N87-11721

FLUTTER OPTIMIZATION

IN

FIGHTER AIRCRAFT DESIGN

William E. Triplett
McDonnell Aircraft Company
St. Louis, MO

OPTIMIZATION APPLICATIONS

The efficient design of aircraft structure involves a series of compromises among various engineering disciplines. These compromises are necessary to ensure the best overall design. To effectively reconcile the various technical constraints requires a number of design iterations, with the accompanying long elapsed time. Automated procedures can reduce the elapsed time, improve productivity and hold the promise of optimum designs which may be missed by batch processing.

This presentation includes several examples of optimization applications including aeroelastic constraints. Particular attention is given to the success or failure of each example and the lessons learned. The specific applications are shown in Figure 1. The final two applications were made recently.

Program	Design Phase	Configuration
COPS	Conceptual	F-15 Stabilator[1-2]
TSO	Preliminary	Various Configurations[3-4-5]
FASTOP	Preliminary	NASTRAN Beam-Rod Wing[6-7]
NASTRAN "Sensitivity"	Detail	NASTRAN Beam-Rod Stabilator

Figure 1

COPS ANALYTICAL MODEL

Figure 2 illustrates the modeling of the stabilator in the Computerized Optimization Procedure for Stabilators (COPS); Reference 1 describes the procedure. The analytical model is a single-cell torque box idealized by eight discrete rigid chord streamwise sections with three mass points per section. Quasi-steady aerodynamic forces act at user specified locations in each section. Nondimensional geometrical design parameters may be specified for taper ratio, thickness ratios at root and tip chords, aspect ratio, leading edge sweep angle, tip cut-off angle, pitch axis hinge line angle, pitch axis intersection with the mean aerodynamic chord (MAC), and spar locations.

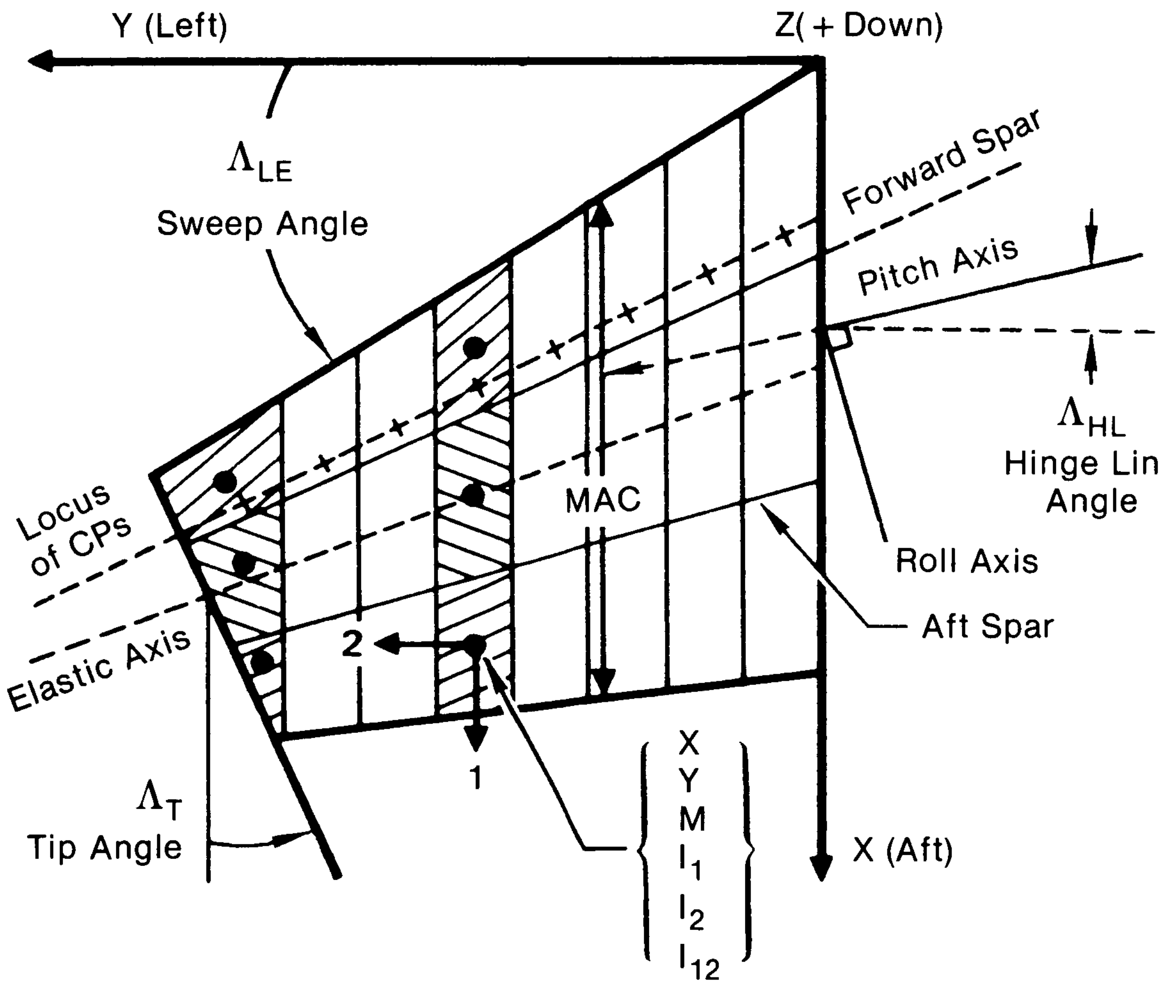


Figure 2

COPS CONCEPTUAL FLOW DIAGRAM

A greatly simplified flow diagram is shown in Figure 3. The procedure synthesizes, from the input data, a stabilator which satisfies all system constraints except those for flutter and divergence. A systematic perturbation of design variables for 1) torsional stiffness, 2) balance weight, 3) pitch restraint and 4) roll restraint follows until the aeroelastic constraint is satisfied for minimum additional weight. The procedure may be used in its basic sequential optimization scheme, where a new dynamic system is established after each iteration step. It may alternately be used in its simultaneous optimization mode, where each design variable is individually and exclusively evaluated from the same initial design point. The basic COPS program contains a realistic representation for every significant aspect of a believable stabilator flutter analysis and is fast enough, on the computer, to be used as an integral part of more encompassing aircraft systems optimization programs, as shown in the figure.

