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ASTROS - A MULTIDISCIPLINARY AUTOMATED STRUCTURAL DESIGN TOOL

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INTRODUCTION

ASTROS (Automated STRuctural Optimization System) is a finite-element-based multidisciplinary structural optimization procedure developed under Air Force sponsorship to perform automated preliminary structural design. The design task is the determination of the structural sizes that provide an optimal structure while satisfying numerous constraints from many disciplines. In addition to its automated design features, ASTROS provides a general transient and frequency response capability, as well as a special feature to perform a transient analysis of a vehicle subjected to a nuclear blast.

The motivation for the development of a single multidisciplinary design tool (Figure 1) is that such a tool can provide improved structural designs in less time than is currently needed. The role of such a tool is even more apparent as modern materials come into widespread use. Balancing conflicting requirements for the structure's strength and stiffness while exploiting the benefits of material anistropy 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 their insight into the overall task.

OBJECTIVES

- AN AUTOMATED TOOL FOR PRELIMINARY STRUCTURAL DESIGN
- EMPHASIZE INTERDISCIPLINARY FEATURES OF THE DESIGN TASK
- PROVIDE A NATIONAL RESOURCE

PAYOFFS

- IMPROVED COMMUNICATION AMONG DESIGN TEAM MEMBERS
- IMPROVED DESIGN
- REDUCED DESIGN TIME

Figure 1

ENGINEERING DISCIPLINES

At the core of the ASTROS engineering disciplines (Figure 2) is finite-element structural analysis. This central analysis discipline is augmented by steady aerodynamic loads analysis, unsteady aerodynamics and aeroelastic stability analysis, as well as a limited control response capability. In addition, the automated design features of ASTROS include an analytical sensitivity analysis for the available design constraints and a battery of optimization methods.

The development of the ASTROS system has been predicated on the use of existing software resources whenever possible. The NASTRAN (Ref. 1) system has served as the most substantial resource for the ASTROS development although in many cases, it proved expedient to program the NASTRAN algorithm rather than modify the NASTRAN code and, in all cases, substantial modification of the NASTRAN software was required. USSAERO (Ref. 2) and MICRO-DOT (Ref. 3) played a similar role for the steady aerodynamic analysis and optimization methods, respectively, although fewer modifications were made to integrate them. In addition to these software resources, earlier automated design systems served to guide the design of the ASTROS system in the area of multidisciplinary optimization. Most notable among these are the TSO (Ref. 4) and FASTOP (Ref. 5) systems.

