Computer Aided Stabilator Design Including Aeroelastic Constraints

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A computerized direct optimization procedure has been developed to aid in the design of an aircraft all-moveable stabilator. The procedure systematically evaluates a set of design variables so that the near optimum stabilator is synthesized from input nondimensional geometry and material characteristics to satisfy design constraints of performance, control requirement, stability margin, strength, and flutter velocity. The procedure can be used in the search for either the minimum weight stabilator or maximum performance aircraft. Nonunique solutions are obtained for a particular candidate stabilator when initial perturbation step sizes are varied. The payoff surface changes, for this case, as steps are made in the direction of the extremal point. Because of this possibility of nonstationary payoff surface, it is questionable whether any sequential optimization scheme can consistently find the truly minimum weight flutter free surface. These results indicate significant weight improvement possibilities and emphasize the necessity for including aeroelastic constraints in a coordinated systems approach to aircraft design as early as possible in the design cycle.

Introduction

THE efficient design of any aircraft structure involves a series of compromises among various engineering disciplines. These compromises are necessary to ensure the best over-all design instead of one which, for example, is optimum only for aerodynamics or strength or flutter. To effectively reconcile the various technical requirements with each other involves a number of design iterations, with the accompanying long elapsed time.

It has been our experience that all-moveable, especially differential all-moveable, stabilators present one of the more complex aircraft design problems because of a relatively large number of apparently conflicting requirements originating from the various technical disciplines. The pronounced sensitivity of the performance and weight of fighter aircraft to small changes in weight and aerodynamic drag of the empennage also makes it imperative that all aspects of stabilator design be considered as early as possible in the development of an aircraft. We have, therefore, developed a direct computerized optimization procedure to aid in the design of an aircraft all-moveable stabilator.

The procedure, as presented in this paper, approaches the problem of stabilator design from a practical engineering viewpoint. All of the elements of a traditional engineering design cycle are present in the system so that the aeroelastic constraints of flutter and divergence, as well as strength, aerodynamic stability, control and performance are all integral design considerations. The procedure was developed with the primary objective of reducing the turn-around time in the stabilator design cycle. To that end, a computerized system was created with features to aid in the search for the optimum stabilator.

The intent throughout the development effort has been to create a unique and dependable automated procedure suitable for use in all phases of an aircraft development cycle from configuration selection, through aircraft sizing, to detail design. To accomplish this, practical and efficient levels of analytical sophistication—based on proven engineering criteria—are incorporated for each of the various technical requirements in stabilator design. This results in a computerized procedure which is able to give correct trends and reasonably accurate quantitative answers. Further detailed analyses are necessary to finalize the design.

Numerous publications have appeared in the literature dealing with structural optimization to satisfy the strength constraints of stress and deflection. For many reasons there has been very little effort given to the development of automated techniques for including aeroelastic constraints. Johnson and Warren[1] have included a flutter constraint in a finite element structural optimization procedure by ensuring zero-airspeed vibration mode frequency separation as the structural system is modified. Turner[2] has presented a numerical procedure for determining the relative proportions of selected elements of an aircraft structure for a specified flutter speed. Lagrange Multipliers are used to represent the dynamic constraints and the linearized system equations are repeatedly optimized for a fixed value of flutter speed and a succession of values of flutter frequency. The mass distribution for minimum total mass is then determined graphically. These efforts are both concerned with detail design and begin with a specified strength and aerodynamic configuration for which a flutter analysis has been performed.

Basic Program Description

The Computerized Optimization Procedure for Stabilators (COPS) program is presented by a greatly simplified conceptual flow diagram in Fig. 1. Input data are required by the program for the system constraints, material properties and geometrical design parameters. The procedure then synthesizes, from these input data, a stabilator which satisfies all system constraints except the aeroelastic constraints of flutter and divergence. A systematic perturbation of a set of control variables suitable for flutter prevention follows, until the aeroelastic constraint is satisfied for minimum additional weight.

The COPS program is currently formulated to synthesize, evaluate, and modify both metallic and composite structural

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materials. The analytical model is a stabilator with a torque box structure, as shown in Fig. 2. It is idealized by eight discrete rigid chord streamwise sections with three mass points per section. Quasi-steady aerodynamic forces act at the quarter chord of each section. The following nondimensional geometrical design parameters are specified for the model as input data: taper ratio; thickness ratio at root chord; thickness ratio at tip chord; aspect ratio; leading-edge sweep angle; tip cutoff angle; pitch axis hinge line angle; pitch axis intersection with the mean aerodynamic chord (MAC); spar locations.

Description of Modules

After input data have been specified, an initial pass is made through the chain of modules representing aerodynamics, strength, weight, and structural dynamics.

