ASTROS—A Multidisciplinary Automated Structural Design Tool

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ASTROS (Automated Structural Optimization System) is a multidisciplinary software system that can be used in the preliminary design of aerospace structures. The approach taken in this development project was to blend proven engineering tools into an efficient unified system through the use of a specifically designed software environment. ASTROS has reached the stage at which significant test cases have been performed that have demonstrated the power and versatility of the system. This paper first presents background information that motivated the development of this new system, followed by a discussion of the engineering technologies that have been integrated into ASTROS. Emphasis is placed on some of the more novel features, such as the treatment of flutter constraints and the linking of physical design variables. This discussion is then followed by two representative test cases.

Nomenclature

A^I	= imaginary part of the generalized aerodynamic influence coefficient matrix
A^R	= real part of the generalized aerodynamic influence coefficient matrix divided by the reduced frequency
b	= reference semichord
C_L	= lift coefficient
C_m	= pitching moment coefficient
F	= objective function
$GFACT$	= scaler normalization factor
g	= inequality constraint or the gravitational constant
i	$= \sqrt{-1}$
K	= generalized stiffness matrix
k	= reduced frequency
M	= generalized mass matrix
m	= number of applied inequality constraints
ndv	= number of global design variables
$nroot$	= number of flutter roots
nv	= number of velocities
p	= complex response frequency and eigenvalue, $= k(\gamma + i)$
Q^I	= imaginary part of the generalized aerodynamic influence coefficient matrix
Q^R	= real part of the generalized aerodynamic influence coefficient matrix
t	= physical design variable
$\boldsymbol{u}$	= eigenvector of modal coordinates
V	= selected velocity
$\boldsymbol{v}$	= adjoint flutter vector
x	= global design variable
x^l, x^u	= lower and upper bound on global design variable, respectively.
α	= angle of attack
γ	= damping factor
δ_e	= angle of the longitudinal trim surface
ρ	= air density
σ_c	= compressive normal stress
σ_t	= tensile normal stress
τ_{xy}	= shear stress

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Background

At the preliminary design stage of an aerospace structure, the configuration has been defined and the materials have been selected. The design task is the determination of structural sizes that will provide an optimal structure while satisfying the numerous constraints that multiple disciplines impose on the structure. The motivation for the development of a single automated structural optimization tool is that such a tool can provide improved structural designs in less time than is currently needed. This is particularly true as composite materials come into widespread use. Balancing conflicting requirements for the structure's strength and stiffness while exploiting the benefits of anisotropy (e.g., aeroelastic tailoring) is, perhaps, an impossible task without assistance from an automated design tool. Finally, the use of a single tool can bring the design task into better focus among design team members, thereby improving the insight into their overall task.

The development of a system to meet the preceding needs is by no means a new endeavor. Concepts of automated structural design have been advanced for over 30 years and a number of software procedures have been developed. Notable among these are the TSO[1] and FASTOP[2] procedures that were both developed under U.S. Air Force sponsorship. NASA has been very active in this area and has sponsored, or performed in-house, many programs that have served to crystallize the methodologies that are applicable in this area.[3,4]

Before differentiating the ASTROS (Automated Structural Optimization System) from these previous efforts, another relevant background item should be discussed. This relates to the fact that engineering related software applicable in an automated design task has matured in recent years to the extent that there are well-known engineering codes available that are generally accepted in engineering analysis. The NASTRAN (NASA Structural Analysis) system[5] is a clear example of a general purpose code with the Doublet Lattice[6] and USSAERO[7] codes as examples of special purpose software that have gained widespread acceptance.

The basic objective in developing ASTROS is to provide a state-of-the-art design tool that integrates existing methodologies into a unified multidisciplinary package. Concepts from TSO and FASTOP have been adapted for ASTROS; for example, TSO's capability to simultaneously design to strength, flutter, displacement, and other requirements has been incorporated into ASTROS, as has FASTOP's use of finite element structural analysis.

The distinctive attribute of ASTROS is the scope of conditions it can consider in a design task. Multiple boundary conditions, each permitting a range of analyses (e.g., statics, modes, and flutter) can be treated. Also, for the most part, limits on problem sizes have been removed. A special purpose software environment was constructed that permits this generality and includes a general purpose executive, a scientific data base management system, and a problem oriented control language. This software environment has been discussed in detail in Ref. 8, therefore, minimal mention is made here of its features. Instead, emphasis is placed on the engineering technologies incorporated in ASTROS and on how the environment has been applied to achieve the multidisciplinary capabilities.

