll-reversal and flutter velocity, and varying the angle of the layup orientation with respect to a specified reference axis. Design studies in this paper were conducted with an existing optimization, program, ASTROS.[1,2] Optimization in ASTROS is based on modified feasible directions.

II. Review of Related Design Studies

In Ref. 3 the authors made a design optimization study on a composite wing. The object was to evaluate the effect of the composite laminate layup (ply orientation) on the optimized wing weight with strength and flutter behavior as constraints. This study, although not conclusive, indicated that the optimal designs are relatively insensitive to the laminate layup. This view is not necessarily shared by other investigators.[4]

Lerner and Markowitz[5] and Lerner[6] presented composite wing design studies with strength and static and dynamic aeroelastic constraints (control surface effectiveness, flexible surface lift-curve slope, divergence speed, etc.). The studies included both aft-swept and forward-swept wing models. A distinguishing feature of the studies is that they used finite element models of built-up wings with laminated composite skins. Most of the studies prior to this were based on beam or flat-plate structural models. However, their optimization was based on a sequential approach. The structure was resized first for strength using the fully stressed (FSD) concept and then resized for aeroelastic constraints. During the latter step the strength design was considered at minimum sizes. This procedure resulted in satisfactory designs, but, nevertheless, they were significantly heavier than the original FSD designs. Such a significant weight penalty may not be necessary if the structure is optimized with the simultaneous imposition of all the constraints. The current MDO technology (as in ASTROS and other systems) allows such an investigation. We hope to address this in the future.

Bohlman, Love et al.[7] made extensive strength and aeroelastic design studies on full and scale models of VAT (Validation of Aeroelastic Tailoring[8]) wings. Lockheed Martin's (then General Dynamics-Ft Worth) ELAPS program (a modified version of TSO) and ASTROS were used in this design study. An ELAPS structures model is a RITZ flat-plate representation, whereas the ASTROS models are FEM based. The earlier VAT studies included wind-tunnel test data with static, aeroelastic, and flutter models to demonstrate the benefits of aeroelastic tailoring. The value of these studies is in the comparison of the analytical and test results.

Yurkovich's recent study[9] using the ASTROS system indicated some interesting trends and benefits that are not obvious intuitively. For example, in this study the weight minimization of wings is relatively insensitive to the number of spars and ribs. If this is true, then wing panel buckling may not be a serious concern in design.

Numerous other design studies, using new software systems, are providing a wealth of information toward understanding the behavior of optimal designs. Some of these results defy our intuition and should be examined critically. They need validation in the laboratory and also in flight testing. The important benefit of these design studies is in providing information on the interaction and coupling of the variables, constraints and performance. This information is vital in making decisions on a return of investment in MDO systems.

III. Formulation of the Design Study

The constrained optimization problem is generally stated as follows:

Minimize or maximize:

$$F(\boldsymbol{X}) = F(x_1, x_2, \ldots x_n) \tag{1}$$

subject to the inequality constraints

$$g_i(\boldsymbol{X}) = g_i(x_1, x_2, \ldots, x_n) \leq \bar{g}_i, \qquad i = 1, 2, \ldots, k \tag{2}$$

equality constraints

$$g_i(\boldsymbol{X}) = g_i(x_1, x_2, \ldots, x_n) = \bar{g}_i \qquad i = k+1, \quad k+2, \ldots, k+p \tag{3}$$

and manufacturing constraints on the variables

$$\boldsymbol{X}^L \leq \boldsymbol{X} \leq \boldsymbol{X}^U \tag{4}$$

The physical parameters (thickness, etc.) are the variables. The normalized inequality constraints can be written as

$$G(\boldsymbol{X}) = g(\boldsymbol{X})/\bar{g}(\boldsymbol{X}) - 1 \leq 1.0 \tag{5}$$

or

$$G(\boldsymbol{X}) = g(\boldsymbol{X})/\bar{g}(\boldsymbol{X}) - 1 = 0 \tag{6}$$

In aircraft preliminary design the most common objective function is the weight. The constraints are generally on the stresses and displacements under static loads (a load being a combination of steady air loads and inertia forces resulting from various maneuvers of the aircraft). In addition there are constraints derived from static and dynamic aeroelasticity. In this paper stress constraints because of static loads, a flutter constraint, and an aileron effectiveness constraint are considered.