Aerodynamic system module

This module is first in the chain of modules shown in Fig. 1. It consists of three submodules as described in the following paragraphs. 1) Aerodynamic submodule—This sizes the stabilator to satisfy the system constraints of aircraft stability margin and performance for the specified set of input geometrical design parameters. The required tail moment for a fixed wing-tail separation distance determines the area of the stabilator. A linear variation of thickness ratio from root to tip and a four digit NACA airfoil shape, in equation form,[3] are used to calculate the chordwise airfoil thicknesses. Aerodynamic lift and drag coefficients for the tail surface are read from tabular two-dimensional arrays as a function of the aspect ratio and leading-edge sweep angle. 2) Air load submodule—This calculates the air load distribution on the specified stabilator planform and the resulting bending moment, shear, and torque along and about the elastic axis. The torque distribution calculation has an additional functional dependence on the mean aerodynamic chord of the surface. 3) Control dynamics submodule—This sizes the hydraulic actuator to satisfy the design aerodynamic hinge moment requirement subject to the system constraints of aircraft power limitation and space restriction. The spring constant associated with the hydraulic actuator oil column is calculated for the mid-stroke point of an assumed stable hydraulic actuator. When required by the program, the control dynamics submodule resizes the hydraulic actuator, subject to the horsepower and space constraints. Spring constants for the actuator back-up structure, linkage and bell crank are input quantities based on external analysis, and are not varied by the current program.

Strength module

The basic structural idealization in the strength module is indicated in Fig. 2. This idealization is a representation of a two-spar, single-cell torque box structure with metal spars and spar caps and either metal or composite upper and lower skins. Since the leading- and trailing-edge structures contribute very little to stabilator stiffness, they are not varied, nor is their stiffness assessed. Alternate modules for other basic structural concepts, such as a three-spar, two-cell torque box, are easily substituted in the program.

Torque box cross-sectional areas normal to an assumed elastic axis at each spanwise station are calculated for the four digit NACA airfoil shape which is evaluated in the aerodynamic submodule. Initial skin and spar thicknesses are calculated in response to the bending moment, shear, and torque distributions received from the air loads submodule, subject to the constraints of specified minimum thicknesses. Allowable stress levels are specified as input data and are not modified by the procedure.

Structural cross-sectional skin and spar areas at each spanwise station are calculated for use by the weight module.

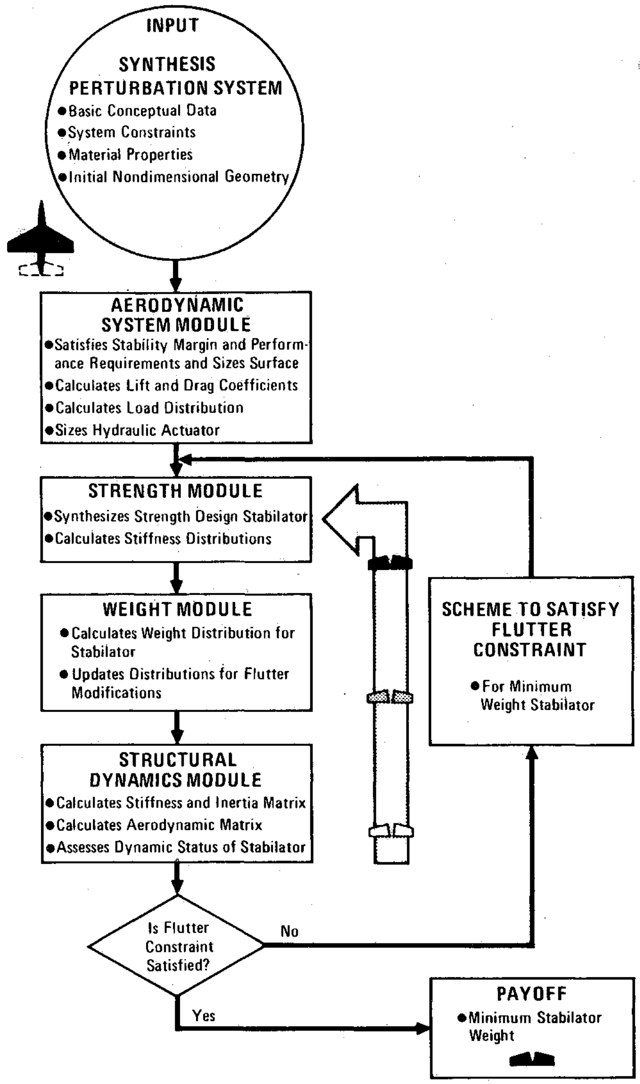

Fig. 1 COPS—basic conceptual flow diagram.

Stiffness distributions in bending (EI) and torsion (GJ) are then calculated for this initial strength and aerodynamic design.

When requested by the program, the torque box skin is increased to give the required torsional stiffness distribution, and the cross-sectional area data are updated for the weight assessment. The corresponding bending stiffness distribution is also calculated.

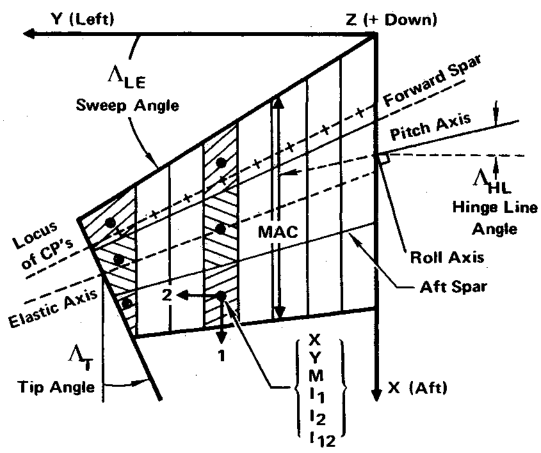

Fig. 2 Analytical model.