Engineering Design Technologies

The design task in ASTROS is the standard one for finding values of *ndv* design variables x which

Minimize

$$F(x) \tag{1}$$

Subject to

$$g_j(x) \leqslant 0, \qquad j = 1,m \tag{2}$$

$$x_i^l \leqslant x_i \leqslant x^u, \qquad i = 1,ndv \tag{3}$$

$F(x)$ is the objective function and is the weight of the structure in ASTROS, although alternative objectives could easily be formulated.

Design variable linking is employed in ASTROS both to reduce the number of design variables and to keep the design from specifying structural sizes that are unrealistic from a manufacturing standpoint. Local or physical variables are related to the global variables through the matrix equation:

$$\{t\} = [P]\{x\} \tag{4}$$

where t is a vector of physical variables and can be any of the following quantities: rod areas, shear element thicknesses, membrane element thicknesses, bar areas and structural inertias, and concentrated masses.

The design variables are such that the element stiffnesses and masses are linear functions of the design variable. For the bar, this requires that the bar area and inertia be coupled by a user specified relationship and that the bending and in-plane element stiffnesses be treated separately. The linearity of the design is exploited in ASTROS by storing the invariant portions of the stiffness and mass matrices and then multiplying these invariant portions by the current design variable value during the assembly of the global matrices.

Composite materials are treated as having independent physical variables for each of the user specified ply directions. This treatment is similar to that of TSO and FASTOP, except that TSO's capability to treat the ply orientation as a design variable has not been incorporated.

Three linking options are available in ASTROS:

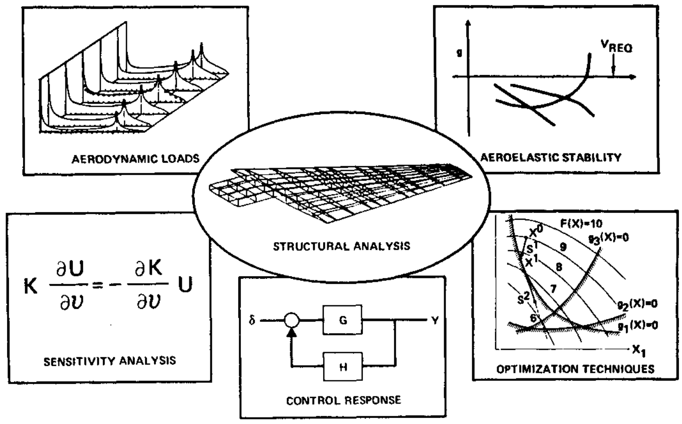


Fig. 1 Engineering design technologies in ASTROS.

No linking. The physical and global design variables are the same. The relevant row in the P matrix has only one nonzero term of unit value.

Regional linking. Each global design variable uniquely defines a group of physical design variables. The rows in the P matrix have only one nonzero term that has a user specified positive value.

Shape function linking. Each physical design variable is the weighted sum of a number of global design variables. The term shape function refers to the fact that this type of linking could be used to define shapes, such as thickness, that is uniform over a wing surface or that tapers linearly with the span station. This emulates the design variables of the TSO procedure and can be used to create designs that vary smoothly over a surface. The relevant row in the P matrix can have an arbitrary number of nonzero values.

Constraints in the design tasks are standard for an aerospace structural design task and include the following: stress-strain; displacement; modal frequency; aeroelastic effects—lift and aileron effectiveness; and flutter response.

Further details on the form of these constraints are given in the following subsections. Figure 1 is a useful illustration for beginning this discussion in that it shows that structural analysis is the central discipline of the ASTROS design procedure and that it is supplemented by steady and unsteady air loads, flutter analysis, sensitivity analysis, control system response, and optimization methodologies.

Structural Analysis

Structural analysis includes both statics and normal modes capabilities. The statically applied loads include mechanical (i.e., discrete forces, moments, and pressures), thermal, and gravity loads. The NASTRAN system has served as a substantial resource in this development. A key attribute of ASTROS is that the input data requirements emulate those of NASTRAN, with enhancements for the design task. NASTRAN terminology has also been adapted liberally to the ASTROS development in that there is considerable replication in the names of modules, data base entities, and solution methods. Although the NASTRAN source code provided an excellent starting point, it required substantial revision to make it compatible with the ASTROS environment and, in many cases, it proved to be expedient in redoing the programming task while retaining the basic algorithms.