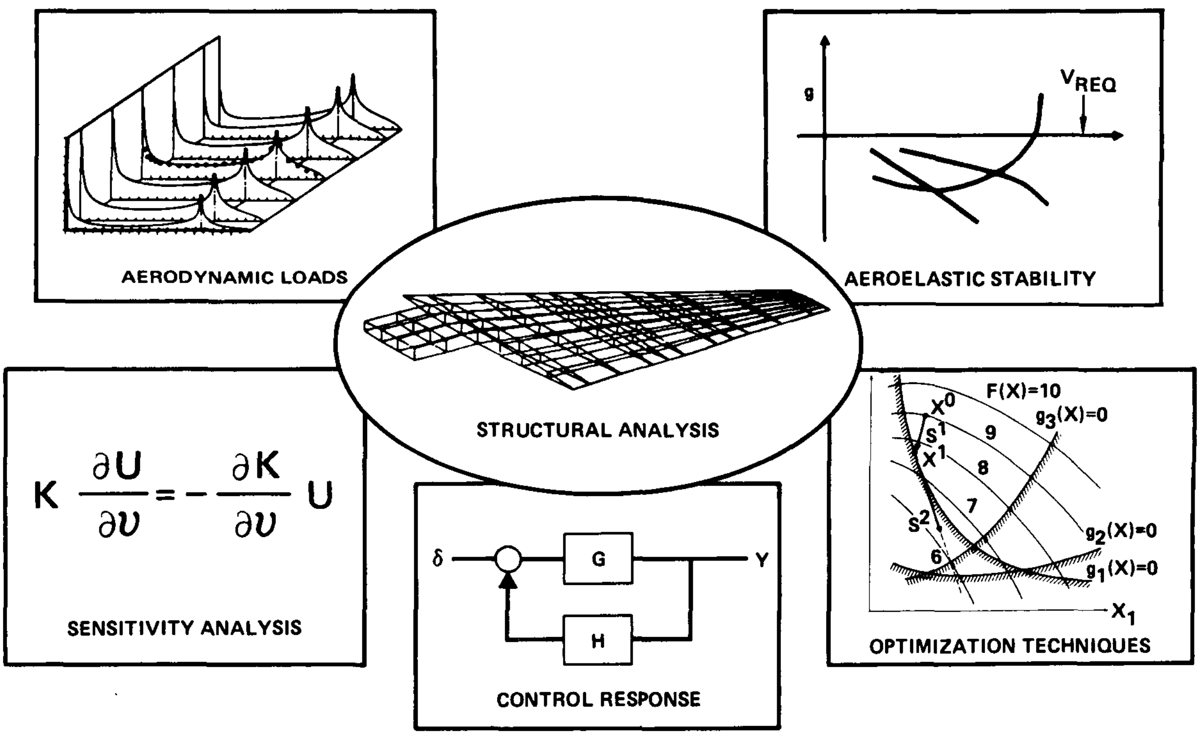

Figure 2

STRUCTURAL ANALYSES

The structural analyses in ASTROS (Figure 3) include statics, normal modes, transient response and frequency response using either modal or direct coordinates. The statically applied loads can be composed of any combination of mechanical (i.e., discrete forces, moments and pressures), gravitational or thermal loads.

In addition to the structural analyses, the steady aerodynamic loads capability in ASTROS is used to generate aerodynamic loads and aeroelastic corrections which are then used to perform symmetric or antisymmetric aeroelastic trim analyses. Finally, a pair of unsteady aerodynamics analyses is used to provide a p-k flutter analysis capability. The subsonic unsteady aerodynamics uses the Doublet Lattice Method (DLM) (Ref. 6) while the supersonic aerodynamics uses the Constant Pressure Method (CPM) (Ref. 7) The unsteady aerodynamics analyses are also used to provide harmonic gust loads for the frequency response and to provide frequency dependent aerodynamic forces for the nuclear blast analysis.