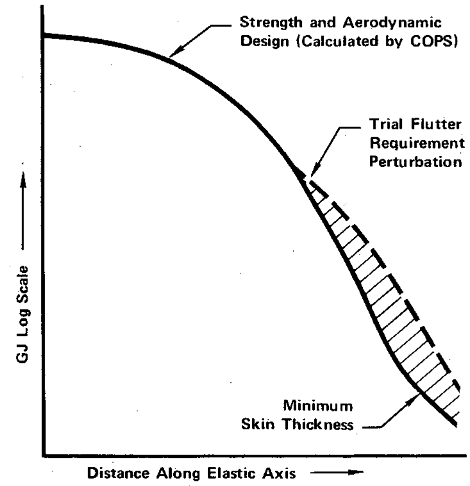

Fig. 3 Example of torsional stiffness perturbation.

Weight module

The weight module assesses both the total and the distributed weight of the stabilator in terms of the analytical model of Fig. 2. The leading- and trailing-edge sections are assessed on the basis of input density and thickness data and remain constant. The torque box weight is assessed on the basis of the structural cross-sectional areas, for each spanwise station, received from the strength module.

Since a straightforward calculation of weight based only on the cross-sectional areas is not realistic, the weight module compares the calculated weight with an evaluation of the probable weight of the stabilator based on a statistical procedure. As a result of this comparison, the module defines three nonoptimum factors for the weight distribution; one each for the leading-edge, torque box, and trailing-edge sections. A valid assessment of the weight and weight distribution requires a set of nonoptimum factors which do not include weight to satisfy the flutter constraint. Therefore, these nonoptimum factors are adjusted to eliminate the statistical effect attributable to the fact that all of the samples are real-world articles and thus must have satisfied flutter constraints. The module also assesses the weight of the hydraulic actuator and associated back-up support on a statistical basis.

Structural dynamics module

The basic differential equations of motion for the aeroelastic system are evaluated in the structural dynamics module. A set of linear homogeneous equations is expressed in terms of generalized coordinates describing the vertical translation and streamwise pitch of each rigid streamwise section, and the translation, pitch and roll of the rigid stabilator at the intersection of the pitch axis with the stabilator root chord. The dynamic status (aeroelastic stability) of the stabilator is assessed by a parametric variation of the freestream dynamic pressure using Conceptual Flutter techniques.[4] Divergence is sensed by direct interpretation of the eigenvalues and flutter is sensed by a quantity called the Flutter Margin (FM).[4] The COPS program uses the FM expressed in terms of the four lowest roots of the characteristic equation. Thus, the program is able to sense the occurrence of flutter involving any combination of these four lowest modes. Any drastic and abrupt changes in mode shape caused by system modifications, as well as changes of flutter mechanisms, are sensed whenever they happen to occur.

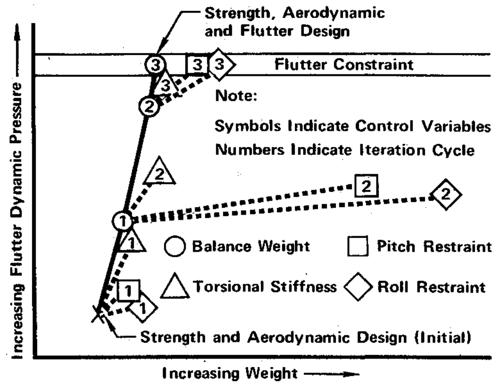

Fig. 4 Example of scheme for satisfying the flutter constraint.

The QR algorithm[5] is used by the COPS program to solve the eigenvalue problem. Eigenvectors are calculated for interpretative purposes only since mode shapes are not necessary for the solution technique.

The inertia matrix is assembled from the local distributed mass data calculated in the weight module. In addition, the total stabilator inertia matrix, referenced to the pitch axis-root chord point, is calculated and the uncoupled pitch and roll frequencies of the rigid stabilator are evaluated, again for interpretative purposes only.

The stiffness matrix is formulated as the inverse of an influence coefficient matrix which is composed of two separate parts. One part is calculated for the torque box of the stabilator, considered as a cantilevered beam rod, with torsional and bending stiffness distributions received from the strength module. The other part evaluates the flexibility of the support structure and actuation system. This part assumes a rigid surface with a support system having flexibility in pitch, roll, and translation.

The aerodynamic stiffness matrix is formulated on the basis of a quasi-steady streamwise aerodynamic lift curve slope. Lift on each discrete streamwise section, indicated in Fig. 2, is expressed in terms of the local section area, freestream dynamic pressure, and the angle-of-attack created by generalized coordinate motion. The lift is assumed to act at the quarter chord of the section. Values of lift curve slope are read from a table as a function of aspect ratio and leading-edge sweep angle. This table is based on wind-tunnel test data and is tabulated for a Mach number just prior to the transonic center of pressure shift. This is the most adverse combination of lift and center of pressure for flutter. A program option allows the user to specify lift curve slope and center of pressure for each section.

Flutter Control Variables

COPS satisfies the aeroelastic constraint for an initial strength and aerodynamic design, for the all-moveable stabilator of Fig. 2, by the use of the four flutter control variables: balance weight; pitch restraint of the support; roll restraint of the support; torsional stiffness level. These four flutter control variables are arbitrary, and both the number and nature of the variables may be changed by minor modifications of the program. The current choice is based on experience and engineering judgement as to the primary ingredients in the flutter mechanisms of all-moveable stabilators. It is significant to note that only one of the four control variables is directly concerned with the structural characteristics of the stabilator. In fact, any optimization routine which concentrates on the structural characteristics alone, without providing for the competitive evaluation of balance weights and rotational restraint, could not be expected to converge consistently to a realistic minimum-weight, all-moveable stabilator for an aeroelastic constraint.