The statically applied loads produce deformations that can be included in the design task by placing user defined constraints on the structural deformations and/or the element stresses and strains. The displacement constraints can be imposed as a weighted sum of any number of structural degrees of freedom, thereby permitting the specification of, for example, structural twist and camber. Stress constraints can be imposed using von Mises or Tsai-Wu criteria, whereas strain constraints are imposed through limits placed on the two principal strains in a laminate.

For the modal analysis, lower and/or upper bounds can be imposed on any of the structure's natural frequencies.

Steady Airloads

The USSAERO code of Ref. 7 is used in ASTROS to provide the steady aerodynamic loads and aeroelastic corrections. A number of modifications were required in this code to make it operational in ASTROS:

1) Input data were modified to make them compatible with NASTRAN bulk data formats.

2) The numerous tape units required for intermediate data storage were replaced with data base entities.

3) An aerodynamic influence coefficient matrix capability was inserted to provide the loads due to aeroelastic deformations. This capability, although it represents an approximation in the USSAERO algorithm, is considered a necessity for performing preliminary structural design.

A trim analysis is performed in ASTROS by imposing an unrestrained boundary condition that models an aircraft in steady flight. Invariant aerodynamic unit load vectors are applied to the structure, and inertial effects are included to determine control surface and angle of attack values that permit steady flight at prescribed flight conditions. The stress (or strains) that result from this trimmed condition can be included in the design task, as can displacement limits.

Unsteady Aerodynamic and Flutter Analysis

Two methods are available in ASTROS for computing unsteady aerodynamics. The Doublet Lattice method[6] is used for subsonic velocities, whereas the Constant Pressure method[9] has been implemented for supersonic velocities. As part of the initial processing, invariant matrices that relate forces on aerodynamic panels to panel displacements are calculated at user specified Mach numbers and reduced frequencies. In the design task, these matrices are converted to generalized forces using the natural mode shapes and then applied in the flutter analysis.

The flutter stability analysis is based on the p-k method with an equation of the form:

$$\left[(V/b)^2p^2[M] + [K] - \rho(V^2/2)(p/k[Q^I] + [Q^R])\right]\{u\} = 0 \quad (5)$$

Equation (5) is similar to the equation used in FASTOP with the exception of the p/k multiplier on the out-of-phase portion of the aerodynamic matrix. This change was made to allow the proper evaluation of the aircraft's response at low, highly damped frequencies, such as those required to estimate the aircraft's short period frequency.

The ASTROS flutter constraints are specified in the form:

$$g = \frac{\gamma_{jl} - \gamma_{j\mathrm{REQ}}}{GFACT} \leqslant 0 \qquad j = 1,2,\ldots,nv, \quad l = 1,2,\ldots,nroot \quad (6)$$

where γ_{jl} is a damping value given by $\mathrm{Re}(p)/k$ for the lth root at the jth velocity. $\gamma_{j\mathrm{REQ}}$ is the user-defined required damping value, with the j subscript indicating that the user can specify this requirement to be a function of velocity. Most typically, the selected value would be zero for all velocities. *GFACT* is a scale factor that converts the damping numbers into a range consistent with other constraints in the design task. This is also a user input, with suggested values in the range of 0.1–0.5.

The user specifies that this constraint be satisfied at a series of velocities up to, and perhaps above, the required flutter speed. Of the velocities, 3–10 appear to be adequate. This constraint form represents a synthesis of existing constraint formulations and offers several advantages when combined with the p-k method of flutter analysis:

1) There is no requirement for the computation of the flutter speed. The exact computation of this speed can consume substantial resources.

2) By using the p-k method of flutter analysis, solutions are obtained only at the velocities of interest.

3) The constraint is evaluated at several velocities to handle the appearance of "hump" modes that could become critical at velocities below the required flutter speed. Flutter analysis at flight speeds that are 0.5, 0.75, 0.9, 1.0, and 1.1 times the required speed should be adequate for precluding this undesirable behavior.

4) In a similar fashion, the simultaneous consideration of a number of branches in the flutter solution handles the complication of more than one branch becoming critical. Also, when a number of modes are considered, there is no necessity for tracking a specific mode, with its attendant increase in logic complexity.

5) There is no large penalty associated with the calculation of the $nroot \times nv$ constraints given by Eq. (6) since only the critical γ_{jl} conditions require gradient information. Typically very few such constraints are active for a given design iteration.

