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Aeroelastic Tailoring Studies in Fighter Aircraft Design

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William E. Triplett*
McDonnell Aircraft Co., St. Louis, Mo.

Studies have been conducted on the use of the directional properties of composite material to provide design improvements for fighter aircraft. The TSO (Aeroelastic Tailoring and Structural Optimization) computer program, developed by the Air Force Flight Dynamics Laboratory, was used in these investigations. The configurations evaluated covered a wide spectrum of fighter aircraft aerodynamic surfaces, including the F-15 composite wing, a preliminary design horizontal tail, a prototype aircraft wing, and a future conceptual aircraft wing. Both drag reduction and increased roll effectiveness, with no weight cost, are predicted for the F-15 composite wing. A unique minimum weight design is shown for the preliminary design horizontal tail, in which the anisotropic characteristics of the composite material are used to perform the dual function of strength and flutter balance weight. A more conventional optimum flutter solution, based upon outer panel wing root pitch restraint increases, is shown for the prototype aircraft wing. Finally, significant wing twist, offering potential aerodynamic benefits, can be obtained on the conceptual aircraft wing.

Introduction

THE directional properties of composite material can be used to provide specified deformations for lifting surfaces under air load. Aeroelastic tailoring of these anisotropic characteristics is the design of these deformations under air load to improve the aircraft performance.

Several areas of improvement are possible. Tailoring can be used to obtain a lower weight design which satisfies all of the applicable design constraints such as strength, flutter, and divergence. It can also be used to obtain specified wing twist and camber so as to have beneficial effects on aerodynamic drag, control effectiveness, and air load distribution, leading to potential increases in payload or range. In the preliminary design stage, the design improvements can also lead to a reduction in the aircraft size.

The TSO (Aeroelastic Tailoring and Structural Optimization) computer program[1,2] provides aeroelastic tailoring information for lifting surfaces early in the aircraft design cycle. The procedure uses nonlinear programming techniques to determine optimum composite wing skin thickness distributions and ply orientations that satisfy flutter and strength constraints, based upon aeroelastic loads. It is an

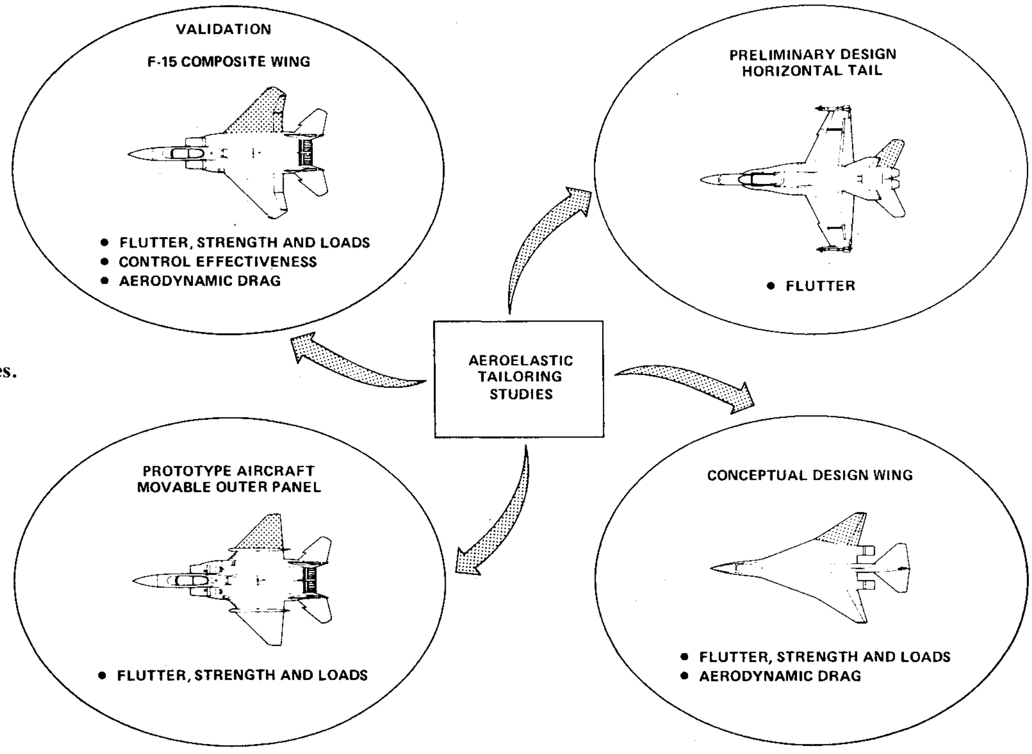

Fig. 1 Aeroelastic tailoring studies.