The balance weight control variable is a concentrated mass added at any one of the 24 mass point locations on the stabilator, as specified by the user. The pitch and roll restraint control variables are based on an idealization of the support structure and hydraulic actuation system subject to appropriate system constraints of available power, control requirement, and minimum strength requirement. These two control variables are strongly configuration dependent. They have a significant effect on the dynamic behavior of an all-moveable surface and, for some stabilators, may be the only feasible method for satisfying the flutter constraint.

The torsional stiffness level control variable is defined so that the torsional stiffness for each of the stabilator torque box sections is modified for each trial perturbation of the control variable. The procedure defines the control variable as the torsional stiffness level at a specified spanwise station. A table containing a two-dimensional array of elements as a function of the stabilator elastic axis percent span and the surface taper ratio is called by the program, and relative values of torsional stiffness for the other stabilator torque box sections are obtained. A comparison is then made with the initial synthesized strength design level for each section, and the envelope of these two levels is used for the trial torsional stiffness level perturbation. The perturbation of the control variable thus results in a modified distribution of torsional stiffness over the torque box span, subject to the strength design constraint and minimum skin gauge requirement. The user may specify each element in the table so that any desired predetermined torsional distribution can be evaluated by the procedure. An example of the torsional stiffness level perturbation is shown by Fig. 3 for a table based on a criterion which assumes constant strain energy per unit weight of torsional material. The criterion gives a distribution proportional to the fourth power of the chord. The figure illustrates the tendency for the trial modification to fill in the weakest areas in the stiffness distribution first.

If composite material is being considered, the required stiffness is achieved by adding additional plies to the surface skin. The composite fiber orientation for this additional material can be specified for each section at any desired value. The procedure is thus able to exploit the potential of composite material to enhance the aeroelastic characteristics, with minimum effect on the strength characteristics. A planned modification of the procedure is to incorporate the concept of replacing layers of fibers for strength (for example at 0° orientation, i.e., parallel to the elastic axis) with layers of fibers for flutter (for example at 45° orientation) subject to the constraint that the resulting design still satisfies the strength design requirement.

Scheme to Satisfy Flutter Constraint—Proportional Constraint Deficiency Method

The COPS program uses a first-order search routine based on partial derivatives expressed as finite differences. After input data have been specified, an initial pass is made through the chain of modules shown in Fig. 1. The structural dynamics module performs a flutter analysis for the initial aerodynamic and strength design, and the dynamic status of the stabilator is evaluated in terms of three possibilities: divergence; flutter; flutter free, divergence free.

If divergence occurs, the main program increases the rigid surface pitch restraint and re-evaluates the weight and dynamic status of the design until divergence no longer occurs. If flutter occurs for a value of dynamic pressure Q_F less than the required flutter constraint dynamic pressure Q_{REQ} the deficiency in flutter dynamic pressure $\Delta Q = Q_{\text{REQ}} - Q_F$ is calculated. An attempt is made to reduce a proportional part of this constraint deficiency by the perturbation of each flutter control variable. The step size for each control variable perturbation is calculated as $\Delta X_i = (\text{PCD})(\Delta Q)/(dQ_F/dX_i)$ where ΔX_i is the trial perturbation for flutter control variable X_i, and PCD is the Proportional Constraint Deficiency factor. A PCD factor of one-half has been found to be a good compromise between computer run time and accuracy in the several test cases examined.

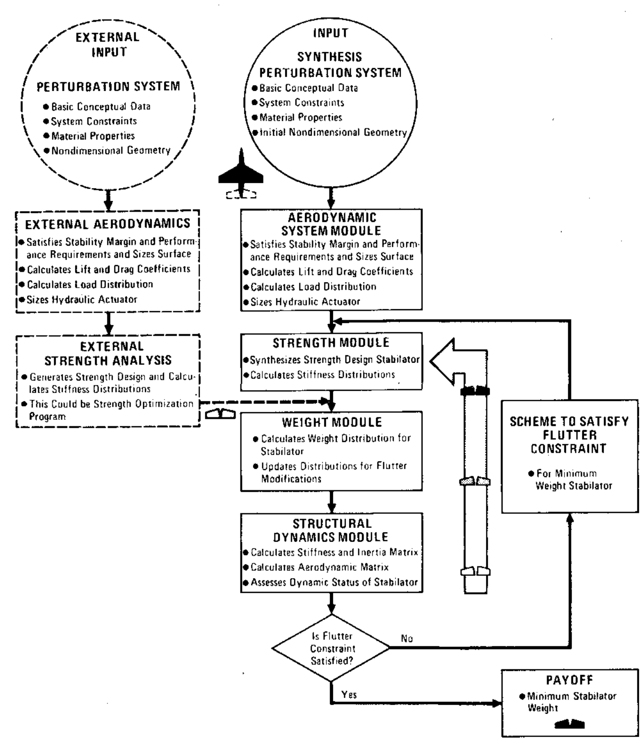

Fig. 5 COPS—conceptual flow diagram—with alternate input.