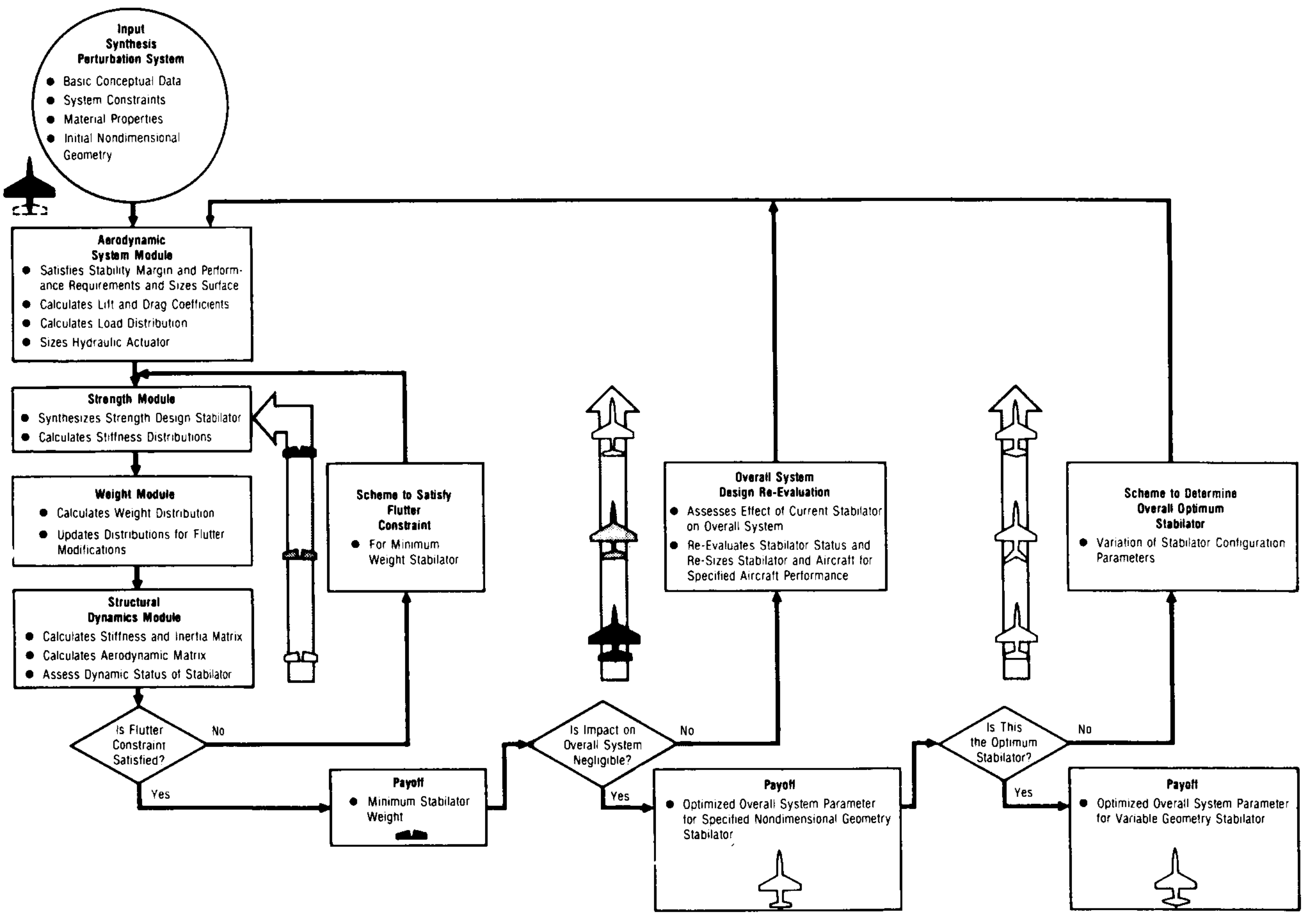


Figure 3

COPS EXAMPLE - EARLY CONCEPTUAL DESIGN FOR F-15 STABILATOR

Using the semi-automatic "simultaneous" procedure, the COPS program was used to calculate the ratios of the change of flutter dynamic pressure to weight change ($\Delta Q/\Delta W$) for separate perturbations of stiffness at each of the elastic axis stations, as shown in Figure 4a. Flutter was calculated for specified levels of $\Delta Q/\Delta W$ and compared, in Figure 4b, with optimization runs based on a torsional stiffness distribution proportional to the fourth power of the local chord and separately by balance weights at the tip leading edge. The balance weight of approximately 15 lb is the minimum weight solution. Figure 4c shows the stiffness distributions for both the C^4 and sensitivity approaches.