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*Sr. Staff Engineer, Structural Dynamics. Associate Fellow AIAA.

interdisciplinary program combining aerodynamic, static aeroelastic, structural, and flutter calculations.

The structural box stiffness and mass matrices in TSO are generated using a direct Rayleigh-Ritz energy formulation. Legendre polynomials are used to generate the static and dynamic mode shapes subject to a set of plate boundary conditions. The design variables consist of the composite ply orientation angles, the skin thickness polynominal coefficients, and mass ballast weights at arbitrary locations.

An interior penalty function is used for the optimization. Constraints are established for any quantity calculated during the design loop for which an upper or lower limit exists. The objective function includes a weighted combination of weight, twist, camber, roll effectiveness, and flutter velocity.

The program was validated by a comparison with an existing F-15 composite wing design. It was then applied to several diverse configurations as shown in Fig. 1.

F-15 Composite Wing

The F-15 composite wing, shown in Fig. 2, was chosen for the validation because of the availability of test data. Flight test, ground test, and wind tunnel data for the basic metal wing were applicable since the composite wing design was constrained to have the same distributed stiffness characteristics as the production metal wing.

The Woodward aerodynamic program,[3] which is one of the modules of TSO, was used to model the steady aeroelastic characteristics of the aircraft. A 20 section body cylinder with specified local radii was used to describe the fuselage. The inlet, a portion of the inner wing, and the tail boom fairing were modeled as an equivalent NACA 640XX airfoil. A wing-body interference region was established at the apex of the theoretical wing and extended to the end of the fuselage. The exposed wing with 64 boxes and the horizontal tail with 25 boxes completed the steady aerodynamic model. The aircraft was trimmed for 7.33 g at $M = 0.9$, sea level, using the Woodward data.

The doublet lattice aerodynamic program[4] was used to model the unsteady oscillatory aeroelastic characteristics. The exposed wing was modeled by the same 64 boxes used for the Woodward program. Aerodynamic influence coefficient matrices were calculated for 20 values of reduced frequency.

A number of structural approximations were necessary because of the restrictive modeling requirements of TSO. For example, TSO provides for only three separate layers of composite material, each with a specified fiber orientation. The thickness of each layer is described by polynomial equations which are second order in both span and chord. The upper and lower skins of a symmetrical single cell torque box are assumed to be identical. The torque box depth is described by another second-order polynomial in two dimensions.

The three layers for this pseudo-orthotropic validation case were a primary layer for bending along the elastic axis (EA, 0 deg) and layers for torsion at ±45 deg. Lumped masses were used to represent 1) the internal substructure of the wing, which is not modeled by TSO; and 2) the leading and trailing edge regions, which are outside the torque box.

In spite of these structural and inertial approximations, the predicted aeroelastic properties of the aircraft were surprisingly close to measured values. The trimmed angle of attack, horizontal tail deflection, and wing tip deflection at 7.33 g, $M = 0.9$, sea level, agreed within about 10% of measured values for the production metal wing. The vibration modes agreed well with the ground vibration test (GVT) measurements for the composite wing. The flutter characteristics were close to those calculated for the composite wing, based upon the GVT measured vibration modes.

The objective function for these first test cases was minimum weight, subject to required flutter (and divergence) speeds, without exceeding allowable strain constraints or minimum gage. For a run in which only material thickness was varied, the weight was 30 lb (2.3%) less per side than the baseline design.