The basic equations of static structural analysis are represented as

$$\boldsymbol{P} = K\boldsymbol{u} \tag{7}$$

where $\boldsymbol{P}$ is a vector of applied maneuver loads that include both aerodynamic and inertia loads at the peak of the maneuver. The aeroelastic (flexibility effects) are included in the loads computations. The K on the right-hand side of Eq. (7) is the stiffness matrix of the structure, and $\boldsymbol{u}$ is the resulting displacement vector of the structure. The number of load vectors in $\boldsymbol{P}$ constitutes the number of maneuvers considered in the design. After solving for the displacements, the stress and strain values in all of the elements are computed. The stresses and strains are then compared to see if they exceeded the limits imposed.

The basic structural dynamics equation that governs the aeroelastic behavior of the structure is given by

$$M\boldsymbol{u} + C\dot{\boldsymbol{u}} + K\boldsymbol{u} = P(u, t) \tag{8}$$

The mass M, damping C, and stiffness K represent the structural properties. The right side of Eq. (8) represents the external forces (aerodynamic and other forces) on the system. As can be seen from the equation it is a nonconservative dynamic system because $\boldsymbol{P}$ is a time- and displacement-dependent system. In the static aeroelastic case, such as divergence, control surface effectiveness, etc., the system is treated as time independent, in which case the mass and damping terms are generally ignored. Then the static aeroelastic case can be written as

$$(K - A_S)\boldsymbol{u} = \boldsymbol{P\delta} \tag{9}$$

where K is the structural stiffness matrix, A_S is the aerodynamic influence coefficient matrix, and $\boldsymbol{\delta}$ is a vector of configuration parameters such as angle of attack and elevator angle. P is a unit aerodynamic loads matrix. See Ref. 1 for detailed definitions and solution of Eq. (9).

Now, aileron effectiveness is defined as

$$\varepsilon_{ff} = -\left(C^F_{l\delta} \big/ C^R_{lp}\right) \tag{10}$$

where $C^F_{l\delta}$ is the flexible rolling moment coefficient created by an aileron rotation δ, and C^R_{lp} is the flexible rolling moment coefficient created by a roll rate p. For further details see Ref. 1.

IV. Sensitivity Analysis

The sensitivity analysis represents the gradients of the objective and constraint functions. As examples of how the fiber orientation variable affects the sensitivity analysis, a brief discussion of weight as an objective function and stress, flutter velocity, and aileron reversal as constraints is included here. If the weight of the structure is the objective function, then the sum of the weights of the elements in the finite element model plus any nonstructural attachments constitutes the total weight. Usually the nonstructural attachments are independent of the structural variables, and they are not included in the objective function definition. The gradients of the objective function F with respect to the thickness variables would be greater than zero.

$$\frac{\partial F}{\partial x_i} > 0 \qquad \text{for thickness variables} \tag{11}$$

The basis for stress and displacement constraints are the equilibrium equations given in Eq. (7). The gradient of the stress constraint in the ith element can be written as

$$\frac{\partial G}{\partial x_i} = \frac{1}{\bar{g}_i}\frac{\partial g_i}{\partial u}\frac{\partial u}{\partial x_i} \tag{12}$$

if $\bar{g}_i$ is constant, otherwise the equation needs to be modified to account for the variation. Because the stress is a linear function of the displacements, the first term on the right of Eq. (12) does not contain any other derivatives, while the second term contains the derivative of the element stiffness matrix as follows:

$$\frac{\partial G}{\partial x_i} = \frac{1}{\bar{g}_i}\frac{\partial g_i}{\partial u}K^{-1}\frac{\partial k_i}{\partial x_i}u \tag{13}$$

The element stiffness matrix is a function of the thickness variable, and is generally a nonlinear function. Nevertheless, this derivative involves only the element in question for the thickness variable.

The equation governing the flutter condition can be written as

$$\{-\omega^2 M + K - (\rho V^2/2)[a(\omega b/V, m)]\}\boldsymbol{q} = 0 \tag{14}$$

where M and K are the mass and stiffness matrices. The circular frequency of vibration corresponding to the harmonic motion at the flutter condition is ω, and V is the freestream velocity or the flutter speed. The parameter b is the reference aerodynamic chord, m is the Mach number, and a represents the aerodynamic matrix that is a function of the reduced frequency k and the Mach number, and $\boldsymbol{q}$ is the vector of generalized coordinates. The reduced frequency k is defined as

$$k = \omega b/V \tag{15}$$

The flutter velocity and the frequency gradients with respect to the design variables can be written as[3]

$$V_{,i} = -(b\omega/k^2)K_{,i} - (b\omega^3/2k)\,\bar{\lambda}_{,i} \tag{16}$$

$$\lambda_{,i} = \frac{\left[p^t(K_{,i} - \lambda M_{,i})q - \lambda p^t A_{,k} q K_{,i}\right]}{p^t(M + A)q} \tag{17}$$

where $\lambda = \omega^2$, $\bar{\lambda} = 1/\omega^2$, p^t is the left-hand eigenvector corresponding to q, and A is $a[(\omega b/V), m]$ defined in Eq. (14). The key derivatives in the two equations are the element mass and the element stiffness matrices with respect to the design variables. The derivative of the aerodynamic matrix is with respect to the reduced frequency and not the variables in the design. The element mass matrix and stiffness matrix are functions of the thickness variable.