Sensitivity Analysis

All sensitivities (i.e., gradients of the objective function and of the constraints) are calculated analytically in ASTROS. The system has been streamlined so that all invariant matrices are computed once and stored on the data base. The sensitivity of the flutter constraint is presented here as an example of these calculations because it is the most complex sensitivity calculation in ASTROS and because it is somewhat novel.

The partial derivative of the constraint given by Eq. (6) with respect to a design variable is

$$\frac{\partial g_{jl}}{\partial x_i} = \frac{1.0}{GFACT}\frac{\partial \gamma_{jl}}{\partial x_i} \quad (7)$$

The gradient of γ_{jl}, in turn, is given by

$$\frac{\partial \gamma_{jl}}{\partial x_i} = \frac{1.0}{k_{jl}}\left(\frac{\partial \mathrm{Re}(p_{jl})}{\partial x_i} - \gamma_{jl}\frac{\partial \mathrm{Im}(p_{jl})}{\partial x_i}\right) \quad (8)$$

The gradients of the eigenvalues are based on Eq. (5), which can be condensed to

$$[F]\{u\} = 0 \quad (9)$$

with an adjoint relation

$$\{v\}^T[F] = 0 \quad (10)$$

Using Eqs. (9), (10), and (5) and the notation $A^R = Q^R$ and $A^I = Q^I/k$, the following derivative expression can be formulated:

$$\{v\}^T\Bigg[\left(\frac{V}{b}\right)^2 p^2\frac{\partial[M]}{\partial x_i} + \left(\frac{V}{b}\right)^2 2p[M]\frac{\partial p}{\partial x_i} + \frac{\partial[K]}{\partial x_i} - \frac{\rho V^2}{2}\left|\frac{\partial p}{\partial x_i}[A^I] + p\frac{\partial[A^I]}{\partial x_i} + \frac{\partial[A^R]}{\partial x_i}\right|\Bigg]\{u\} = 0 \quad (11)$$

This equation is solved for the particular unknown eigenvalue gradients, which in turn yield the constraint gradients through the use of Eqs. (7) and (8).

Optimization

The MICRODOT[10] code has been inserted in ASTROS to perform the redesign task. This algorithm employs a method of modified feasible directions with a polynomial interpolation used in the one-dimensional search.

Multidisciplinary Optimization

In order to successfully apply optimization techniques to practical problems, it is necessary to simultaneously optimize for constraints from many disciplines and/or multiple boundary conditions. In ASTROS, this condition is met by 1) performing analyses in several disciplines in any number of boundary conditions, 2) saving the constraints and the necessary data to compute constraint sensitivities, 3) selecting a subset of "active" constraints, 4) computing the sensitivities of these active constraints with respect to the design variables, and 5) performing the optimization task. This sequence is repeated until the optimization has converged. The ASTROS standard executive sequence (coded in the MAPOL[8] language) and solution control directives are carefully designed to allow multidisciplinary optimization. Because these two "packets" of ASTROS input are unique to the multidisciplinary nature of ASTROS, they deserve additional discussion in this paper.

The standard MAPOL sequence, the counterpart of a NASTRAN DMAP rigid format, has been designed for simultaneous multidisciplinary optimization. Unlike a NASTRAN rigid format, all disciplines are supported by this single executive sequence. As much generality as possible has been coded into the MAPOL sequence so as not to preclude performing analyses from many different disciplines within a single boundary condition. This is desirable for efficiency in that the formation of the system level matrices need only be done once. On the other hand, it is important not to attempt to perform mutually incompatible analyses within the same boundary condition. In order to avoid this pitfall, the solution control syntax within ASTROS has been carefully designed to allow a clear and rigorous definition of a boundary condition as a set of parameters that yield uniquely defined system matrices that can subsequently be used for a number of "subcases" of the desired analysis disciplines.

Examples

In order to demonstrate the multidisciplinary design features of ASTROS, a relatively simple wing model was devised based on the swept wing example of Ref. 11. This model was designed with flutter constraints, a modal frequency constraint, and stress constraints for a steady aeroelastic trim condition. As a second example, a strength design of the Northrop N372-4 generic advanced fighter wing is included to show the handling of larger models and composite materials. This latter model is representative of the size expected to be used in industrial applications of the ASTROS procedure.