Contour plots for the three separate layers and the total laminate of the optimized wing are shown in Fig. 3. Similar to the baseline wing design, the ±45 deg layers have a thickness distribution which is nearly constant over the entire torque box. The bending oriented fibers (0 deg) tend to be maximum near the forward part of the box near midspan, with progressively thinner regions in the directions of tip and root

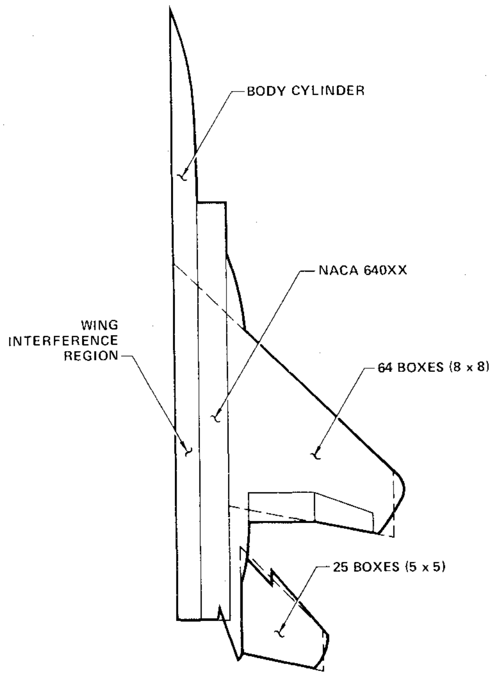

Fig. 2 F-15 composite wing, aerodynamic idealization.

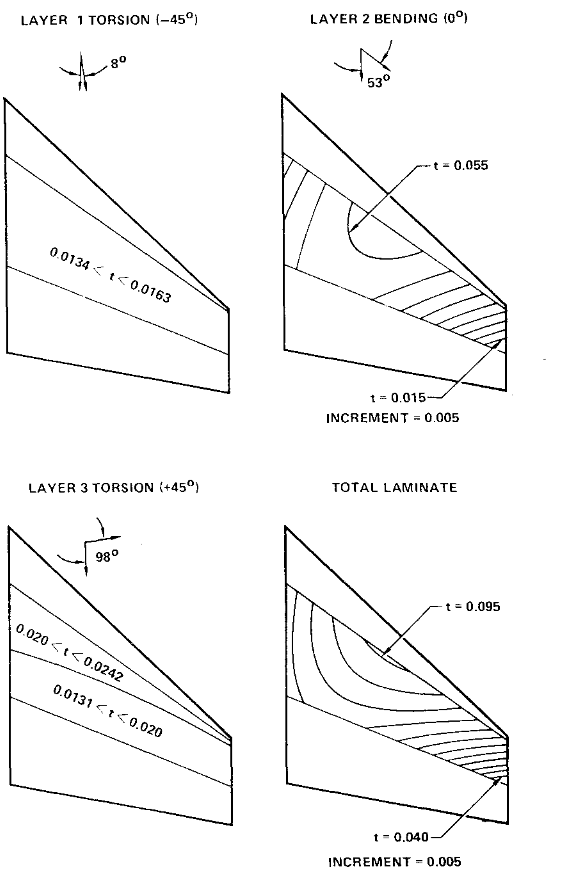

Fig. 3 F-15 composite wing, weight optimized composite laminate thickness distributions.

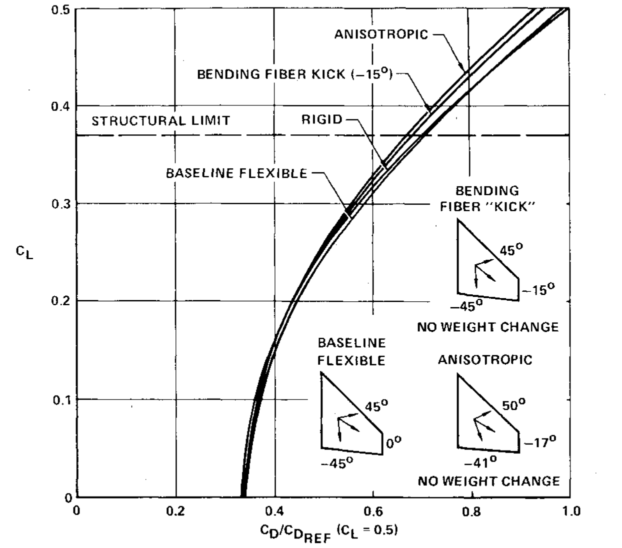

Fig. 4 F-15 composite wing, normalized drag polar, Mach 0.9, sea level, 7.33 *g*.