V. Optimization Algorithm

The basic modified feasible directions optimization algorithm, with some variation, is of the form

$$\boldsymbol{X}^{\upsilon+1} = \boldsymbol{X}^{\upsilon} + \tau^{\upsilon}\boldsymbol{D}^{\upsilon} \tag{18}$$

where $\boldsymbol{X}^{\upsilon+1}$ and $\boldsymbol{X}^{\upsilon}$ are the design variable vectors in two consecutive cycles of iteration. The procedure starts with an initial design vector $\boldsymbol{X}^0$, i.e., $\upsilon = 0$. υ is incremented, $\upsilon = \upsilon + 1$, and the objective function $F(\boldsymbol{X}^{\upsilon-1})$ and constraints $g_j(\boldsymbol{X}^{\upsilon-1})$ $j = 1, \ldots, k + p$ are evaluated. A set of critical or active constraints J is identified, and the gradients of the objective function $\nabla F(\boldsymbol{X}^{\upsilon-1})$, and the gradients of the constraints $\nabla g_j(\boldsymbol{X}^{\upsilon-1})$ for all j in J, are calculated. The active constraints are the most violated constraints and those within a prescribed tolerance of them. A search direction $\boldsymbol{D}^{\upsilon}$ is determined, and a one-dimensional search is made to find τ^{υ}. Equation (18) is then evaluated to determine $\boldsymbol{X}^{\upsilon+1}$. The preceding procedure is repeated with the new design vectors until the design satisfies the optimality conditions or some other termination criterion. The critical parts of the optimization algorithm consist of the following:

1) Find a feasible search direction $\boldsymbol{D}^{\upsilon}$.

2) Find the scalar parameter τ^{υ} that will minimize $F(\boldsymbol{X}^{\upsilon} + \tau^{\upsilon}\boldsymbol{D}^{\upsilon})$ subject to the constraints.

3) Test for convergence to the optimum and terminate the procedure when convergence is achieved.

VI. Design Studies

All of the design studies in this paper were made with the three-spar wing shown in Fig. 1. In all of these studies the basic composite layup consists of four fiber directions, 0, 90, ±45 deg. It is also assumed to be a balanced layup where the +45- and −45-deg fibers are equal. Ply orientation is not a variable in this study. Instead, the layup is fixed, the 0-deg fibers are at an angle with reference to the midspar of the wing. The percentage of fibers in the four directions is changed in the optimization. In the next design the angle of the 0-deg fibers is incremented by +5 deg. Similarly, the remaining design studies are with 5-deg increments both in the positive and negative directions from the midspar. The program ASTROS was used in this study.

Three categories of design studies are presented for Mach 0.8 and 1.2. The finite element model of the wing is shown in Fig. 2. In all cases the wing is subjected to three independent static loads. The first loading condition was generated from a subsonic forward center of pressure distribution for a Mach 0.9 flight condition, and the second loading condition was generated from a supersonic near-uniform pressure distribution for a Mach 2.0 flight condition. Both flight conditions were at 30,000-ft altitude and 2-deg angle of attack. The third loading condition was generated to give a twist to the wing. Details on the load distribution are given in Ref. 10. The material properties of graphite/epoxy for the wing skins and aluminum for the spars, ribs and posts are given in Table 1. For the present study an aileron was added to the aerodynamic planform. The 32.4-in.