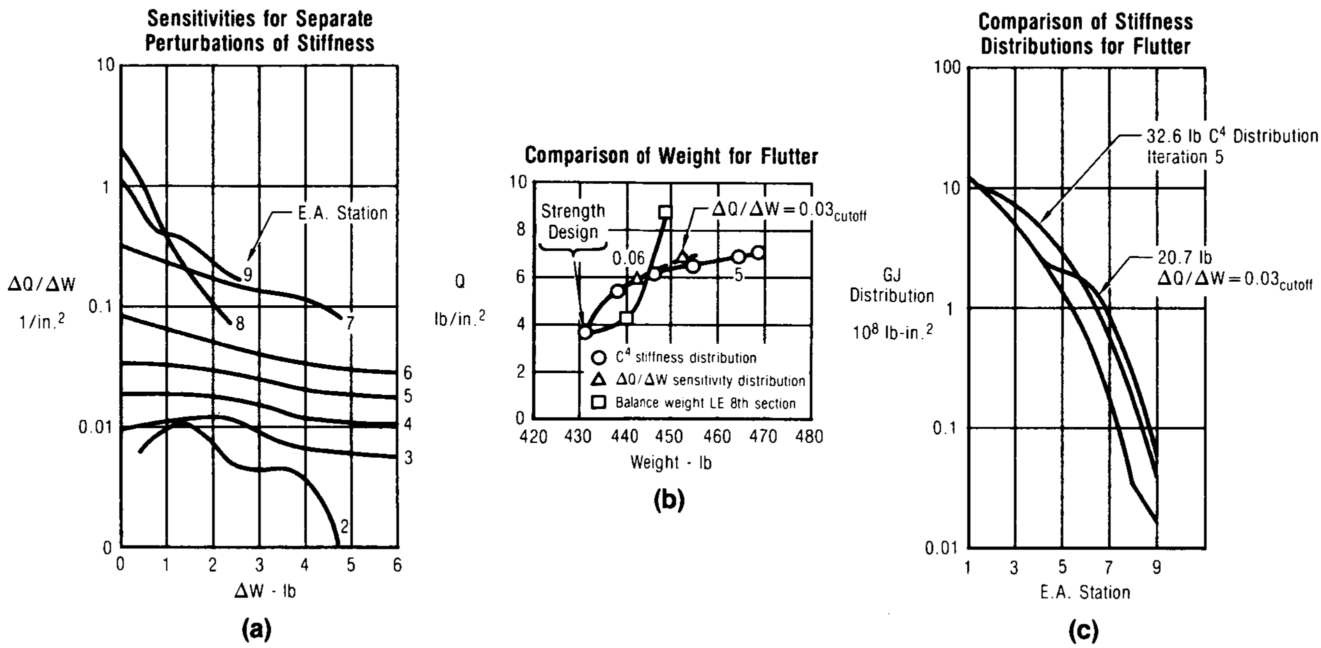
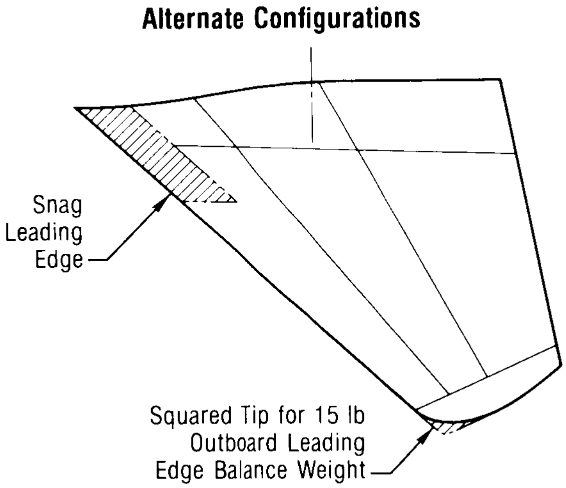


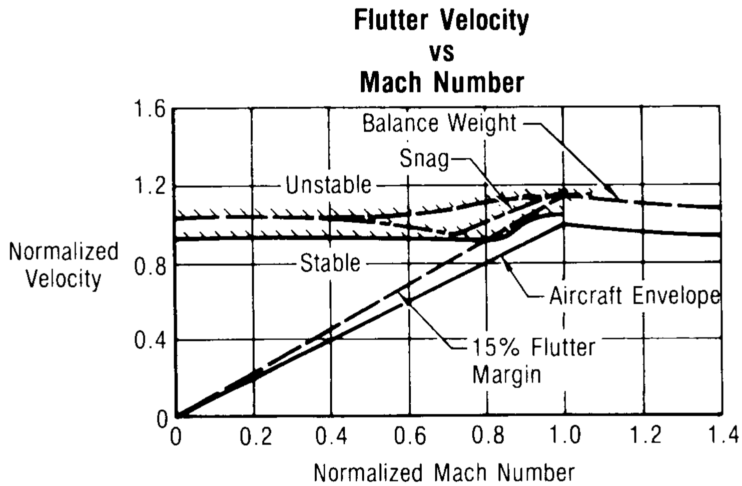
Figure 4

DETAIL DESIGN OF OPTIMUM F-15 STABILATOR

Two separate configurations were considered for the final F-15 detail design, as shown in Figure 5a and discussed in Reference 2. The flutter model test results are summarized in Figure 5b. The 15-lb balance weight produces an overall increase in flutter speed with Mach number. The snag leading edge produces an overall increase in flutter speed, similar to that for the balance weight, at low speeds. However, the speed variation with Mach number is quite different, with the snag showing an initial sharper drop with increasing Mach number followed by a subsequent sharper rise with further Mach number increase. Analyses indicated the favorable sharper rise to be associated primarily with the aft shift in stabilator aerodynamic center attributable to the area removed by the snag. The snag offered a significant weight savings over the balance weight with no effect on subsonic drag, aircraft stability or flying qualities. A small supersonic drag penalty was offset by the attendant weight reduction.



(a)



(b)

Figure 5

AEROELASTIC TAILORING STUDY CONFIGURATIONS

Studies have been conducted on the use of the directional properties of composite material to provide design improvements for fighter aircraft as discussed in Reference 3. The TSO (Aeroelastic Tailoring and Structural Optimization) computer program, Reference 4, which was developed by the Air Force Flight Dynamics Laboratory (AFFDL), was used in these investigations. The configurations evaluated, shown in Figure 6, covered a wide spectrum of fighter aircraft aerodynamic surfaces, including 1) the F-15 composite wing, 2) a preliminary design horizontal tail, 3) a prototype aircraft movable outer panel, and 4) a conceptual wing for a future aircraft. The TSO program was validated with the F-15 composite wing which was designed to have the same distributed stiffness characteristics as the production metal wing. In spite of the structural approximations required by the TSO program, the predicted aeroelastic properties were surprisingly close to measured values.