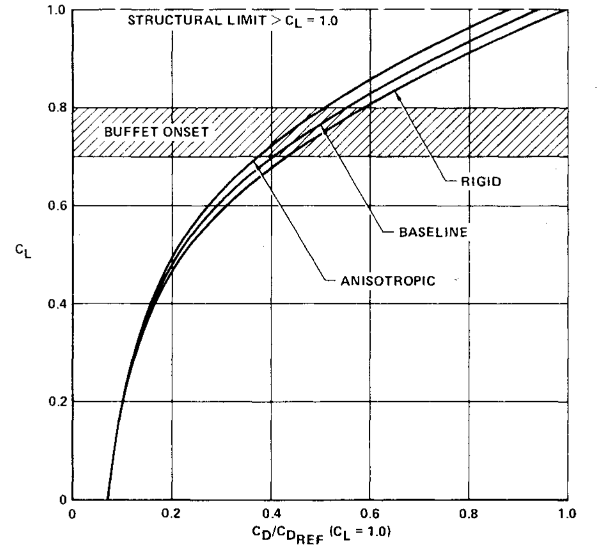

Fig. 5 F-15 composite wing, normalized drag polar, Mach 0.9, 30,000 ft, 7.33 *g*.

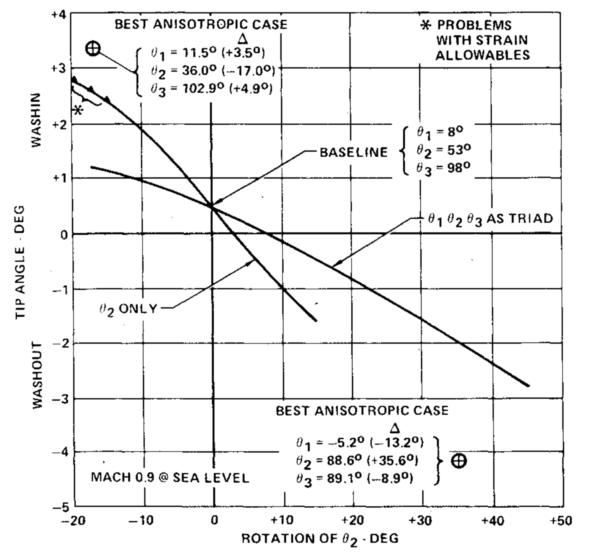

Fig. 6 F-15 composite wing, tip angle vs bending laminate rotation.

trailing edges. The bending fibers for the baseline wing are maximum near the aft part of the box at approximately 30% span, with thinner regions in the directions of tip and root leading edges.

Other runs used the same thickness design variables as before but included the orientation of the laminate layers as additional design variables. The optimized results give laminate orientations at −45, 0, and +23 deg with respect to the EA. The weight saving for this anisotropic case was 55 lb (4.3%) per side.

The analysis of the F-15 composite aircraft wing was continued in an effort to improve aerodynamic drag and control effectiveness, using the improved version of TSO.[2] The improved version expanded the scope of the program to include drag and control effectiveness. There were no changes in the basic mathematical model, so the original validation of the procedure for flutter, strength, and loads was still applicable.

The aircraft was trimmed for 7.33 *g* at the following design points: $M=0.9$ at sea level and 30,000 ft, and $M=1.2$ at 30,000 ft. Control effectiveness of the ailerons compared well with that obtained in wind tunnel tests for the production metal wing. The drag polars were matched to the F-15 data by two successive TSO runs. The first run established a preliminary drag polar for the rigid F-15 which was reasonably close to the measured data. Mathematical parameters describing the drag polar were then adjusted for the second run to give a good curve fit of the measured data.

Optimization runs were made for many combinations of design variables and objective functions. The most promising results were obtained when only the fiber orientations, with no thickness changes and thus no weight cost, were used to create wing twist under air load.