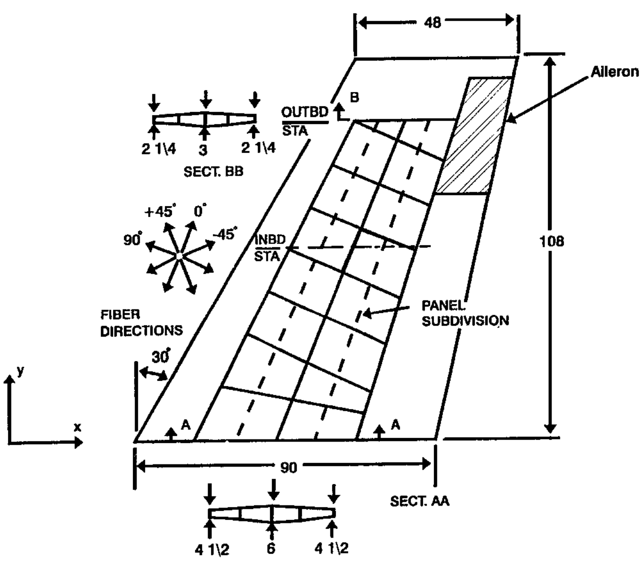

Fig. 1 Aerodynamic planform and structural arrangement of the wing.

aileron was attached to the structure at the 73.3% chord 10.8 in. from the tip of the wing (Fig. 1).

A. Category I Studies

In the first category the wing is optimized for static loads with stress and size constraints only. A total of nine optimum designs were made with ASTROS. In the first design the 0-deg fibers of the composite layup coincide with the midspar. The remaining optimum designs are generated with 5-deg increments of the 0-deg fibers from the midspar up to ±20 deg. The optimum structural weights are plotted against the layup orientation in Fig. 3. The data are summarized next. 0-deg ply orientation = 20, 15, 10, 5, 0, −5, −10, −15, and −20 deg. ASTROS = 37.373, 35.579, 34.562, 34.857, 35.861, 37.420, 40.623, 41.581, and 43.512 lb. As can be seen from Fig. 3, the optimum weight is not very sensitive to ply-layup variation.

These optimum wings were then analyzed at various dynamic pressures, and the aileron effectiveness was calculated from Eq. 10. Further, the reversal dynamic pressure at which the aileron is rendered completely ineffective for producing a rolling moment is determined. The reversal dynamic pressure is calculated from a zero condition of the aileron effectiveness. A plot of dynamic pressure vs aileron effectiveness for the 15-deg rotation angle for Mach numbers 0.8 and 1.2 is shown in Fig. 4. Table 2 summarizes the reversal pressure for the different layup orientations. From Table 2 the values of $q = 8$ for Mach 0.8 and $q = 6$ for Mach 1.2 were selected, and the corresponding values of aileron effectiveness were calculated. The results are tabulated in Table 3. Table 3 shows that the maximum value of aileron effectiveness for $q = 8$ Mach 0.8 occurs at −15 deg and for $q = 6$ Mach 1.2 at −10 deg.

Table 1 Material properties of the wing

Spars	Ribs	Posts
	Aluminum	
$E = 10.5 \times 10^6$ psi	$\sigma_t \leq 67$ ksi	$\rho = 0.10$ lb/in.^{3}
$\vartheta = 0.30$	$\sigma_c \leq 57$ ksi	$t_{\min} = 0.02$ in.
	$\tau_{xy} \leq 115$ ksi	
	Graphite/epoxy	
$E_1 = 18.5 \times 10^6$psi	$\vartheta_{12} = 0.25$	$\rho = 0.055$ lb/in.^{3}
$E_2 = 1.6 \times 10^6$psi	$G_{12} = 0.65 \times 10^6$ psi	$t_{\min} = 0.00525$in.
	$\lvert\sigma_x\rvert \leq 115$ ksi	
	$\lvert\sigma_y\rvert \leq 115$ ksi	

B. Category II Studies

The wing was then optimized with the static loads with stress and size constraints and an aileron effectiveness constraint. The aileron effectiveness constraint corresponding to the −15-deg rotation angle (0.1028) was imposed for all other rotation angles at Mach 0.8, and the aileron effectiveness constraint corresponding to the −10-deg rotation angle (0.0532) was imposed for all other rotation angles at Mach 1.2. The starting designs for each rotation angle were the

Table 2 Aileron reversal dynamic pressure for each rotation angle

	Aileron reversal dynamic pressures	
Rotation angle, deg	Mach 0.8, psi	Mach 1.2, psi
20	11.905	8.720
15	10.083	7.384
10	8.869	6.456
5	9.381	6.893
0	10.380	7.635
−5	11.923	8.862
−10	13.617	9.861
−15	13.681	9.838
−20	13.313	9.508