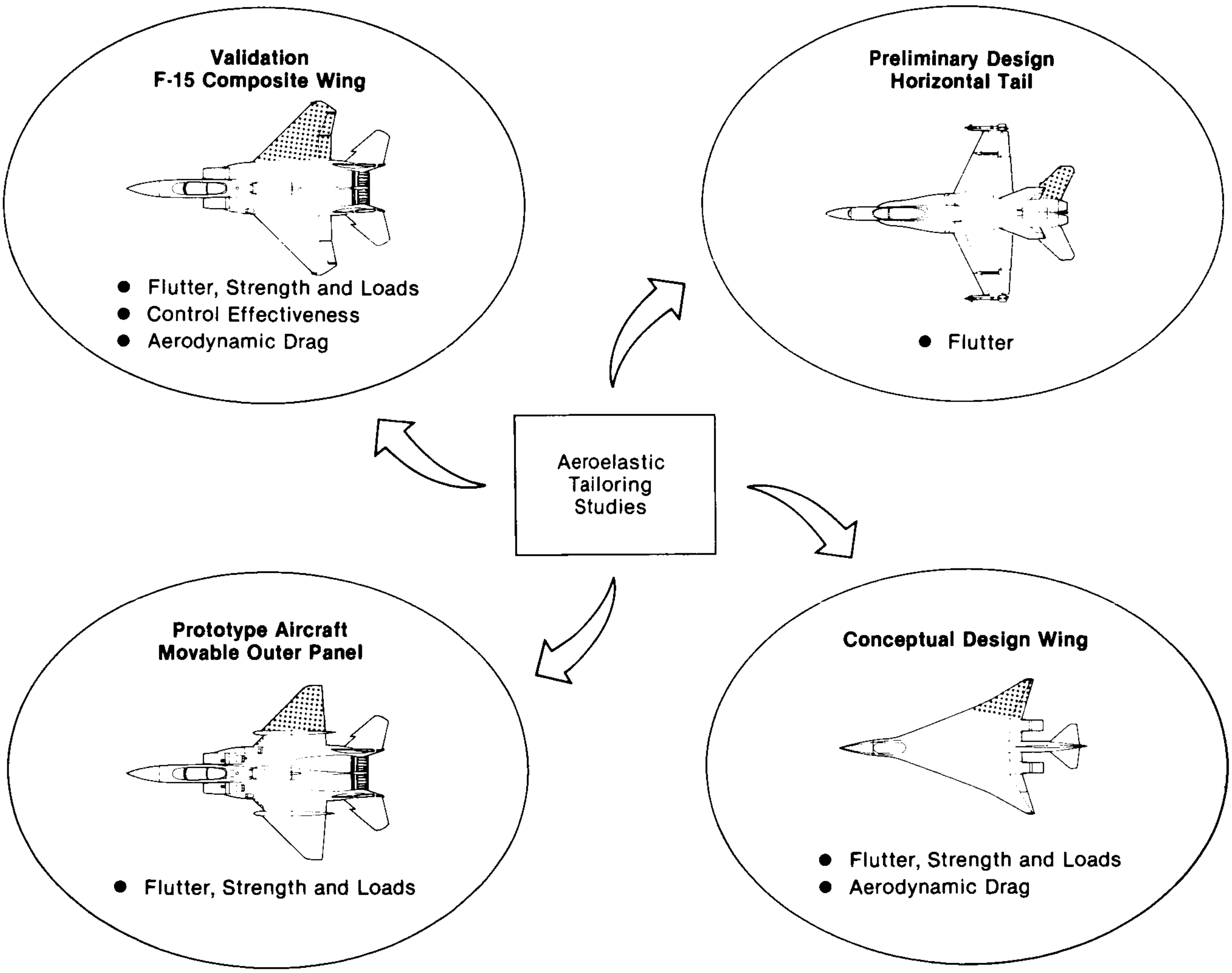


Figure 6

AEROELASTIC TAILORING RESULTS

Aeroelastic tailoring can play a significant role in the design of aircraft in various ways, as indicated in Figure 7. Specific detail is given for each configuration in References 3 and 5.

As currently configured, the TSO computer program is appropriate for use primarily in preliminary design. The restrictive structural modeling requirements of TSO lead to converged results which are generally qualitative and which must be liberally interpreted when converting to a design that can be built. The experience gained in the validation studies of the F-15 composite wing design, however, indicates that skillful use of the procedure can also yield good results in final detail design.

F-15 Composite Wing

- Drag Reduction and Increased Roll Effectiveness With No Weight Cost

Preliminary Design Horizontal Tail

- Composite Material Performs Dual Function of Strength and Flutter Balance Weight