Drag reduction, compared to the baseline flexible design, at $M=0.9$, sea level is indicated in Fig. 4 for designs with a 15 deg aft "kick" of the primary bending fibers and a complete anisotropic layup. The drag reduction at the lift coefficient for the structural limit is 3.4% for the aft kick design and 4.6% for the anisotropic design.

The drag polars at $M=0.9$, 30,000 ft are shown in Fig. 5 for the baseline and optimized anisotropic designs. The drag reduction at lift coefficients in the region of buffet onset is on the order of 7-8% for the anisotropic design. At the $M=1.2$, 30,000 ft design point an insignificant change in drag was found.

The aileron roll effectiveness improvement with the anisotropic layup, compared to the baseline flexible, is calculated to be as follows: 100% at $M=0.9$, sea level; 20% at $M=0.9$, 30,000 ft; and 70% at $M=1.2$, 30,000 ft.

Washin is effective for both drag reduction and increased roll effectiveness of this configuration because of the negative camber which is built into the wing. Under airload the optimized wing will washin and thus create an effective airflow which is nearly in line with the wing. Washout, which would be effective for drag reduction of an uncambered wing, increases the drag on this composite wing configuration.

Figure 6 summarizes the wing twist which can be obtained by rotating the principal bending fibers only, and by rotating the three layers as a triad. Two anisotropic cases are also shown in the figure. The anisotropic case for maximum washin is similar to the designs for bending fiber rotation only. The anisotropic case for maximum washout, however, is essentially a two-fiber-direction layup that would probably have severe nonlinear load/deflection characteristics. Its use, in a practical sense, is questionable.

Preliminary Design Horizontal Tail

The TSO program, which is specifically designed for wing aeroelastic tailoring, may also be used for stabilator synthesis as described here. The configuration that was synthesized is indicated in Fig. 1.

The doublet lattice program was used to model the surface aerodynamics. The structural box was specified at 7.5-87.5% chord. Lumped masses represented the leading and trailing

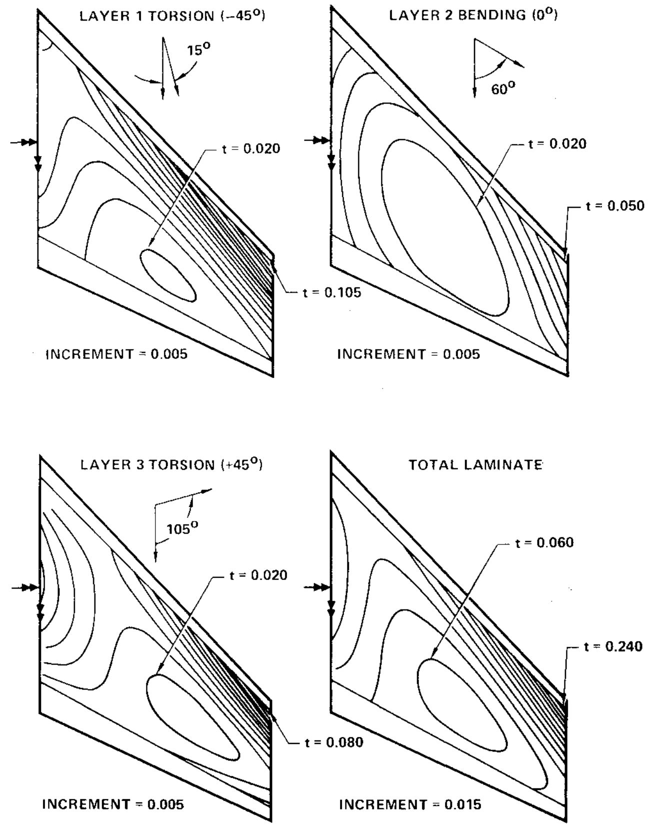

Fig. 7 Preliminary design stabilator, optimized composite laminate thickness distributions.

edges, the substructure, and a portion of the spindle. Only minimum weight was included in the objective function.

The total weight estimate for optimized thickness distributions where every coefficient of the thickness polynomials is allowed to vary is 28 lb (13.5%) lighter per side than the stringent weight goal established for this horizontal tail. Computer generated isometric plots are shown in Fig. 7 for the three separate layers and the total layup. The thickening of the leading edge tip region indicates that the composite laminate is performing the dual function of strength and flutter balance weight.