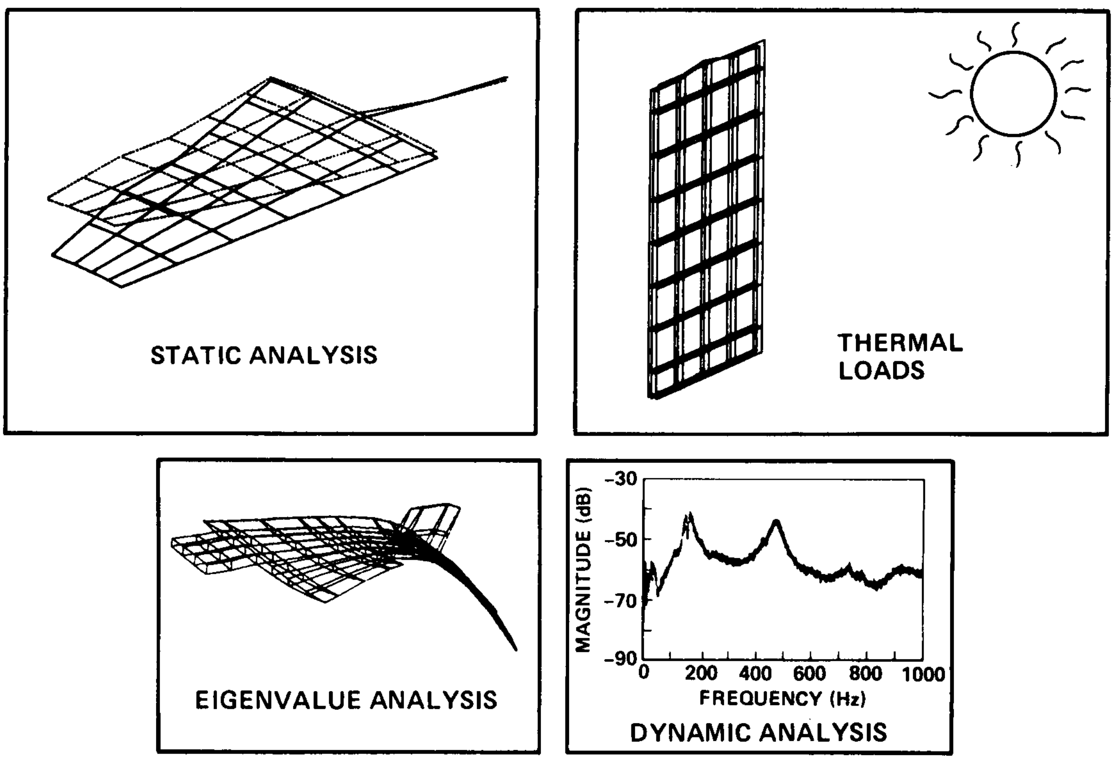

Figure 3

DESIGN PARAMETERS

The local or physical design variables in ASTROS (Figure 4) are such that the 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 extensional behavior be treated separately. ASTROS supports three methods of design variable linking, in which the physical variables are linked to global variables that are actually used in the redesign process. The linking schemes include unique linking and physical linking, in which the global variable controls one or more local variables, and shape function linking in which each local variable is a linear combination of several global variables. In the latter case, the global variables are weighting factors on a "shape" such as a linear taper or a uniform thickness distribution.

The design constraints in ASTROS are standard for an aerospace structural design task and include stress, strain and displacement constraints for statics and/or static aeroelastic disciplines, modal frequency constraints for a normal modes analysis, aeroelastic effectivenesses for the steady aeroelastic analysis discipline and flutter constraint for the aeroelastic stability analysis. Any or all of these constraints types and any number of each type may be combined in a single optimization run in order to achieve an optimal design satisfying all the required design constraints.

DESIGN VARIABLES

- ROD AREAS
- SHEAR ELEMENT THICKNESSES
- MEMBRANE ELEMENT THICKNESSES
- BARS
- CONCENTRATED MASSES

CONSTRAINTS

- STRESS-STRAIN
- DISPLACEMENT
- MODAL FREQUENCY
- AEROELASTIC EFFECTS
  - LIFT EFFECTIVENESS
  - AILERON EFFECTIVENESS
  - DIVERGENCE SPEED
- FLUTTER RESPONSE

Figure 4

MULTIDISCIPLINARY OPTIMIZATION

The effective application of automated optimization methods to structural design requires the simultaneous consideration of all conditions that are critical in determining the final design. Figure 5 presents a schematic diagram of the ASTROS program flow for the automated design task. It indicates that there are three phases to the design task in ASTROS. In the first phase, the required engineering analyses are performed for the current design. Any number of boundary conditions may be applied and within each boundary condition any number of disciplines (i.e., statics, normal modes, etc.) may be analyzed. Further, any number of "subcases" (e.g., load conditions or flight conditions) may be analyzed in each discipline. As indicated in the figure, each of these analyses generate constraints that must be satisfied for the design to be considered acceptable.

In the second phase, those constraints that are most critical for the current redesign are chosen and their sensitivities computed. This constraint screening process is desirable in order that the optimization remain tractable while still capturing the critical design constraints. An important benefit of such a step is that entire boundary conditions or disciplines may be eliminated from the computationally intensive sensitivity evaluation. Finally, in the third phase, the information on the objective function (which is the weight in ASTROS) and the active constraints and their sensitivities are used to perform a redesign to satisfy the constraints while minimizing the objective function.