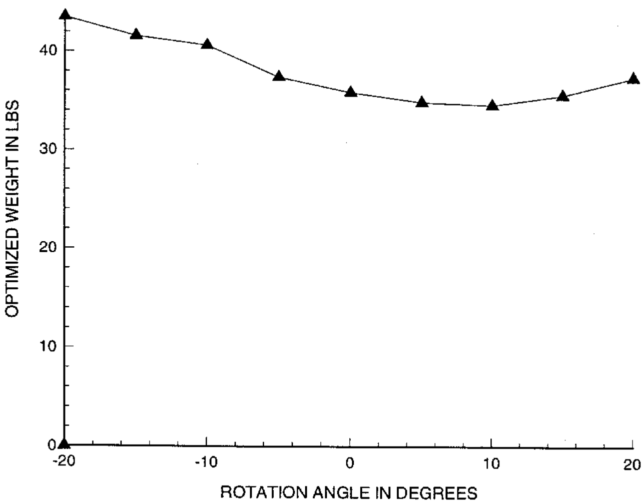

Fig. 3 Optimum weight vs the rotation angle.

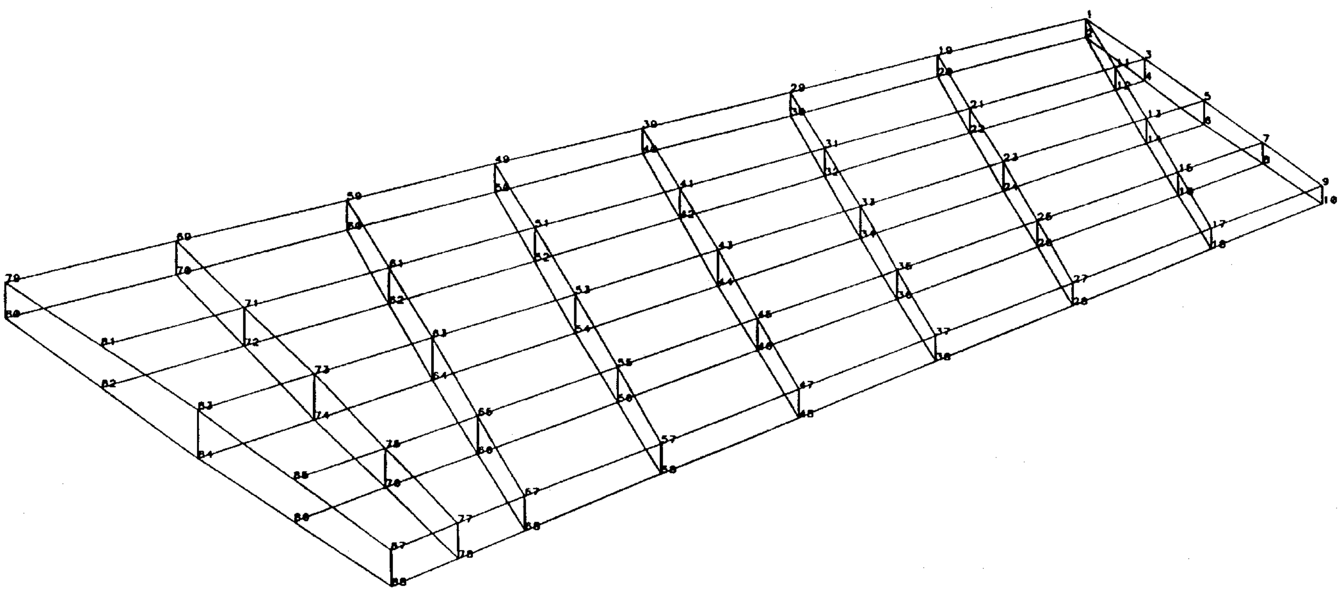

Fig. 2 Finite element model of the wing.

Table 3 Aileron effectiveness for $q = 8$ psi Mach 0.8 and $q = 6$ psi Mach 1.2

Rotation angle, deg	Aileron effectiveness Mach 0.8 $q = 8$ psi	Mach 1.2 $q = 6$ psi
20	0.0823	0.0410
15	0.0509	0.0228
10	0.0236	0.0078
5	0.0359	0.0157
0	0.0549	0.0261
−5	0.0807	0.0409
−10	0.1019	0.0532
−15	0.1028	0.0522
−20	0.1013	0.0504

Table 4 Optimum weights for each rotation angle

	Optimized weight		
	Stress, size, and aileron		
Rotation, deg	Mach 0.8, lb	Mach 1.2, lb	Stress and size,
20	37.883	37.625	37.373
15	37.646	37.306	35.579
10	37.391	37.031	34.562
5	37.206	36.867	34.857
0	36.880	36.715	35.861
−5	37.385	37.271	37.420
−10	38.736	38.744	40.623
−15	40.310	40.332	41.581
−20	42.361	42.386	43.512