Initial estimates of the rates of change of flutter dynamic pressure with respect to each of the control variables are submitted to the program as input data. After the first iteration cycle and for each succeeding cycle, the rates of change are updated based on a finite difference calculation.

An assessment is made of the effects of each trial perturbation on the weight and dynamic status of the system. After a perturbation has been made for each flutter control variable, the perturbation giving the maximum increase in flutter dynamic pressure for minimum weight increase is determined and implemented, thus creating a new design. The procedure is repeated for this new design, and the process is continued until the flutter constraint is satisfied with a minimum weight design. The scheme is illustrated by Fig. 4 where the solid line indicates the minimum weight solution.

The procedure is basically a first-order sequential optimization scheme. Each design modification is evaluated and implemented based on the previous trial design. A new dynamic system is established for each iteration step. The program has been formulated, however, so that each flutter control variable may be preselected as the preferred solution

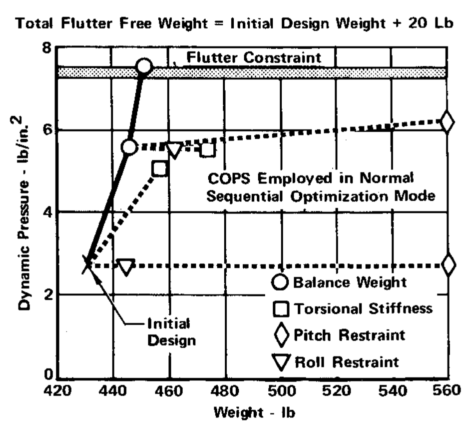

Fig. 6 Solution for candidate stabilator—large initial steps.

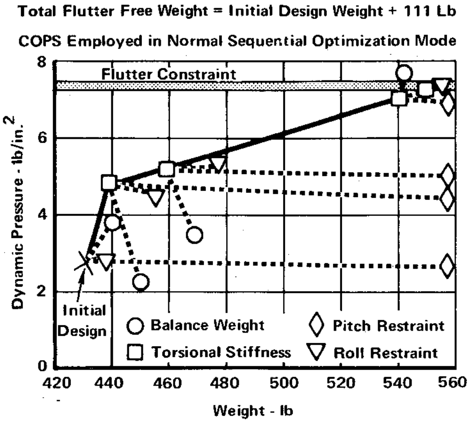

Fig. 7 Solution for candidate stabilator—small initial steps.

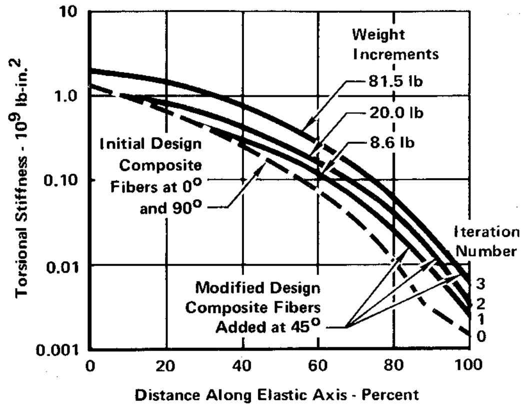

Fig. 9 Torsional stiffness distribution—candidate stabilator—stiffness solution.

to the aeroelastic constraint. The program is thus able to be employed in an alternate simultaneous optimization scheme where each flutter control variable is individually and exclusively evaluated from the same initial design point.

An alternate input, shown in Fig. 5, is incorporated into the program to accept a fixed geometry aerodynamic and strength design stabilator, such as generated in the detail design phase of an aircraft development cycle. The input data must agree with the analytical model of the program. The design could also be the output of a structural optimization program for the strength constraints of stress and deflection. The design should have no structural stiffness other than the minimum necessary for the strength requirements. The COPS program will satisfy the aeroelastic constraint for this fixed design by the same routines used for the more complete synthesizing procedure. The program is not suitable for use in automated aircraft sizing or configuration selection optimization studies when the alternate fixed geometry input is used.

Application

The COPS program has been applied in its basic sequential optimization mode to several advanced fighter aircraft stabilators. The optimization procedure was able to converge rapidly to a unique solution using this technique, with a Proportional Constraint Deficiency factor of one-half. There was, however, one stiffness critical candidate stabilator among the test cases which exhibited a nonunique solution when the perturbation step size was varied. This test case will be discussed since it both shows the application of the program and points out a potential problem.

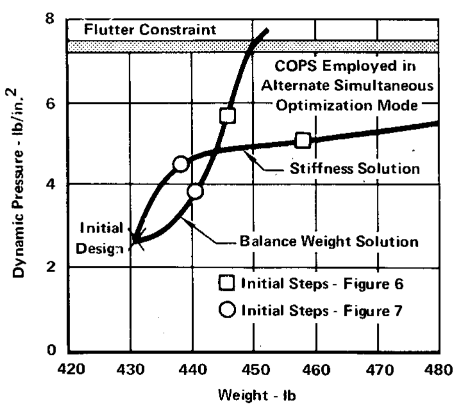

Fig. 8 Alternate solutions for candidate stabilator—effect of step size.

Candidate Stabilator Application

Results for the candidate stabilator, when large initial steps are used in both stiffness and balance weight control variables, are shown in Fig. 6. In this case, the solution for the flutter prone initial design is obtained after just two iteration cycles. The balance weight for this case is applied at the leading edge of the outboard section and is clearly the preferred control variable for each iteration cycle. The flutter constraint is satisfied with just 20-lb additional weight over that necessary for the initial strength and aerodynamic design.