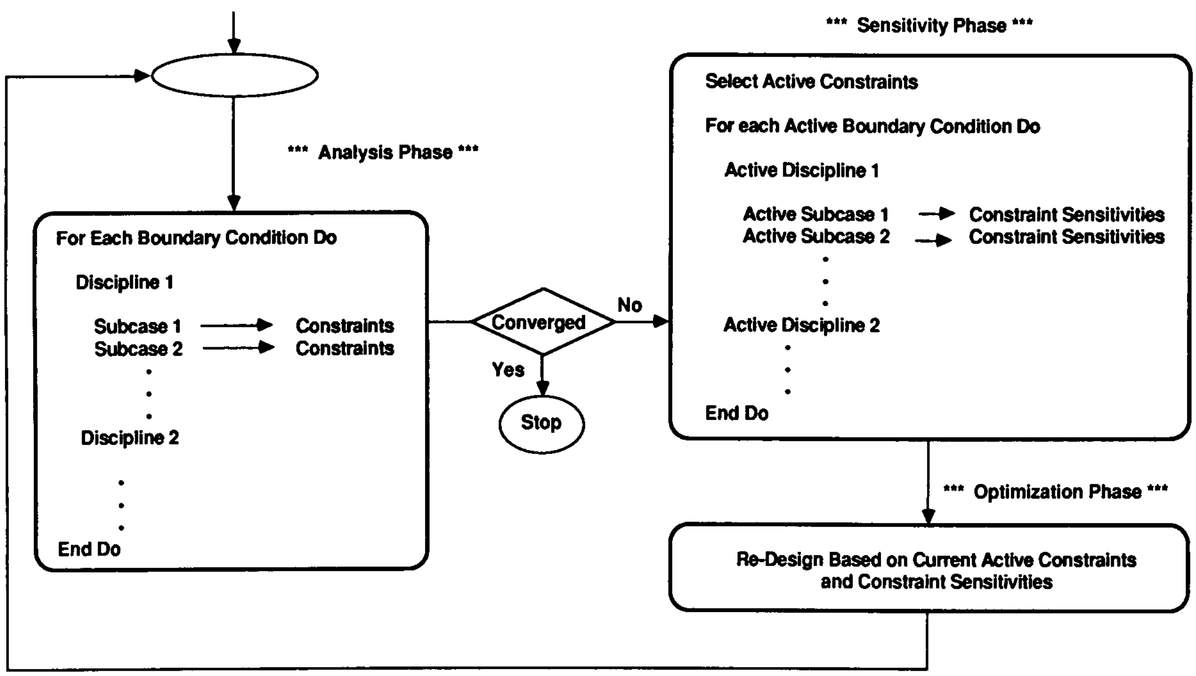

Figure 5

AN ARCHETYPICAL ASTROS APPLICATION

The ASTROS system has been delivered to the Air Force and is available for application to "real world" preliminary structural design problems. Figure 6 shows one such problem that may be considered archetypical of the problem for which the ASTROS procedure was developed. Given the structural configuration and materials represented by a finite-element model and a set of design requirements, the ASTROS procedure will determine the structural sizes of the designed elements to minimize the weight of the structure while satisfying the potentially numerous multidisciplinary constraints.

One should not limit ASTROS, however, by this single example. The true potential for an optimization system such as ASTROS lies in its ability to generate additional information that allows a rapid assessment of the quality of competing design concepts through the comparison of "optimal" solutions. In addition, ASTROS enables the designer to accommodate conflicting constraints at a much earlier stage in the design cycle, thereby avoiding potentially serious conflicts later. Finally, the use of formal optimization in the preliminary design enables the designer to develop nonintuitive solutions to the complex interdisciplinary design problems that can occur in modern aerospace structural design.