Prototype Aircraft Movable Outer Panel

- Optimum Solution Based on Wing Root Pitch Restraint Increases

Conceptual Design Wing

- Significant Wing Twist Offering Potential Aerodynamic Benefits

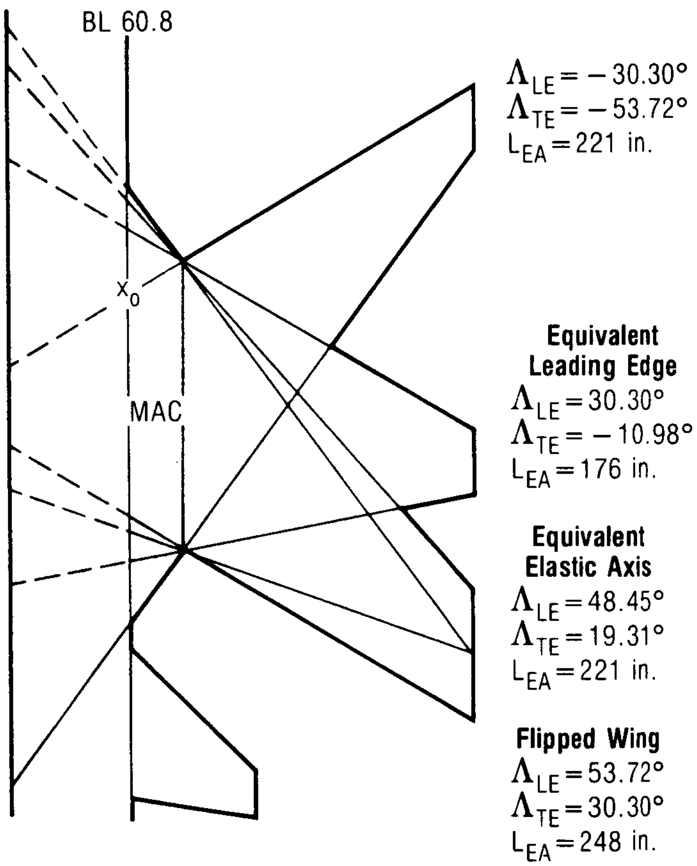
Forward Swept Wing

- Zero Weight Cost for Divergence

Figure 7

EQUIVALENT AFT SWEPT WING MODELS

The optimized forward swept wing (FSW) was compared with three equivalent aft swept wings (ASW), shown in Figure 8, and evaluated for the same design constraints, as discussed in Reference 5. They are 1) an Equivalent Leading Edge sweep, where the ASW leading edge sweep angle is the negative of the FSW leading edge sweep angle, 2) an Equivalent Elastic Axis sweep, and 3) a Flipped Wing. The wing geometry applies to all four wings. The wings were shifted longitudinally to give the same locations for the mean aerodynamic chords (MAC). The same aerodynamic and structural models were used for all four wings. One of the apparent effects of the equivalent leading edge design is a structural bending axis that is about 20% shorter than the axis of the FSW. The bending axis for the flipped wing design, on the other hand, is about 12% longer.



Wing Geometry NACA 64A0XX	
Theo Area	382.92 ft^2
Aspect Ratio	3.80
Taper Ratio	0.15
Span/2	228.9 in.
C_R (Theo)	209.5 in.
C_T	31.4 in.
Mean Aero Chord $\bar{c}$	142.5 in.
$\bar{Y}_{MAC}$	86.3 in.
t/c (Root)	0.052
t/c (Tip)	0.050

Figure 8

COMPARISON OF FORWARD SWEPT WING WITH THREE EQUIVALENT AFT SWEPT WINGS

Each of the ASWs was optimized by TSO and the results are shown in Figure 9. The FSW has the highest torque box skin weight and the Equivalent LE ASW, which is essentially a straight wing such as on the F-18, has the lowest weight. This weight advantage of the nearly straight wing is a direct result of the reduced structural axis length, which can be seen by comparing the bending moment normal to the elastic axis at the fuselage moldline. The air loading is also most favorable for the design of the fuselage carry-through structure on the FSW and the straight wing, as shown by considering both pitch and roll moments at the wing root. The ASWs are divergence free but have an active flutter constraint. The FSW has favorable flutter properties, primarily because the frequency of the wing bending mode changes very little with increasing airspeed. Coupling with the torsion mode still occurs, but at a higher velocity than for the ASWs.

	FSW Optimum	**ASW Equivalent Leading Edge**	**ASW Equivalent Elastic Axis**	**ASW Flipped Wing**
Composite Layer Orientation - deg (θ_1, θ_2, θ_3 With Respect to Bending Axis)	−80.9, +11.1, +14.5	−45, 0, +45	−45, 0, +45	−45, 0, +45
Torque Box Skin Weight - lb	227.5	118.9	162.1	158.9
Wash-in Angle at Tip - deg (Elastic)	5.1	−0.2	−5.1	−7.6
Total Panel II Load	59,159	64,973	62,240	59,604
Roll Moment at Panel II Root About BL 60.8 - in.-lb $\times 10^6$	4.03	4.51	4.10	3.78
Pitch Moment at Panel II Root About X_0 - in.-lb $\times 10^6$	−1.65	3.56	5.63	6.08
Bending Moment Normal to Elastic Axis at Moldline - in.-lb $\times 10^6$	6.32	4.27	4.47	4.54
Divergence Velocity - kt (Required Velocity = 912)	936	NA	NA	NA
Flutter Velocity - kt	1,050	810	820	760
Aileron Roll Effectiveness = Total RM / Rigid RM	1.13	0.43	0.35	0.29
Flexible / Rigid Panel II Lift Ratio	1.19	1.01	0.85	0.80

Mach 0.9, Sea Level, 7.33 g

Figure 9

FASTOP APPLICATION TO NASTRAN BEAM-ROD DYNAMIC MODEL

The FASTOP (Flutter and Strength Optimization Program) computer program (Reference 6) which was developed by the AFFDL, has been applied to a beam-rod vibration and flutter idealization of a wing/store flutter model. The chosen configuration for this detail design application was a wind tunnel model with two stores on an outboard pylon and wing tip missile on,as described in Reference 7. The NASTRAN model is shown in Figure 10. The NASTRAN beam elements are based on GJ and EI stiffness distributions, referred to an elastic axis, with similar distributions for the leading and trailing edge control surfaces and the missile. There are rigid bars to connect the various components with the proper boundary conditions. Concentrated-elasticity members are used to represent integral springs, e.g. actuators, wing fold, missile/launcher/wing interfaces and wing/fuselage attachment. Structural optimization is not feasible because FASTOP does not calculate stresses in the beam elements. Steady air loads are not required because the starting point is an existing strength design. It was felt that the chances for success would be excellent for this simple straightforward model which has only 147 structural members.