A significant number of additional runs were made in an attempt to improve on the design. Tip balance weights were initially placed in the outboard leading edge region to determine if they would be preferred to the buildup of the composite material. The TSO program systematically reduced the passive weights to zero and increased the composite material in the leading edge tip region as before.

An optimum load path case was tested in which the laminates were oriented as if the surface were not swept, aligning the principal bending load path of the outer panel with the spindle. TSO rejects this case because of a low flutter velocity, caused by the first bending frequency being too high.

A pseudo-orthotropic case was run in which the initial laminate layup of 15, 60, and 105 deg was allowed to rotate as a triad with the pseudo-orthotropic relationship maintained. TSO converges to a layup with the principal load path rotated about 10 deg forward of the elastic axis (i.e., 25, 70, 115 deg) and with additional material in the outboard leading edge region as before. The optimization was stopped, by the flutter constraint, at a weight which is 5 lb heavier than the design of Fig. 7.

Separate passive flutter studies, using the FACES computer program,[5] determined that tip balance weights alone are only about one-half as efficient in eliminating flutter as the composite laminate which performed the dual function of strength and balance weight.

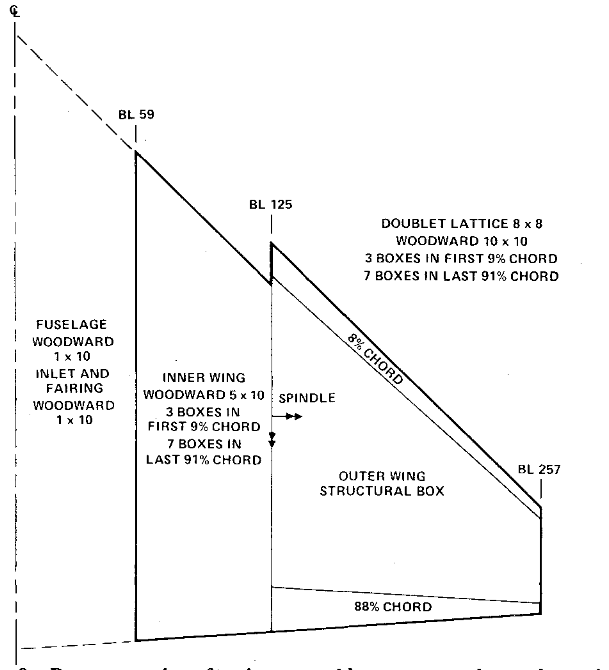

Fig. 8 Prototype aircraft wing movable outer panel aerodynamic and structural idealization.

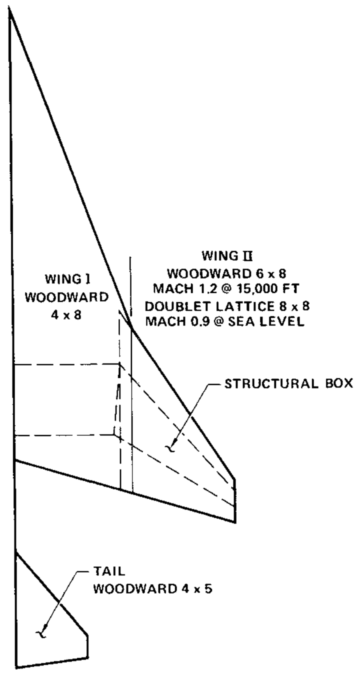

Fig. 9 Conceptual design aircraft, aerodynamic and structural idealization.

Prototype Aircraft Movable Outer Panel

This design prototype aircraft, described in Fig. 8, has an all-movable outer wing. It was chosen as a practical vehicle for further investigations into the payoffs of aeroelastic tailoring. The doublet lattice oscillatory aerodynamic model for the outer wing panel was based upon 64 boxes, as with the previously analyzed composite wing, on which the design is based. The most recent version of the TSO program,[2] which allows up to 200 total boxes, was used so that the Woodward steady aerodynamic model could be significantly more detailed. The 100 boxes on the outer wing were uniformly distributed spanwise, but were specified to give three boxes in the first 9% of the aerodynamic chord with the seven remaining boxes evenly distributed over the other 91% of the chord. This distribution was chosen to allow for a very accurate monitoring of the leading edge separated flow, which is an important factor in the determination of the break point on