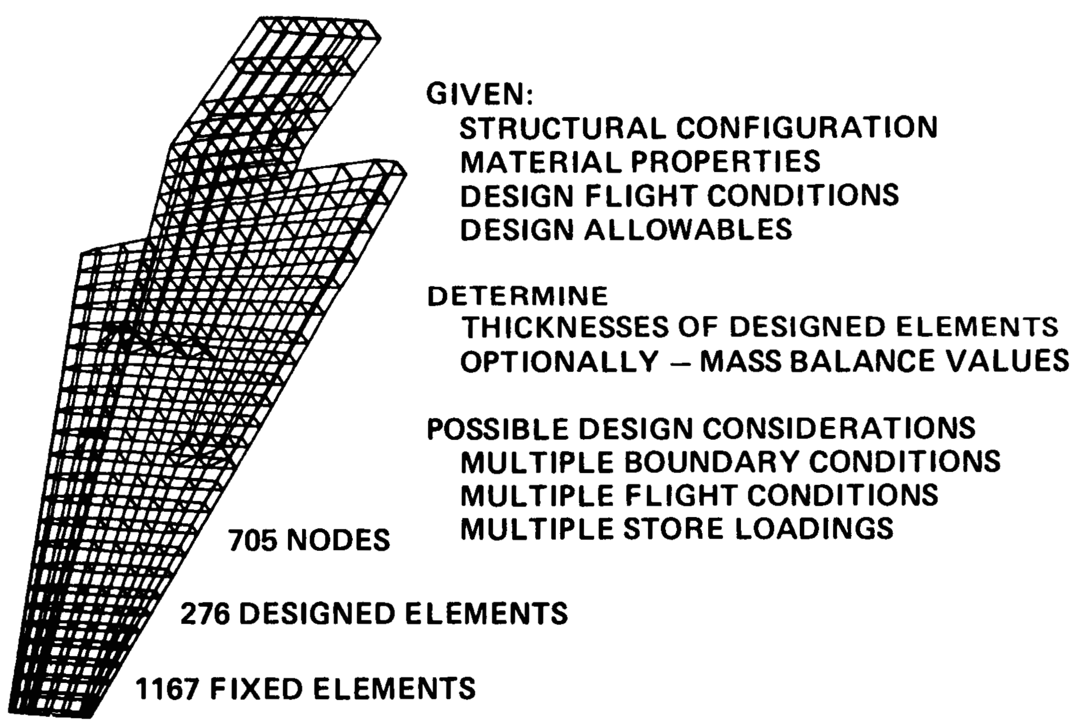

Figure 6

INTERMEDIATE COMPLEXITY WING EXAMPLE - GEOMETRY

As an example of the ASTROS system, the Intermediate Complexity Wing (ICW) problems that were developed to test the FASTOP system were duplicated in the ASTROS system. These tests both confirm the accuracy of the ASTROS system and serve to highlight the differences in the treatment of multidisciplinary constraints in these two systems.

The ICW structural model, shown in Figure 7, uses quadrilateral and triangular membrane elements to model the composite wing skins and shear panels to model the substructure. Rod elements are used as posts to complete the interconnection of the upper and lower surfaces. The model is cantilevered at the root and all rotational degrees of freedom are constrained at each node. The substructure material is modeled as aluminum, while the wing skins are made of a graphite/epoxy composite.

No. of Nodes	No. of Elements		No. of DOF's	
88	39	Rods	294	Constrained
	55	Shear Panels	234	Unconstrained
	62	Quadrilateral Membrane	528	Total
	2	Triangular Membrane		
	158	Total		

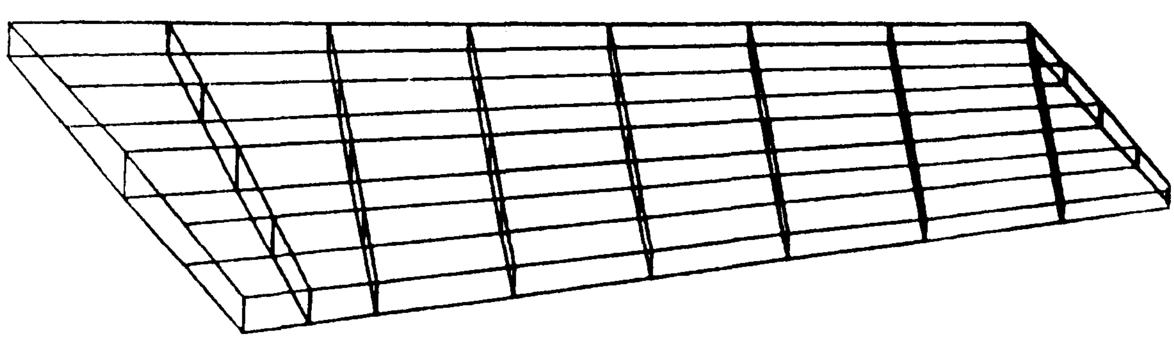

Figure 7

DESIGN REQUIREMENTS FOR THE INTERMEDIATE COMPLEXITY WING (ICW)

The design problem (Figure 8) minimizes the weight of the structure subject to the material stress allowables and gauge constraints under two static loads representing a subsonic and a supersonic air load and subject to a minimum required flutter speed of 925 KEAS at Mach 0.80. To examine the behavior of different design variable linking options, two different design models were used in ASTROS. The first was developed to emulate the FASTOP results and links the upper and lower skin surfaces for each ply orientation (128 design variables), treats each spar element as a separate design variable (23 design variables) and links all the posts and rib shear panels together as two additional design variables for a total of 153 global design variables. In the second linking scheme, the ASTROS shape function design variable linking option was utilized. The shapes for each ply orientation for the wing skin elements were uniform, a linear spanwise taper, a quadratic spanwise taper and a linear chordwise taper with the upper and lower surfaces linked as before (16 design variables). A uniform and a linear spanwise taper were used for each of the three spars (6 design variables), and the posts and ribs are linked as before for a total of 22 shape function design variables and two physically linked design variables.