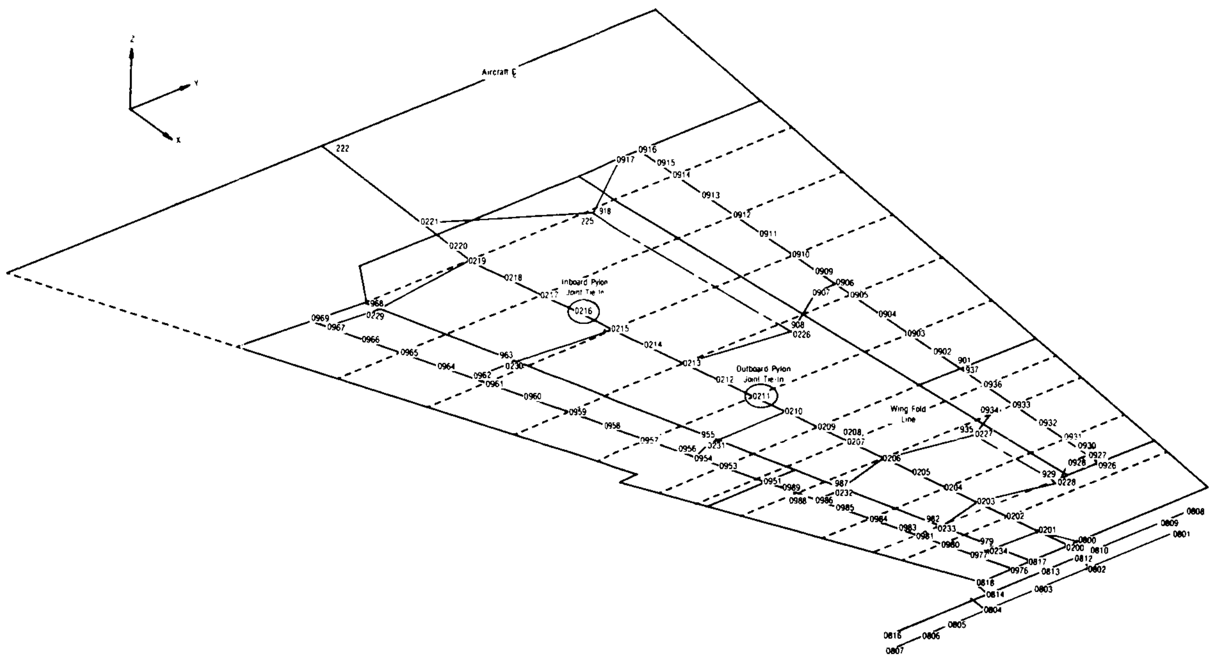


Figure 10

FASTOP ANALYTICAL CONSIDERATIONS

Many approximations and computational difficulties were encountered in converting the NASTRAN model to FASTOP, as indicated in Figure 11.

Strength Analysis

- Concentrated Elasticity Converted to Pseudo Rigid Beams
- Rigid Bars Converted to Pseudo Rigid Beams
- Grid Points Renumbered to Satisfy Bandwidth Requirement
- Trailing Edge Control Surface Actuator Beams Placed in Plane of the Wing
- Pylon and Stores Eliminated From Analysis

Vibration Analysis

- Diagonal Inertia Matrix to Satisfy Positive Definite Check
- Vibration Calculated for Only 20 Normal Modes
- Frequency Comparison Better Than Expected Considering Structural Compromises

Unsteady Aerodynamics

- Three-Dimensional Missile Model Converted to Flat Plate to Satisfy Interpolation Procedure

Flutter Analysis

- Non-Optimum Weight Factors Defined for Each Beam Element
- Resizing Permitted Only for Main Torque Box and Control Surfaces

Figure 11

FASTOP FLUTTER OPTIMIZATION RESULTS

The results shown in Figure 12 look promising until one examines the redesign changes in the individual elements. The first 3 design cycles add increments of weight to the structural elements in proportion to their flutter velocity derivatives, $\partial V_f/\partial W_i$, provided the derivatives are larger than an arbitrary minimum. This arbitrary minimum, which is not specified by the user, leads to an uneven spanwise distribution with peaks and valleys. It suffers from the lack of a built-in French Curve, which would smooth out the peaks and valleys to create a near-optimum design that could be built. The design cycles 4-10 continue the optimization by adjusting the weight distribution, while maintaining the desired flutter velocity. This weight adjustment reduces the increments along the wing torque box and builds up a large mass at the leading edge of the wing. The final design has only a large mass at the leading edge, near mid span, much like a forward mounted engine on a transport aircraft wing.