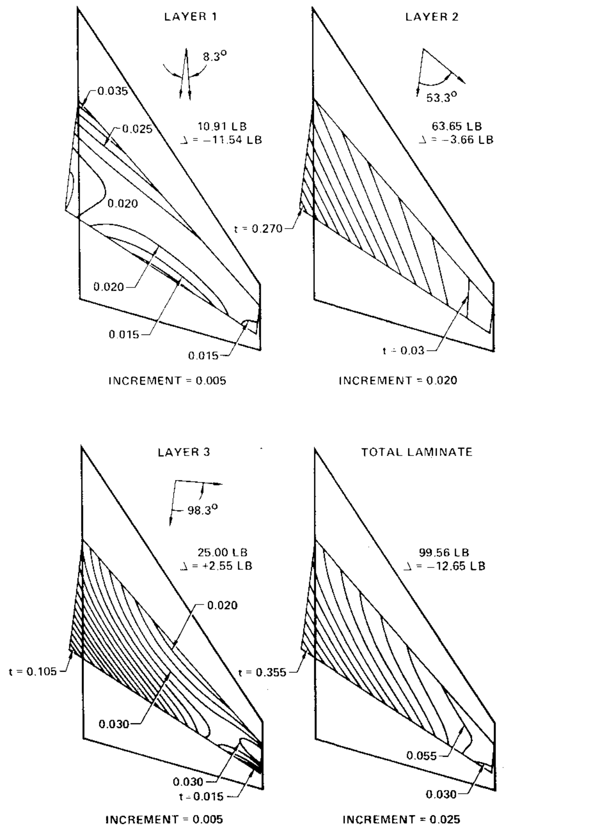

Fig. 10 Conceptual design aircraft wing, 8 g weight optimized composite laminate thickness distributions.

the drag polar. One hundred additional boxes were used to model the remainder of the aircraft. The aircraft was trimmed for 7.33 g at $M=0.9$, sea level for the loads and strength analysis.

The baseline stength design was flutter critical. The initial effort was thus directed toward satisfying the flutter constraint since the penalty function procedures of TSO will not work if the flutter constraint is violated.

In the search for the optimum flutter solution, systematic variations were made in mass ballast weights at 10 separate locations along the leading and trailing edges, composite fiber orientation angles both individually and as a triad, skin thickness distribution, and the outer wing root restraint matrix in both pitch and roll. Outer wing root pitch restraint increases were found to be the optimum means for achieving the required flutter velocity for the classical pitch-bending mechanism.

The optimum flutter free configuration was further studied to determine if drag could be reduced. It was reluctantly concluded, after several systematic searches with TSO, that improvements in drag by aeroelastic tailoring are minimal for this configuration. The relatively small size of the movable surface, combined with the flexibility of the single angle point spindle support, severely limit the drag improvements.

Conceptual Design Aircraft Wing

The TSO program was also applied to a modified double delta supersonic fighter configuration as indicated in Fig. 9. The aircraft was trimmed for 8 g at the design point of $M=1.2$, 15,000 ft, based upon the Woodward model shown in the figure. The doublet lattice aerodynamics were calculated at $M=0.9$ for use in the flutter analysis.

The relatively small structural box shown in Fig. 9 for wing II is only about 40% of the streamwise chord. The box changes direction near the root chord of wing II and continues in a normal direction with respect to the aircraft centerline. This inboard portion of the structural box was represented in TSO by four sets of root support springs at the root chord of wing II with pitch, roll, and translation springs at each support point.

The TSO structural and inertial model for the baseline 8 g design was based upon an optimized (uniformly stressed) finite element strength idealization. The TSO model agrees well with the original strength design in all respects.

Weight optimization runs were made for the baseline 8 g design using all 30 allowable design variables in various combinations. The most promising run reduced weight by 13 lb. This is 11% of the variable weight, which is rather impressive, but is only 3% of the total weight. The thickness distributions for the optimized case are shown in Fig. 10.