Swept Wing Example

The planform of the first example is shown in Fig. 2. It shows the structural model and the aerodynamic models. An attempt is made to be sufficiently detailed in the following description of this model to allow other investigators to generate and test this case.

The structural model divides the structural box into six equally spaced spanwise bays and two equal chordwise segments. The skins on both the upper and lower surface are modeled as isoparametric quadrilateral membrane elements. The ribs and spars are modeled using shear panels with rod elements for spar caps. Rod elements are also used as posts connecting all upper and lower surface nodes. This results in 57 rod elements, 24 quadrilateral membrane elements, and 32 shear panels. The posts are fixed at 0.3 in.^{2}, and the spar caps are initially 8.0 in.^{2} in cross-sectional area. The wing skins and the ribs begin with a thickness of 0.16 in. and the spars with a thickness of 0.32 in. All the elements use the material properties of aluminum having Young's modulus of 10.0×10^6 psi, a Poisson's ratio of 0.30, and a weight density of 0.10 lb/in.^{3}.

Both of the aerodynamic models represent the wing as a flat plate with 50 boxes per surface. The unsteady aerodynamic

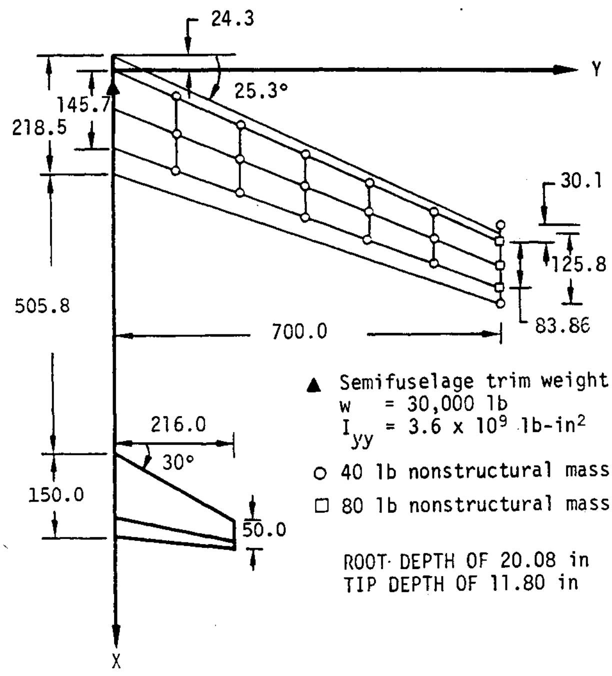


Fig. 2 Model geometry for swept wing example.

model has 10 equally spaced spanwise boxes and 5 chordwise boxes, whereas the steady model has its chordwise boxes spaced in a cosine distribution $\{x_i = [1.0 - \cos(i\pi/5)]/2.0\}$. The steady aerodynamic model has a horizontal stabilizer to enable trim for both lift and pitching moment. Like the wing, the tail is represented as a flat plate with 10 equally spaced spanwise boxes and 5 chordwise boxes distributed using a cosine distribution. The last two boxes in each chordwise strip are used to represent an elevator. There is no structure associated with this tail panel. Both aerodynamic wing models transfer the forces to the structural nodes on the upper surface of the structural box through the use of a linear surface spline. The tail forces for the steady aerodynamics model are rigidly transferred to the center root of the structural box.

For this example, three engineering disciplines and two boundary conditions are applied. The first boundary condition cantilevers the wing root and uses the lowest five normal modes to represent the structure in a flutter analysis. The modal frequency of the first bending mode is constrained to be above 1.5 Hz, and the flutter damping ratio is constrained to be negative for a flight condition of 0.8 Mach number at sea level (530 KEAS). The flutter analysis is performed at 0.75, 0.80, 0.86, 0.91, 0.96, 1.00, and 1.03 times the required flutter speed in order to preclude the appearance of hump flutter modes. The second boundary condition supports the wing at the center root of the structural box, allowing for rigid pitch and plunge modes about this point. The stresses in the wing skin are constrained by

$$\sigma_t \leqslant 60 \text{ ksi}$$

$$\sigma_c \leqslant 50 \text{ ksi}$$

$$\tau_{xy} \leqslant 30 \text{ ksi}$$

during a trimmed aeroelastic, symmetric 4 *g* pullup at 1.25 Mach number at 25,000 ft.

The optimization problem then consists of finding the minimum weight design that satisfies the modal frequency constraint, 35 flutter constraints and 24 wing skin stress constraints. The design variables control the thicknesses of the wing skins, the spar webs and caps, and the wing ribs.