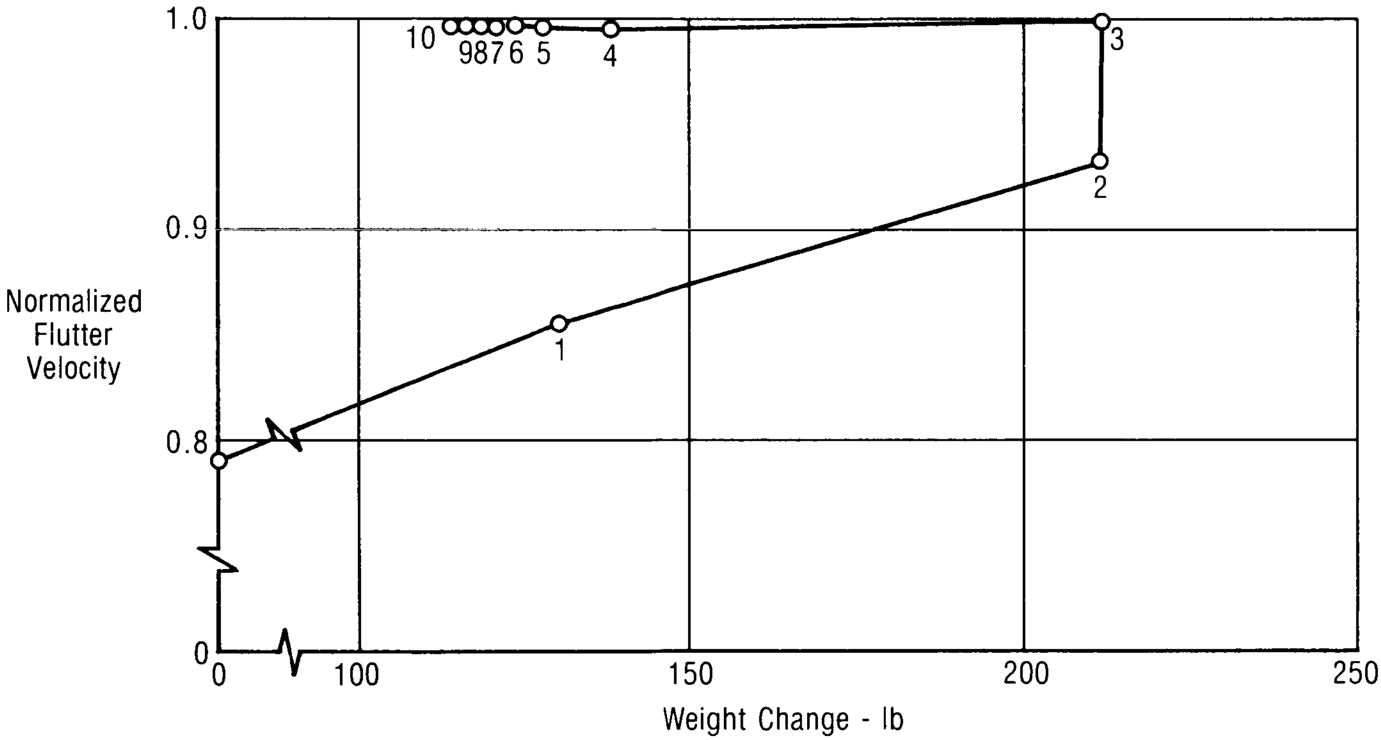


Figure 12

SENSITIVITY ANALYSIS DATA PREPARATION

This approach to flutter optimization is based on a "sensitivity" technique similar to that first explored in conjunction with the development of the COPS program, which is described in Figure 4. The study was done in an extremely short elapsed time using existing flutter data sets for a beam-rod stabilator idealization based on NASTRAN and Doublet lattice. The only new data required are the GJ versus number of 45° plies per skin for several elastic axis (EA) stations, as shown in Figure 13a. With these data the change in GJ versus elastic axis station can be calculated for various weight increments, as shown in Figure 13b.

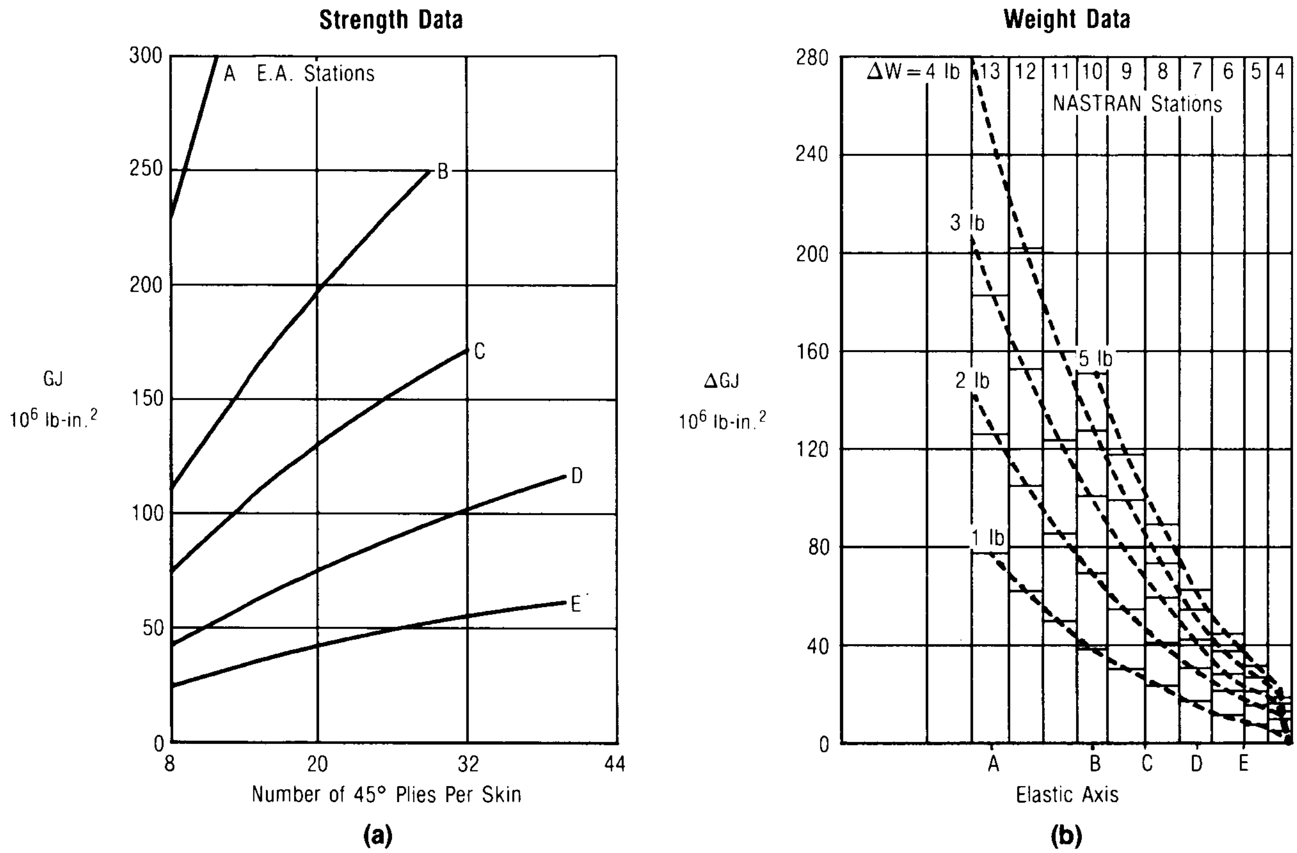


Figure 13

SENSITIVITY OPTIMIZATION RESULTS

The steps in the sensitivity optimization study are given in Figure 14. Each step of the redesign is based on batch submittals of the NASTRAN flutter routines, followed by a conscious choice for the elements to be used in the subsequent step. After step 4 it is possible, by the use of engineering judgment, to specify a redesign distribution which satisfies the flutter requirement and is practical to build. These studies are state of the art in all respects and are quicker, cheaper and more accurate than possible with any currently available automatic optimization procedure.