When small initial steps are used for the same candidate stabilator, the results shown in Fig. 7 are obtained. The torsional stiffness control variable is the preferred choice for the first iteration cycle. The balance weight improves the flutter dynamic pressure but is not as effective as the stiffness variable. For the next two iteration cycles, the stiffness variable is still preferred even though its effect on the flutter dynamic pressure is much reduced. Note that the balance weight perturbation during both the second and third iteration cycles decreases the flutter dynamic pressure dramatically. For the fourth iteration cycle a 1-lb balance weight satisfies the flutter constraint for a total additional weight of 111 lb.

If the initial design had been the design at the end of the first iteration cycle of Fig. 7, it is likely that the only feasible flutter solution for this stabilator would have been increased torsional stiffness. This emphasizes the absolute necessity for no premature stiffening for flutter, since this may negate the beneficial aspects of rather small balance weights, and thus create a design with an unnecessary, and probably unrecognized, weight penalty.

When COPS is run in its alternate simultaneous optimization mode, the reason for the nonunique solution for this candidate stabilator is explained. Results are shown in Fig. 8 for the two control variables of interest, torsional stiffness and balance weight. The stiffness solution is initially more favorable, but to make up the entire constraint deficiency, the balance weight is far more effective. The balance weight solution is the same solution obtained by the sequential mode when large initial steps were used. The trial perturbations for the two control variables are shown on Fig. 8 for both the large step case of Fig. 6 and the small step case of Fig. 7. It is seen that the only way the minimum weight balance weight solution would be chosen by the program would be the use of either 1) steps large enough to exceed the crossover point, in both variables, with the sequential optimization mode, or 2) the alternate simultaneous optimization mode. Either scheme would give a unique solution if there were no crossover of paths. The situation is complicated by the fact that, as soon as a solution is attempted

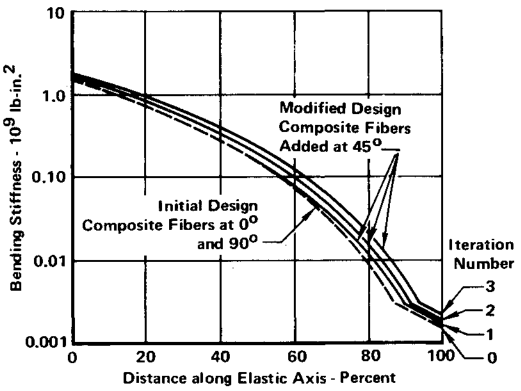

Fig. 10 Bending stiffness distribution—candidate stabilator—stiffness solution.

by moving up the stiffness branch, the system is modified. The balance weight then may not be able to stabilize the system, and the solution branch may disappear altogether, as shown by Fig. 7.

This example illustrates the lack of uniqueness possible with optimization schemes when applied to structural optimization for an aeroelastic constraint.

The COPS program, when operating in its simultaneous optimization mode, approaches the flutter problem in the traditional "try them all" engineering sense. If the initial design has no premature modifications for flutter, this scheme will be able to find an "almost optimum" solution. This "almost optimum" solution will be the unique exclusive solution for the flutter constraint for minimum weight. The "optimum" solution may indeed be this exclusive solution, but the possibility exists that a solution using a combination of control variables might be lighter. As an example, consider the 1-lb balance weight chosen instead of the 10 lb of torsional stiffness for the fourth iteration cycle of Fig. 7, which otherwise would have been an exclusive stiffness solution. Logical control to find the truly optimum solution can be developed in an automated procedure such as COPS. However, unless a great deal of "artificial intelligence" is built into the program, it is likely to require an excessive amount of computer time to improve upon the present capability of COPS to find the "almost optimum" stabilator, in either its simultaneous mode or in its sequential mode with large perturbation steps.

Stiffness Solution with Composite Material

The stiffness solution of Figs. 7 and 8 for the candidate stabilator will be used to illustrate the results of the COPS program when composite material is considered. The torsional stiffness distribution is shown in Fig. 9 for the initial strength and aerodynamic design, and for the modified flutter design of iteration cycles 1–3. In the initial design the fiber orientation is along the elastic axis (at 0° and 90°) to obtain the maximum bending strength. Modifications are made by adding fibers at ±45° to the elastic axis to obtain the maximum increase in torsional stiffness with minimum increase in bending stiffness to satisfy the flutter constraint with minimum effect on the strength characteristics of the surface. The weight increments required for the stiffness modification are shown for each of the iteration steps. The corresponding bending stiffness distributions appear in Fig. 10. The skin and spar thickness distributions for the initial strength and aerodynamic design torque box are shown in Fig. 11. The torque box skin thickness distribution for iteration cycles 1–3 is shown in Fig. 12.