Design variable linking was used to couple elements in each of three spanwise segments, resulting in a total of 12 design variables for structural elements. In addition, the leading edge tip mass was allowed to vary as a 13th design variable representing a mass balance variable.

The design task for the swept wing example converged in 12 iterations is shown in Fig. 3. At the final design, the lower bound frequency constraint was exactly satisfied, and the flutter constraint and some of the wing skin stress constraints were active. The active wing skin stress constraints are shown in Fig. 4. It is clear, therefore, that the final design has been influenced by all of the constraint types imposed. Figure 3 also shows the iteration histories for the cases where the flutter condition is not imposed (frequency and static aerodynamic analyses only) and where no dynamic constraints are imposed. The iteration histories show that the dynamic constraints result in a significant weight penalty relative to the design obtained with only the static aeroelastic constraints.

Figure 4 shows the converged designs obtained for the cases with only static aeroelastic constraints and with the frequency and flutter constraints. The dynamic constraints have generally thickened the structure over the entire span and the mass balance variable is nearly two orders of magnitude larger than its final value in the static case. Table 1 is included for completeness and shows the rigid and flexible stability derivatives used to trim the aircraft at the final design points.

N372-4 Example

The second example problem is the strength design of the N372-4 advanced fighter wing. The geometry of the wing model is shown in Fig. 5 with the y axis denoting the streamwise flow direction. The structural model has 492 nodal points. The wing substructure is modeled using four-noded

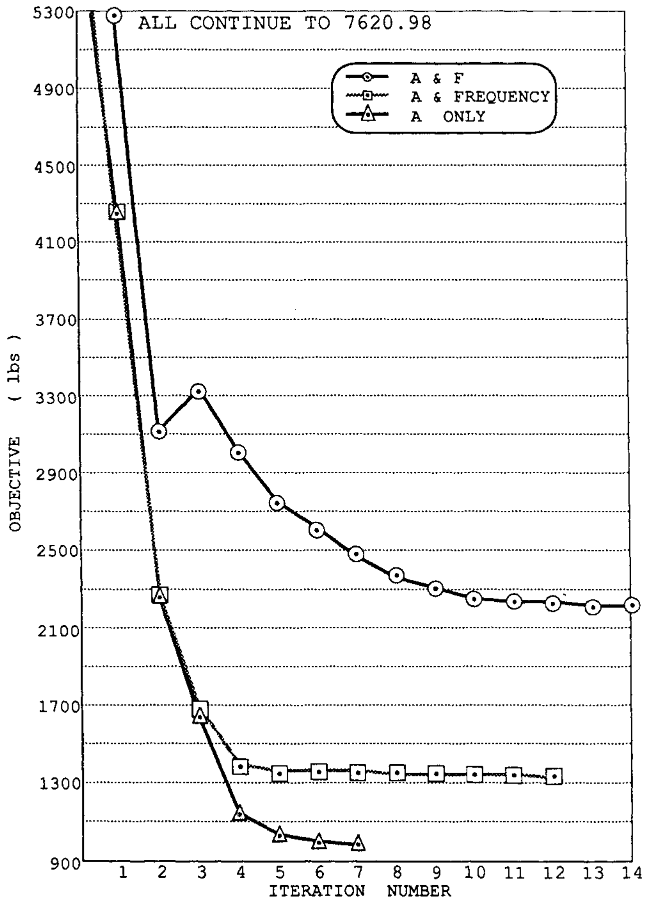


Fig. 3 Swept wing example iteration history.