A separate series of TSO runs was made for a synthesized 4 g design. Trimmed aircraft data for both the 8 and 4 g designs are shown in Table 1. Partly because of the upload on the tail, the trim angle of attack for the 4 g design is less than one-half of the 8 g design value. The wing twist angle caused by the airload is thus slightly less than would be expected for completely equivalent designs. The important point made by these data is that the percent wing twist compared to the aircraft trim angle is greater for the 4 g case than for the 8 g case. This permits greater flexibility in tailoring for aerodynamic considerations.

Runs were made in an attempt to washout the wing. A twist of −4.6 deg was obtained for a weight increase of only 11 lb (2.5%). The flutter velocity was adversely affected, but at 965 knots was still able to satisfy the flutter requirement. The wing root support reactions were reduced somewhat by this washout run.

Thus, in this design, it is possible to induce moderate twist to create wing washout, with the implication of reduced drag, provided that the accompanying weight increase and flutter speed reduction are acceptable.

These runs were made with the original TSO program[1] which did not have procedures for the evaluation of drag. At the time it was believed that increased washout would lead to drag reductions, with decreased roll effectiveness. The studies previously discussed with the F-15 composite wing point out that this assumption is not necessarily true for a wing with significant built-in camber or twist.

A separate investigation was conducted on the baseline 8 g design to determine if layups with a high Poisson ratio can be used to change wing camber. The composite material layup had 90% of the fibers balanced at ±28 deg and 10% at 90 deg. TSO runs with this layup failed to show any significant improvement in wing camber because of the small chord structural box.

The results presented for this conceptual supersonic fighter wing are favorable, but not earth shattering. There are several reasons for the limited impact. The baseline design is an optimized (uniformly stressed) finite element and loads model which is already an excellent design. Also, the structural torque box is only a small percentage of the outer wing and

Table 1 Trimmed aircraft data

g	Tail trim angle, δ_{TRIM}, deg	Aircraft trim angle, α_{TRIM}, deg	Wing elastic twist angle, α_{TWIST}, deg	Wing tip total angle, α_{TIP}, deg
8	−2.9	6.8	−1.8	5.0
4	1.1	1.9	−1.1	0.8

the outer wing, in turn, is only a small percentage of the total theoretical wing, so that TSO has very little structure with which to work. An alternate procedure, which is able to model the entire double delta, should show more favorable results.

Conclusion

Aeroelastic tailoring can play a significant role in the design of aircraft as illustrated by the results summarized below:

1) F-15 composite wing (existing hardware)

Objective function: Weight.

Results: Pseudo-orthotropic with independent thickness, $\Delta W = -30$ lb/side (2.3%). Anisotropic with independent thickness, $\Delta W = -55$ lb/side (4.3%).

Objective function: Wing twist (washin).

Results: Anisotropic layup with no thickness change; drag reduction by neutralizing the effects of built-in camber; 4.6% improvement for small C_L at $M=0.9$, sea level; 7-8% improvement for large C_L at $M=0.9$, 30,000 ft; and improvement in roll effectiveness at all design points.

2) Preliminary design horizontal tail (a synthesized design)

Objective function: Weight.

Results: Pseudo-orthotropic with independent thickness; leading edge tip material buildup performs dual function; 28 lb (13.5%) lighter than design goal.

3) Prototype aircraft movable outer panel (an existing design)

Objective function: Flutter velocity.

Results: Optimum flutter solution by increased pitch restraint.

4) Conceptual aircraft wing

(An existing design, 8 g)

Objective function: Weight.

Results: Rotated pseudo-orthotropic with independent thickness, $\Delta W = -13$ lb/side (3%).

Objective function: Reduced camber.

Results: High Poisson layup with independent thickness; insignificant improvement because of small chord structural box.

(A synthesized design, 4 g)

Objective function: Wing twist (washout).

Results: Rotated pseudo-orthotropic with independent thickness, $\alpha_{TIP} = -4.6$ deg with $\Delta W = +11$ lb/side (2.5%).

As currently configured, TSO is appropriate for use primarily in the preliminary design cycle. The experience gained in the validation of the F-15 composite wing design, however, indicates that skillful use of the procedure can also yield good results in final design.

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