The example of Fig. 7 required 1.4 min on the IBM 360-65/75 for the 17 separate flutter analyses, or an average of about 5 sec per flutter analysis. The program is thus fast

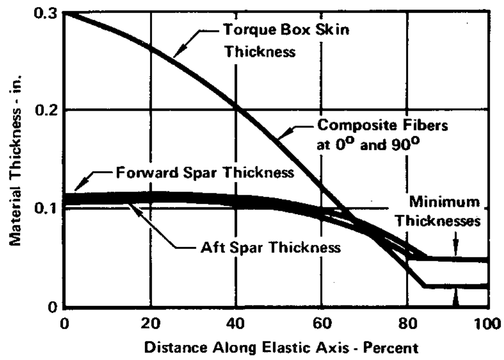

Fig. 11 Torque box skin and spar thickness—candidate stabilator—initial design.

enough to be used as an element in more encompassing over-all aircraft optimization programs.

Expanded Program

The conceptual flow diagram for the expanded version of COPS is shown in Fig. 13. This system offers three separate levels of optimization and is suitable for use in all phases of an aircraft development cycle. These levels of optimization are generated sequentially, as follows: 1) detail design—optimization of a stabilator with specified and sized geometrical design variables to satisfy the flutter constraint for minimum weight, as discussed previously; 2) aircraft sizing—optimization of the aircraft with respect to the stabilator by resizing both the aircraft and the stabilator with specified geometrical design variables to maintain required aircraft performance; 3) configuration selection—optimization of the aircraft with respect to the stabilator by a systematic variation of the geometrical design variables.

The input to the expanded system is the initial point design data for the aircraft and includes all appropriate system constraints, material properties, and initial values for the geometrical design variables. The basic COPS procedure uses these data to synthesize a minimum weight stabilator which satisfies all of the system constraints, including the aeroelastic constraints of flutter and divergence.

If the option to proceed with a higher level of optimization has been chosen by the user, an assessment will be made of the impact of the minimum weight stabilator on the over-all aircraft. If either the aerodynamic drag or the stabilator weight is significantly different from that employed in the point design aircraft analysis, the aircraft design will be re-evaluated. Sensitivity factors are used to relate changes in

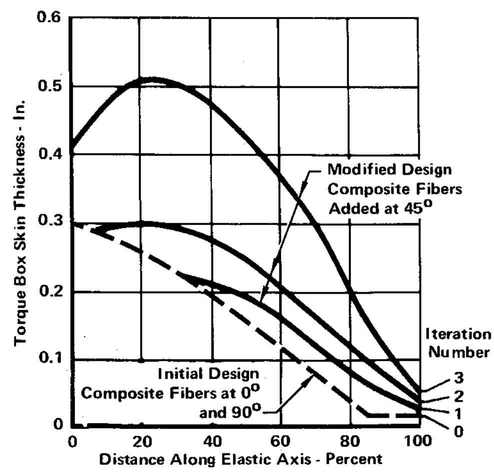

Fig. 12 Torque box skin thickness—candidate stabilator—stiffness solution.