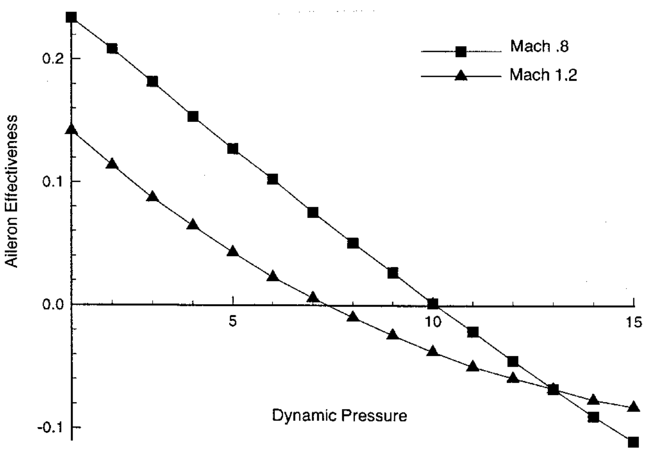

Fig. 4 Aileron effectiveness − 0-deg fibers oriented +15 deg from the midspar.

optimized sizes from the category I studies. The optimized weights for the various rotation angles with strength and aileron constraints are summarized in Table 4 along with the optimized designs with stress and size constraints only. These weights are plotted in Fig. 5 for Mach 0.8 and in Fig. 6 for Mach 1.2. In general, Table 4 implies that the added aileron effectiveness constraint does not significantly change the optimized weight over the range of rotation angles. For example, at rotation angle 10-deg Mach 0.8, the optimized weight is 37.391 lb, which is within 2.919 lb of the weight corresponding to the maximum aileron effectiveness in the category I studies, i.e., 40.310 lb. The results show that the 10- and −15-deg rotations have nearly the same optimum weight, aileron effectiveness, and size and stress constraints. Similar conclusions can be drawn for the other rotation angles. These results seem to imply that the optimum designs are relatively insensitive to the rotation of the 0-deg plies.

C. Category III Studies

For each rotation angle the optimized design from the category II studies was used to find the aileron reversal dynamic pressure. The results are summarized in Table 5 and plotted in Figs. 7 and 8. From Tables 2 and 3 the aileron reversal dynamic pressure for rotation

Table 5 Aileron reversal dynamic pressure for the optimized weights of category II

Rotation angle, deg	Aileron reversal dynamic pressure Mach 0.8, psi	Mach 1.2, psi
20	13.473	9.838
15	13.420	9.721
10	13.384	9.723
5	13.439	9.723
0	13.441	9.724
−5	13.524	9.862
−10	13.565	9.861
−15	13.681	9.838
−20	13.416	9.674

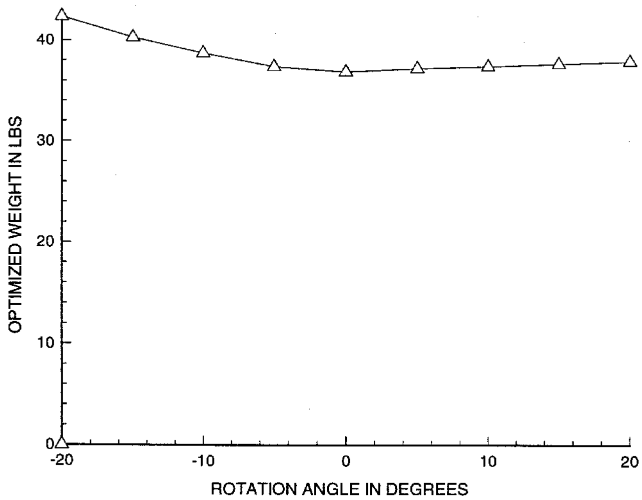

Fig. 5 Optimum weight at Mach 0.8, category II studies. Stress, size, and aileron effectiveness constraints.