- **FLUTTER CONSTRAINTS**

  $V_f \leq 925$ knots

  $\rho = .0023769$ slugs/ft^3

  $M = 0.80$

- **ISOTROPIC MATERIAL IN SUBSTRUCTURE**

  $E = 10.5 \times 10^6$ psi $\qquad \rho = 0.10$ lb/in^3

  $\nu = 0.30$ $\qquad t_{min} = 0.02$ in

  $\sigma_T \leq 67$ ksi

  $\sigma_C \leq 57$ ksi

  $\tau_{xy} \leq 39$ ksi

- **ORTHOTROPIC MATERIAL IN SKINS**

  $E_1 = 18.5 \times 10^6$ psi $\qquad \nu_{12} = 0.25$ $\qquad \rho = 0.055$ lb/in^3

  $E_2 = 1.6 \times 10^6$ psi $\qquad G_{12} = 0.65 \times 10^6$ psi $\qquad t_{min} = 0.00525$ in

  $X_T = X_C = Y_T = Y_C = 1.15 \times 10^5$ psi

  $S \leq 1.0 \times 10^{15}$

Figure 8

ICW STRENGTH DESIGN RESULTS

Figure 9 presents the ply counts for the final strength design obtained from FASTOP, ASTROS using "FASTOP" design variable linking (labeled "153" in the figure) and ASTROS with shape function linking (labeled "ELIST" in the figure). As expected, the final material distribution for ASTROS and FASTOP using identical design variable linking are very similar despite the use of mathematical programming methods in ASTROS and fully stressed design methods in FASTOP. The final objective function values do not compare as well but the ASTROS objective function represents a design with continuous design variables while FASTOP rounds up to the next whole ply prior to the objective function computation. In general, however, the agreement between ASTROS and FASTOP for this case gives confidence that the ASTROS system is functioning properly.

The shape function results are interesting in their own right even though it is not directly comparable to any external results. In this case, the limitations imposed by using shape functions results in the optimizer's selection of all zero degree fibers to satisfy the stress constraints with all other orientations going to minimum gauge. This result is illustrative of an "optimal" solution given external constraints like manufacturing limits or limits in the rates of ply drop-off. Further, compared to the FASTOP linked result, it clearly represents a radically different method of addressing the same set of physical constraints.