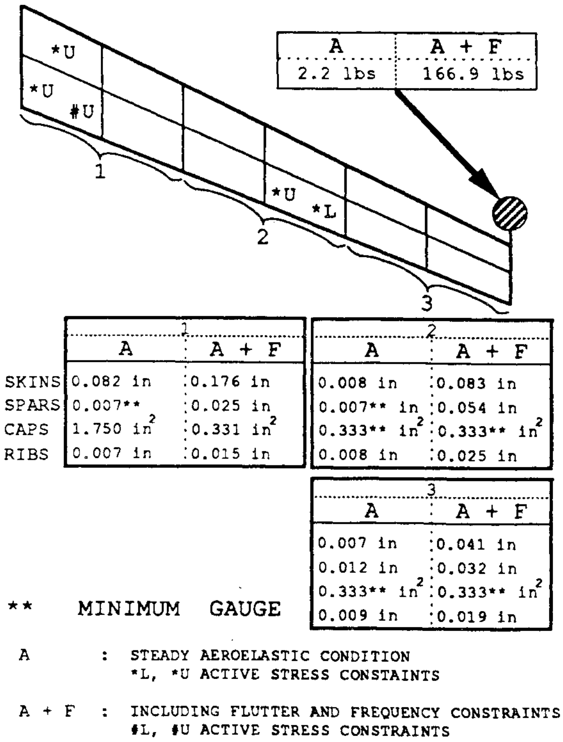


Fig. 4 Swept wing example design results.

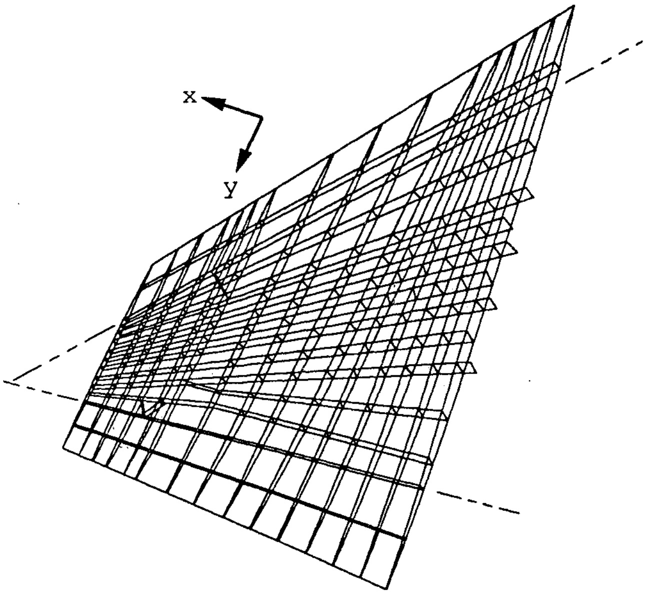
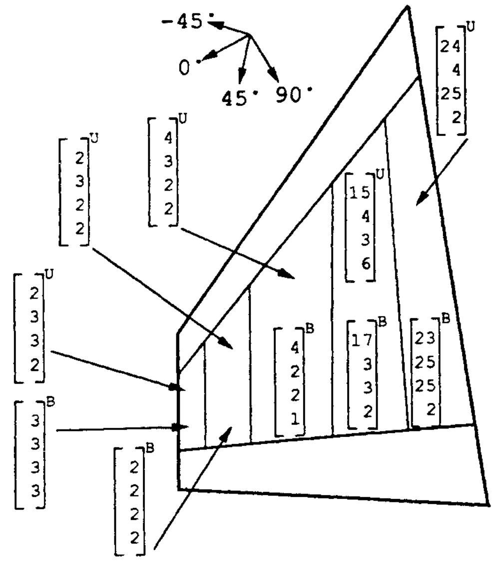


Fig. 5 Finite element representation of the N374-2 wing concept.

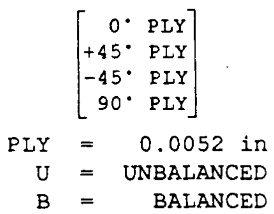
Table 1 Swept wing example stability derivatives at the final design points

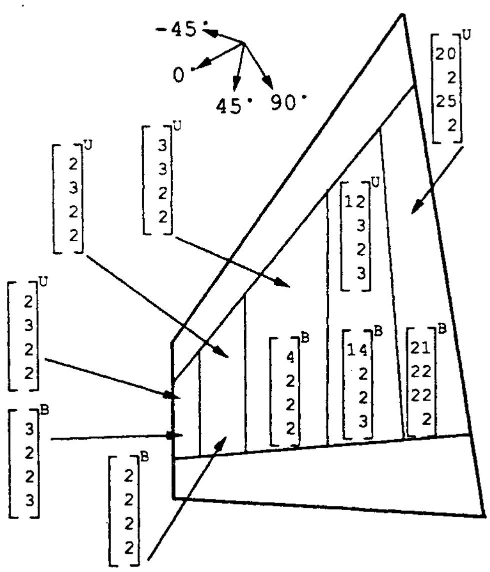
	Supersonic $M = 1.25$		
		Flexible	
	Rigid	Aero only	Aero + flutter
C_{L_α}, 1/deg	0.0908	0.0641	0.0718
$C_{L_{\delta_e}}$, 1/deg	0.0058	0.0062	0.0062
C_{M_α}, 1/deg	−0.0551	−0.1259	−0.1307
$C_{M_{\delta_e}}$, 1/deg	−0.0240	−0.0236	0.0231
α_{trim}, deg	——	5.900	5.174
$\delta_{e\,\text{trim}}$, deg	——	−32.94	−30.54