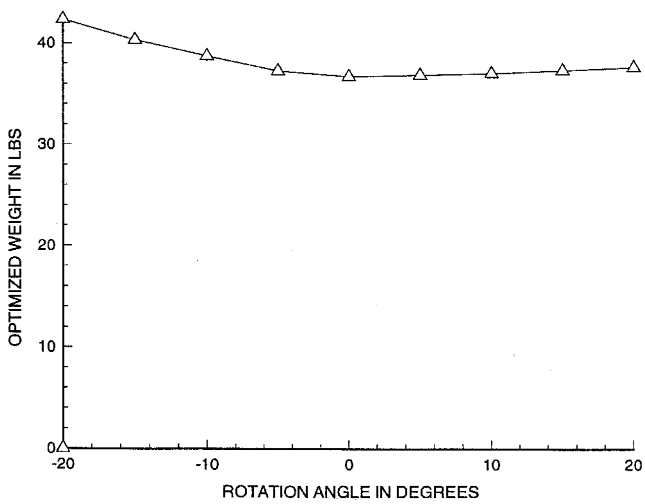

Fig. 6 Optimum weight at Mach 1.2, category II studies. Stress, size, and aileron effectiveness constraints.

angle −15-deg Mach 0.8, which gave the maximum aileron effectiveness (0.1028), was 13.617 psi. Table 5 not only shows a general increase in the aileron reversal dynamic pressures for all rotation angles, but also shows that these values are more in the neighborhood of 13.617 psi. The aileron reversal dynamic pressure for rotation angle −10-deg Mach 1.2, which gave the maximum aileron effectiveness (0.0532), was 9.861 psi. From Table 5 the aileron reversal dynamic pressures for all rotation angles have increased and are more in the neighborhood of 9.861 psi.

The wing was then optimized for angles −20 through 20 deg as in category II for Mach 0.8 with an additional flutter constraint imposed. The flutter constraint was derived by subjecting the optimum designs obtained in the category I studies to a flutter

Table 6 Optimum weights for each rotation angle, category III

	Optimized weight, lb, Mach 0.8	
Rotation angle, deg	Stress, size, aileron effectiveness, and flutter constraints	Stress, size, and aileron effectiveness constraints
20	38.383	37.883
15	38.346	37.646
10	38.040	37.391
5	38.103	37.206
0	36.901	36.880
−5	37.386	37.385
−10	38.736	38.736
−15	40.361	40.310
−20	42.770	42.361

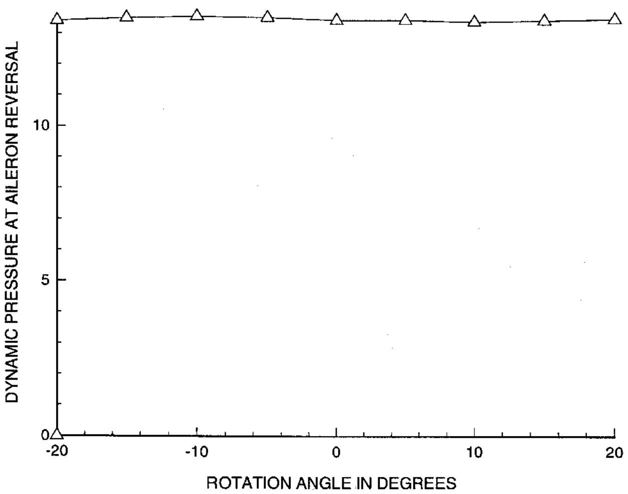

Fig. 7 Aileron reversal dynamicpressure Mach 0.8, category II. Stress, size, and aileron effectiveness constraints.

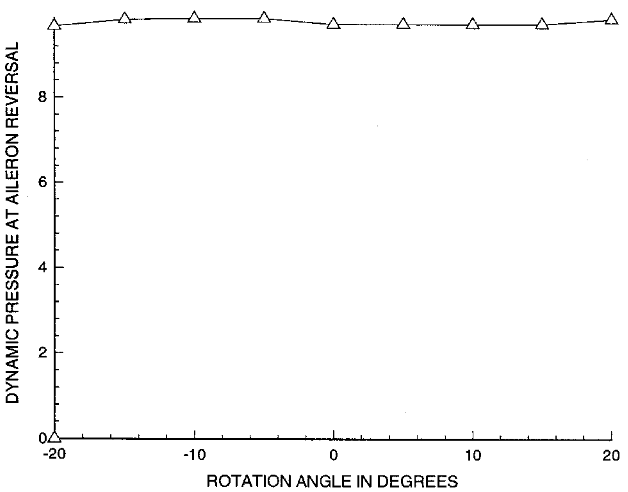

Fig. 8 Aileron reversal dynamicpressure Mach 1.2, category II. Stress, size, and aileron effectiveness constraints.