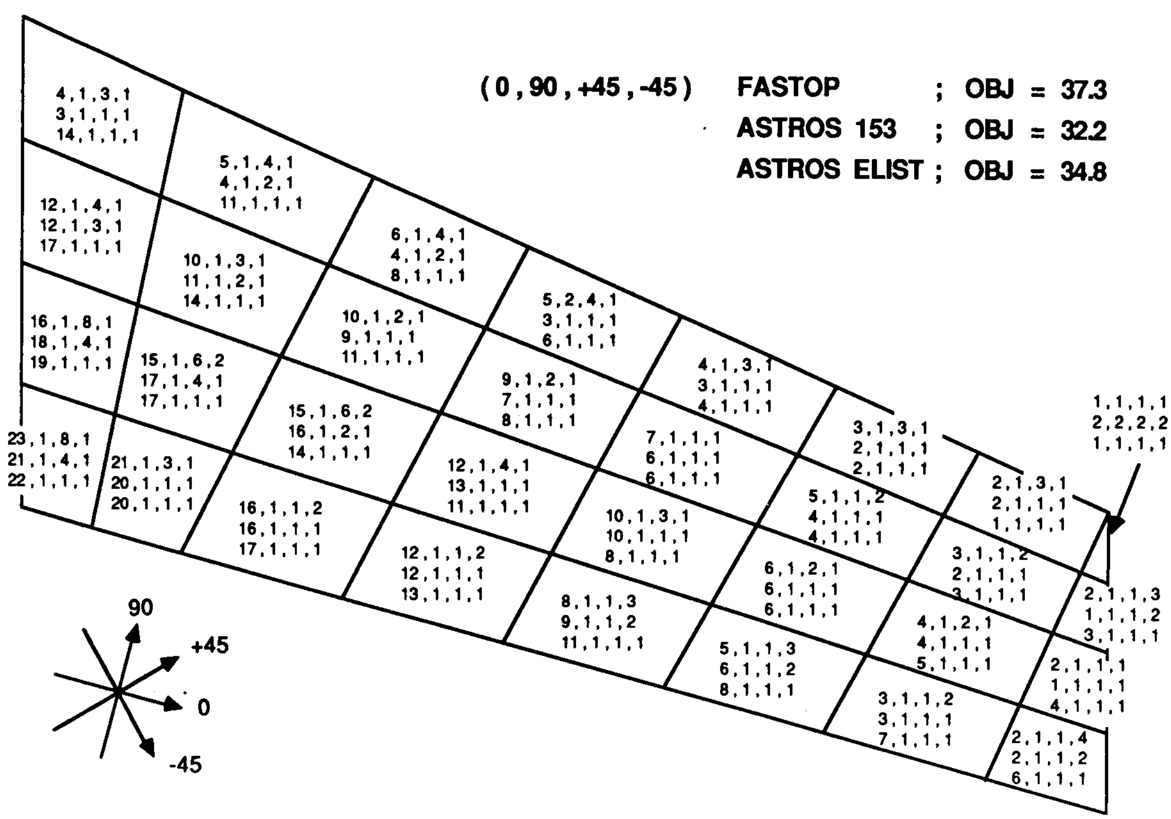

Figure 9

ICW STRENGTH/FLUTTER DESIGN RESULTS

Figure 10 presents the ply counts for the same three final designs obtained for the combined strength and flutter optimization. Unlike the case where the strength constraints were considered alone, there is little agreement between FASTOP and ASTROS in the resultant final design. The ASTROS result is significantly lighter even when the restrictive shape function variables are used. There are several possible explanations for the differences. First, and most important, is that ASTROS treats the strength and flutter constraints simultaneously at each iteration; whereas, the FASTOP algorithm treats each constraint type sequentially and applies ad hoc move limits on "flutter critical" and "strength critical" elements in between each cycle. It is known that such an algorithm does not necessarily lead to an optimal solution. A second important factor is that the two systems use different methods to couple the aerodynamic and structural deflections and may, therefore, produce different flutter results for the same model. A necessary check that has not been made is to analyze the ASTROS result in FASTOP to see if it meets the flutter requirement. Finally, the objective function computations are different due to the rounding to whole plies that takes place in FASTOP at each cycle of the optimization.