Step 1
Initial Design
ΔW = 2 lb Increments

	Station	V_F*	Redesign W
	13	0.864	
	12	0.865	
	11	0.868	
	10	0.868	
	9	0.873	
	8	0.872	
Choose	7	0.879	2
	6	0.877	2
	5	0.881	2
	4	0.878	2
	Redesign 1		8 lb

Step 2
Redesign 1 (8 lb)
ΔW = 2 lb Increments

	Station	V_F	Redesign W
	13	0.936	
	12	0.937	
	11	0.940	
	10	0.940	
Choose	9	0.945	2
	8	0.943	2
	7	0.939	2
	6	0.939	2
	5	0.943	2
	4	0.944	2
	Redesign 2		12 lb

Step 3
Redesign 2 (12 lb)
ΔW = 2 lb Increments

	Station	V_F	Redesign W
	13	0.961	
	12	0.963	
	11	0.965	
	10	0.965	
	9	0.961	2
	8	0.961	2
	7	0.964	2
	6	0.964	2
Choose	5	0.968	4
	4	0.969	4
	Redesign 3		16 lb

Step 4
Redesign 3 (16 lb)
ΔW = 1 lb Increments

	Station	V_F	Redesign W
	13	0.983	
	12	0.984	
Choose	11	0.986	1
	10	0.985	1
	9	0.982	2
	8	0.982	2
	7	0.983	2
	6	0.983	2
	5	0.984	4
	4	0.984	4
	Redesign 4		18 lb

*V_F is normalized to $V_{required}$

Step 5
Engineering Judgment
Test Case

Station	V_F	Redesign W
13		
12		
11		1
10		1
9		2
8		2
7		3
6		3
5		4
4		4
Redesign 5		20 lb

$V_F = 1.0$

Step 6
Verification
Redesign 5 (20 lb)
ΔW = 1 lb Increments

Station	V_F	Redesign W
13	1.003	Step 5 is OK
12	1.004	
11	1.003	
10	1.003	
9	1.003	
8	1.002	
7	1.002	
6	1.002	
5	1.003	
4	1.004	

Figure 14

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are appropriate in the area of flutter optimization.

1) COPS, or a similar routine, is suitable for use in conceptual design for individual lifting surfaces when the geometry is undefined.

2) TSO is suitable for use in preliminary design for individual lifting surfaces when the geometry is defined but there is still no well-defined structural model. Limitations in the structural model allow only limited use in detail design.

3) FASTOP is based on a sound concept but is not general enough for use in detail design and is too difficult to use in preliminary design.

4) NASTRAN based semi-automatic sensitivity techniques are the preferred approach for detail designs when the structural model is well defined but the flutter speed is deficient.

Since NASTRAN is the accepted industry standard for structural analyses it seems appropriate to either 1) incorporate flutter optimization routines in NASTRAN or 2) ensure that any alternate program developments have a complete one-to-one relationship to NASTRAN in all respects, and are designed to include generation of input data by graphics procedures.

Conclusions

- COPS Is Suitable for Conceptual Design
- TSO Is Suitable for Preliminary Design
- NASTRAN Sensitivity Technique Is Suitable for Detail Design

Recommendations

- Incorporate Flutter Optimization in NASTRAN
- If Alternate Procedure, Ensure Complete One-to-One Relationship to NASTRAN Including Graphics Generation of Bulk Data

Figure 15

REFERENCES

1. Triplett, W. E., and Ising, K. D., "Computer Aided Stabilator Design Including Aeroelastic Constraints," Journal of Aircraft, July 1971.

2. Shelton, J. D., and Tucker, P. B., "Minimum Weight Design of the F-15 Empennage for Flutter," AIAA/ASME/SAE 16th Structures, Structural Dynamics and Materials Conference (SSDM), Denver, Colorado, 27-29 May 1975.

3. Triplett, W. E., "Aeroelastic Tailoring Studies in Fighter Aircraft Design," Journal of Aircraft, July 1980.

4. Lynch, R. W., Rogers, W. A., and Braymen, W. W., "Aeroelastic Tailoring of Advanced Composite Structures for Military Aircraft," AFFDL-TR-76-100, Vol. III, February 1978.

5. Triplett, W. E., "Aeroelastic Tailoring of a Forward Swept Wing and Comparisons with Three Equivalent Aft Swept Wings," AIAA/ASME/ASCE/AHS 21st Structures, Structural Dynamics and Materials Conference (SSDM), Seattle, Wash., 12-14 May, 1980.

6. Markowitz, J., and Isakson, G., "FASTOP-3: A Strength, Deflection, and Flutter Optimization Program for Metallic and Composite Structures," AFFDL-TR-78-50, May 1978.

7. Triplett, W. E., "Wind Tunnel Correlation Study of Aerodynamic Modeling for F/A-18 Wing-Store Tip-Missile Flutter," AIAA/ASME/ASCE/AHS 24th Structures, Structural Dynamics and Materials Conference (SSDM), Lake Tahoe, Nev., 2-4 May 1983. (Journal of Aircraft, Spring 1984)