analysis using ASTROS. The results are summarized next. Rotation angle = 20, 15, 10, 5, 0, −5, −10, −15, and −20 deg. Flutter = 565.138, 498.226, 429.025, 444.645, 499.498, 600.714, 654.960, 625.793, and 613.685 kn. The flutter constraint chosen was 654.960 kn at rotation angle −10 deg. Thus, the wing was subject to stress, size, aileron effectiveness, and flutter constraints. The optimized weights for the two constraint sets are given in Table 6. The difference in optimum weight for each rotation angle is negligible, i.e., the additional flutter constraint did not impact the optimized weight. However, the thickness distributions varied somewhat. Figures 9 and 10 show the thickness distribution for the top and bottom skins of the designs in Table 6 for the +20-deg rotation

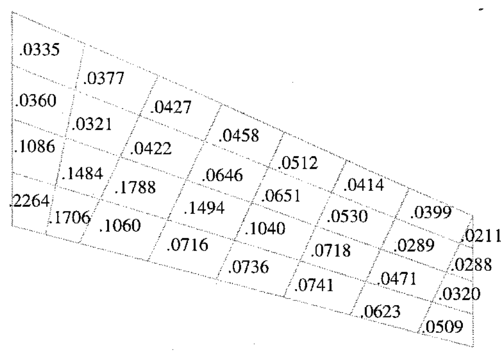

Fig. 9 Thickness distribution for the top and bottom skins +20-deg rotation angle. Stress, size, and aileron effectiveness constraints.

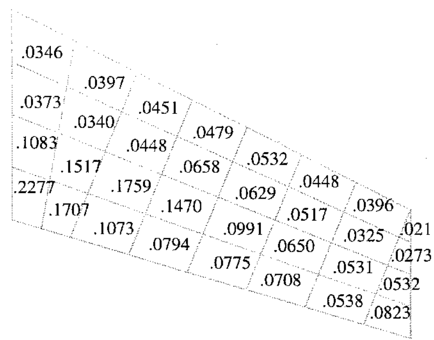

Fig. 10 Thickness distribution for the top and bottom skins +20-deg rotation angle. Stress, size, aileron effectiveness, and flutter constraints.

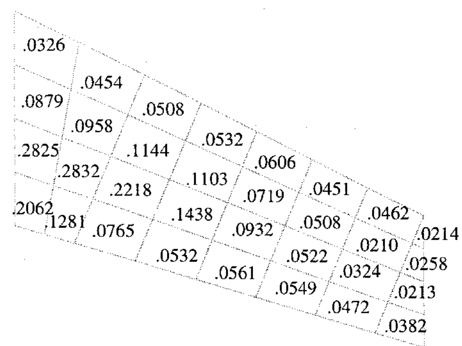

Fig. 11 Thickness distribution for the top and bottom skins −20-deg rotation angle. Stress, size, and aileron effectiveness constraints.

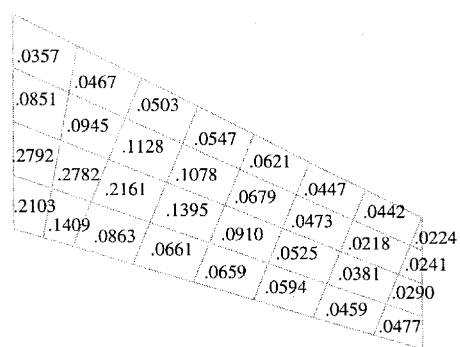

Fig. 12 Thickness distribution for the top and bottom skins −20-deg rotation angle. Stress, size, aileron effectiveness, and flutter constraints.

angle. Figures 11 and 12 show the thickness distribution for the −20-deg rotation angle.

VII. Conclusions

A wing design optimization study was conducted on a composite wing. The effects of the layup orientation of the composite skins on the optimized wing weight, when the wing is subjected to constraints on strength, aileron efficiency, and flutter characteristics, are presented. The wing optimization studies are presented with the composite layups oriented at 5-deg increments up to ±20 deg measured from the midspar of the wing. In the category I studies the wing was subjected to three independent loading conditions and stress constraints. The optimum weight of the wing was relatively insensitive to changes in the layup orientation. The aileron efficiency and the roll-reversal velocities were determined for different fiber orientations of the strength-optimized wing. These results showed a significant variation in the roll-reversal velocities. Nevertheless, the category II studies indicated that it is possible to obtain the maximum reversal velocity corresponding to a selected layup orientation with any layup orientation with the same static loads and constraints on stress and aileron efficiency. The optimal structural weights were relatively insensitive to layup orientation. The category III studies indicate a similar insensitivity to layup orientation of optimal structural wing weights when subjected to strength, aileron efficiency, and flutter constraints. In conclusion, this study indicates that optimal designs of composite wings are relatively insensitive to the orientation of the laminate layup when the wing is subjected to multiple structural constraints.

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