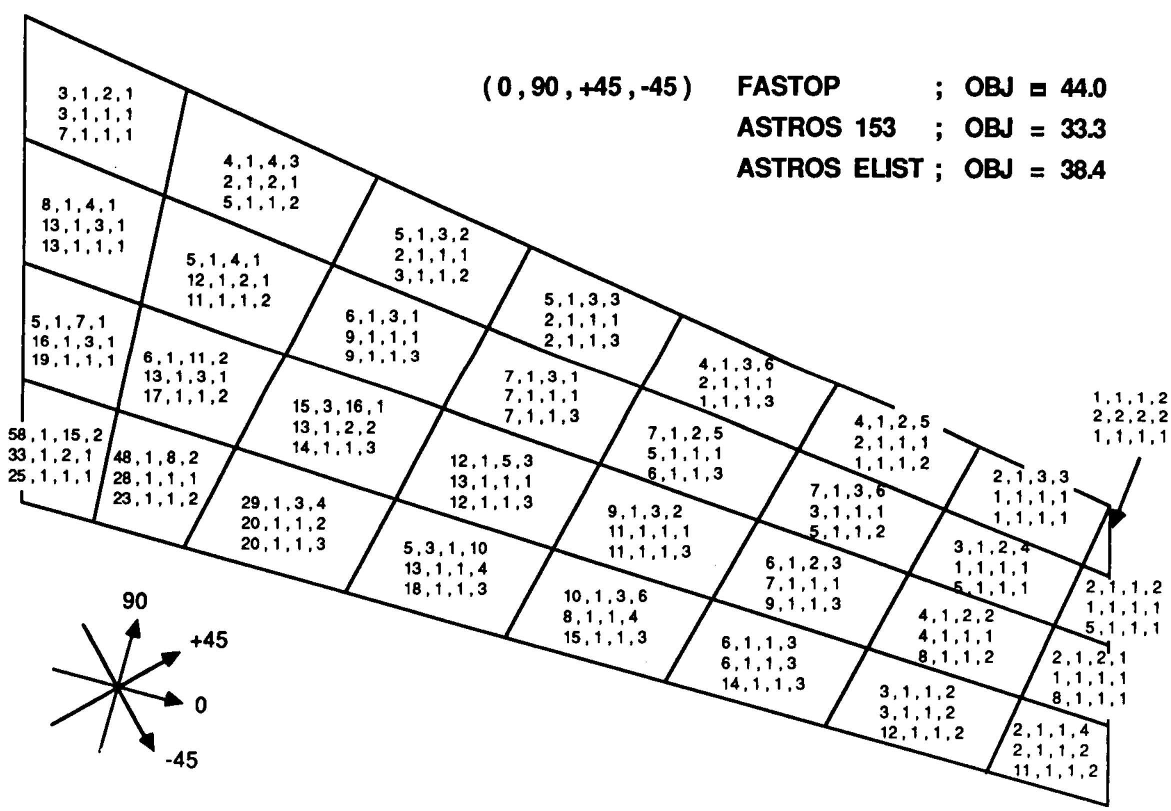

Figure 10

SOFTWARE CONTRIBUTIONS OF ASTROS

While the software development in ASTROS depended to a large degree on existing software systems, several noteworthy software contributions (Figure 11) were made in the course of the ASTROS development. Most importantly, an architecture was designed that is suited to multidisciplinary analysis and design. It includes a data base management system tailored to handle the engineering data common to matrix structural analysis methods, as well as to the design task. Another important contribution was the design of the ASTROS executive system and its control language, MAPOL (Matrix Abstraction Problem Oriented Language). Together, these provide nearly limitless flexibility in the application of the ASTROS system to tasks not explicitly designed into the procedure. Also important to the successful development of ASTROS was the exploitation of modern computer environments to integrate the software components developed by a dispersed development team and to manage the resultant system. The flexibility offered by the microcomputer to tailor the computer environment made the software management task tractable without a great deal of effort on the part of the developers.

- Framework For Multidisciplinary Analysis and Design
- Engineering Data Base
- High Level Executive System
- Obsolescence of Rigid Formats
- Unlimited Problem Size
- Exploitation of Microcomputers
- Built In Maintenance Features
- Improved Special Purpose Utilities
- Balanced Approach to Software Design
- Integration of Dispersed Development Team

Figure 11

ENGINEERING CONTRIBUTIONS OF ASTROS

In addition to its software contributions, ASTROS has made several key engineering contributions (Figure 12). The first and most important is the system's ability to perform multidisciplinary design. This means a simultaneous consideration of an unlimited number of constraints from a set of disparate engineering analyses to obtain an "optimal" design that meets very general design criteria. Included in this capability is an analytical sensitivity analysis for all the constraint forms, the incorporation of approximation concepts in a production optimization code and a number of design variable linking schemes. All these features result in the tractable optimization of large problems with many constraints from many disciplines.

Other engineering contributions include an innovative approach to the treatment of flutter constraints which does not require the expensive computation of the flutter speed and avoids the complex problems of tracking multiple flutter branches. ASTROS also includes a public domain quadrilateral bending plate element, incorporates improvements to dynamic reduction techniques and has integrated advanced aerodynamics for nuclear blast response analysis with finite-element structural analysis methods. Finally, ASTROS has adopted an improved supersonic unsteady aerodynamic analysis (CPM) and has included the computation of aerodynamic influence coefficients for the static aeroelastic analysis.

- Multidisciplinary Analysis and Design
- Analytical Sensitivity Analysis
- Approximation Concepts in a Production Code
- QUAD4 Element in the Public Domain
- Improved Supersonic Unsteady Aerodynamics
- Innovative Flutter Design Technique
- Nuclear Blast Analysis with Finite Elements and Advanced Aerodynamics
- Advanced Methods of Dynamic Reduction
- Design Variable Linking
- Aerodynamic Influence Coefficients For Static Aeroelasticity

Figure 12

CONCLUSIONS

The ASTROS system development is complete in the sense that the basic features desired in the system are in place and the code is available for application to real world problems. It provides a very general tool to perform automated preliminary structural design subject to multidisciplinary constraints. In addition to its design features, the code has been provided with a suite of dynamic analyses and special purpose analyses to improve its utility as a unified tool for structural design.

At this point, however, the ASTROS system is immature from a software standpoint and has known bugs with additional problems sure to show up with increased use. In anticipation of these problems, the Air Force has funded an enhancement effort that will address the quality assurance and software maintenance issues, as well as make several enhancements to the engineering aspects of the code. Among the enhancements are the inclusion of a triangular bending plate element, additional steady aerodynamic analysis features, improved aeroelastic analysis and enhanced treatment of the control system. Also included in this effort is the inclusion of general, multidisciplinary optimality criteria methods as an alternative to the current mathematical programming methods for the redesign task in ASTROS.

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