isoparametric plate elements having only membrane stiffness. The upper and lower surface wing skins on the leading- and trailing-edge flaps are also modeled using this type of element representing composite material having ply orientations of 0, ± 45, and 90 deg, as shown in Figs. 6a and 6b. The composite wing skins on the torque box were modeled using isoparametric quadrilateral membrane elements and triangular membrane elements. Each ply direction is treated as a separate element. A static load representing the rigid air load experienced during a symmetric 13.5 g pullup at Mach 2.5 at 50,000 ft is applied over the entire wing. The principal strains in the wing skins on the torque box are limited to ± 0.005.



a) Upper surface skin ply count





b) Lower surface skin ply count

Fig. 6 N372-4 design results.

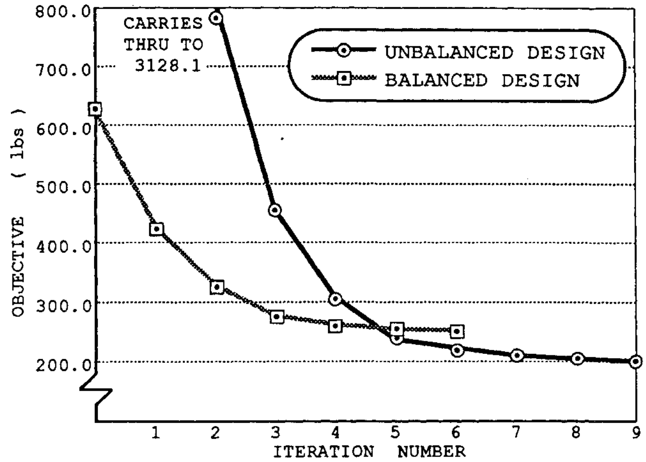


Fig. 7 N372-4 example iteration history.

The design problem, then, consists of finding the minimum weight design that satisfies the 612 strain constraints. Two different design variable linking schemes were used on this model. The first treats the thickness of each layer (a layer being made up of all plies having a particular fiber orientation) in each of five spanwise segments as design variables. The upper and lower surface layer thicknesses are treated separately, resulting in 40 design variables. The second linking scheme requires that the design be balanced (equal number of +45 and −45 plies). This linking scheme results in 30 design variables. The linking schemes are shown in more detail in Figs. 6a and 6b.

The design task for the unbalanced linking scheme converged in eight iterations and is shown in Fig. 7. Based on the results obtained from the first linking scheme, the initial design variable values for the balanced design were started at 20% of the initial values previously used. The resulting optimization converged in six iterations. Figures 6a and 6b show the final ply count for each fiber orientation for the two linking schemes. This ply count is obtained based on a ply thickness of 0.0052 in., rounding up for any fractional ply. The two designs appear to give reasonable results in that the unbalanced design tends to favor the −45-deg fiber orientation inboard. The balanced design trades some 0-deg plies for the required increase in +45-deg plies inboard; whereas outboard, the design tends to reject both +45- and −45-deg orientations in favor of 0- and 90-deg plies. Near the tip, the balanced design has, in some cases, fewer plies than the unbalanced design for the same spanwise segment. This counter-intuitive design probably results because the objective sensitivity for the tip segments is so much smaller than that of the inboard segments.

Conclusions

The examples presented in the preceding section demonstrate that the multidisciplinary optimization capabilities of the ASTROS procedure are operational. No small set of examples, however, can fully reflect the wide range of capabilities in ASTROS to handle other factors, including thermal loads, composite materials, and multiple boundary conditions. Any number of constraints for any number of boundary conditions in any or all of the statics, normal modes, static, and dynamic aeroelastic response disciplines can be imposed on general finite element structural models. A variety of methods to link design variables and to delete constraints allows for the tractable optimization of very large models with many constraints. The ability to simultaneously consider many constraints from each of several disciplines allows the designer to develop nonintuitive solutions to the complex design problems resulting from multidisciplinary constraints placed on modern aerospace structures.

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