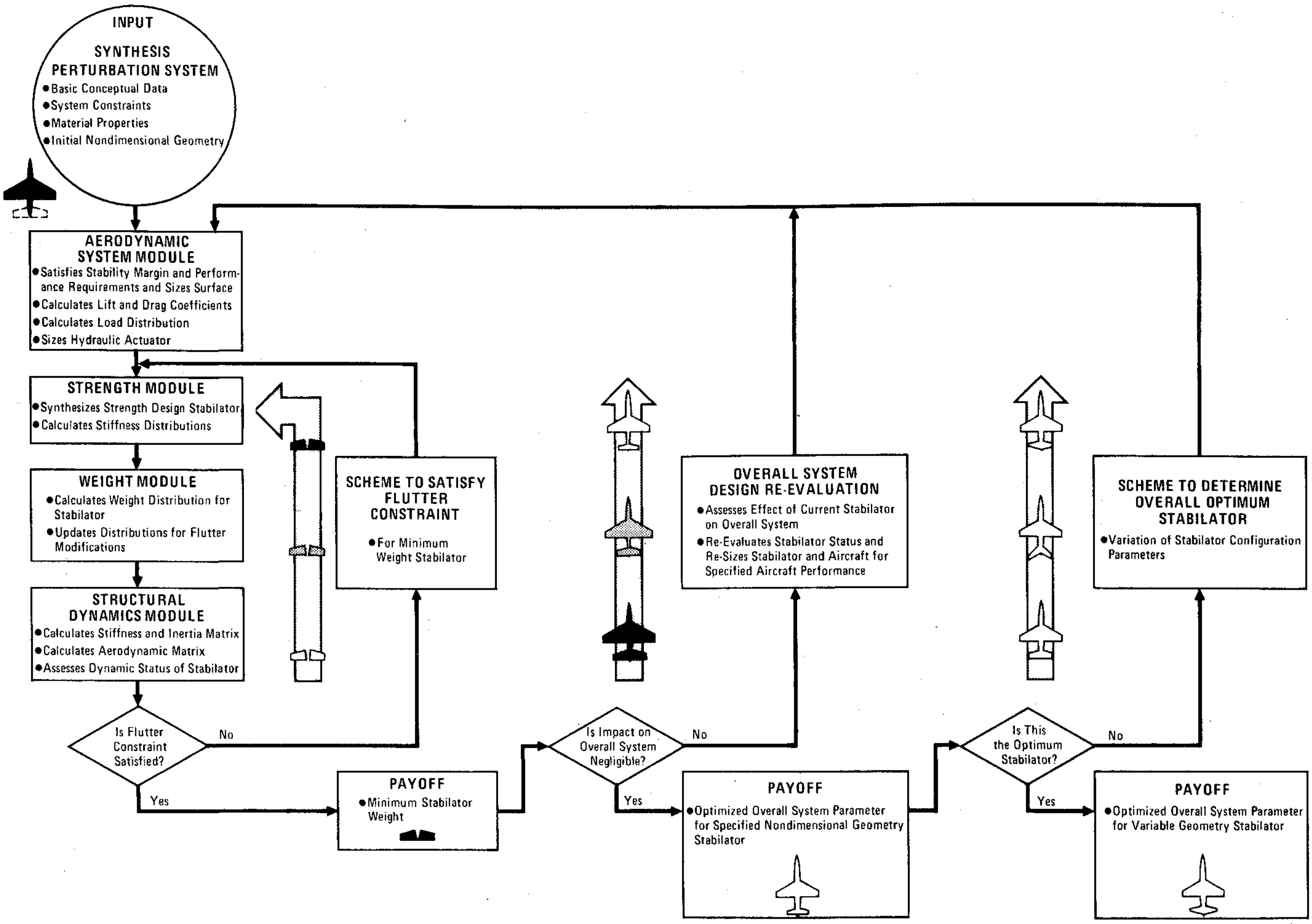

Fig. 13 COPS—conceptual flow diagram—expanded version.

stabilator weight and drag to other aircraft parameters such as takeoff-gross-weight (TOGW) and wing area. The sensitivity factors are based on the point design aircraft and are furnished to the program as input data. The required tail moment to satisfy specified aircraft performance and stability criteria is determined. The stabilator is then resized by scaling its dimensions within the constraint of the specified initial geometrical design variables. The basic COPS procedure is applied to this resized stabilator. The objective function for this level of COPS is nominally the TOGW for the aircraft, but other payoffs, such as range, may be substituted.

If the option to proceed with the next higher level of optimization has been chosen, a systematic search will be made through a selected set of geometrical design variables to determine the "optimum" stabilator.

A modified form of Rosenbrock's method[6] has been chosen to perform the search for the over-all optimum stabilator for the point design aircraft. The method is a zero-order sequential optimization procedure in which the independent variables are repeatedly and systematically perturbed in a given set of directions. The design is modified after each perturbation which successfully improves the objective function within the bounds established by the system constraints. The procedure continues until further perturbations in any direction cannot improve the objective function. The set of directions is then rotated to align one of them with the resultant of the perturbations that successfully improved the objective function. Perturbations continue with this new orthogonal set of directions until another rotation is necessary. The process continues until an extremal point is reached.

Since an iterative optimization method must employ some artful procedures to make it converge rapidly to a solution, part of the task of development involves an investigation into the basic characteristics of the problem. If a number of similar problems are to be worked—as in a parametric study—one may well be justified in experimenting to determine values and bounds for those convergence parameters and constraints which can efficiently and economically solve the problem. This is the current situation in our development of the COPS program. All of the modules necessary for the entire expanded system described in Fig. 13 are in complete form; however, final link-up of the two higher levels of optimization for aircraft sizing and configuration selection is being delayed until further studies are completed using batch processing of the basic COPS program in real-world detail design applications.

Summary

The COPS program has been developed to aid in the design of an all-moveable stabilator. The program is intended primarily as a means of reducing the turn-around time for flutter analysis in an aircraft design iteration cycle. It is, however, also a significant first generation effort at computerized optimization for aeroelastic constraints. The program has the following significant characteristics: 1) Since most modern fighter aircraft stabilators are designed by aeroelastic considerations, primary emphasis has been given to the aeroelastic effects, although an acceptable strength and aerodynamic design is ensured. 2) Modules for each of the technologies are distinct entities which are generated, evaluated and refined by specialists in the technology, and modification of the program to incorporate improved or updated modules is easily accomplished. 3) Interface capability has been built into the program to accept a specified design which might be either generated in the detail design phase of an aircraft development cycle or generated in a structural optimization program for the strength constraints of stress and deflection. 4) Optimization can be conducted either on a component basis or on an aircraft system basis, and thus is usable in all phases of an aircraft development cycle. Batch processing is currently used for this feature of the program. 5) The basic COPS program contains a realistic representation for every significant aspect of a believable flutter analysis and yet is still fast enough, on the computer, to be used as an integral part of more encompassing aircraft systems optimization programs.

Concluding Remarks

Optimization for the aeroelastic constraints of flutter and divergence is inherently one of the more complex and difficult tasks in the field of optimization. The concept of a stationary payoff surface with constant constraint boundaries is not really appropriate for the aeroelastic constraint problem. The payoff surface changes, in many cases, as soon as a step is made in the direction of the extremal point. What is probably more significant, however, is the fact that the new payoff surface thus created may have an extremal point which is considerably different than the initial extremal point.

It is questionable whether any strictly sequential optimization scheme, such as the various gradient techniques, can consistently find the truly minimum weight flutter free surface. Exclusive simultaneous solutions for the flutter constraint, using each of the many possible flutter control variables until the system either satisfies the flutter constraint or saturates, are also unlikely to discover the minimum weight solution. Even if one were to evaluate all of the possible exclusive simultaneous solutions at each redesign step of a sequential approach to the flutter constraint, the unique "optimum" would still not be ensured. A procedure, such as COPS, which is able to efficiently and economically find the "almost optimum" solution thus becomes a very practical and valuable tool for use in a realistic design environment.

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