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Applications of Structural Optimization Methods to Fixed-Wing Aircraft and Spacecraft in the 1980s

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Introduction

This report summarizes the survey of the practical applications of structural optimization methods in the U.S. aerospace industry. Since there was an excellent review[1] on applications of optimization to flight vehicles prior to 1980, we limit this summary to typical accomplishments during the 1980s. The examples presented are based on the inputs provided by experts in the U.S. Aerospace industry. This report was prepared based on the belief that, while proprietary software might not cross the company boundaries, basic philosophy and technology can and should be shared to minimize the risk and to put future effort in proper perspective.

The most notable difference in the '80s is the more widespread acceptance of structural optimization as one of the design tools that support practical structural design. The period in which design engineers kept a "suspicious and respectable distance" from structural optimization may finally be ending. Another significant difference is the development of large scale software tools for production application. Since most of these software tools started appearing in the last half of the 1980s, we are looking only at the beginnings of structural optimization's real impacts on aerospace structural design.

Introduction of new tools in the industrial design environment is by no means simple. It requires the dedicated effort of motivated groups of foresighted engineers to obtain management support to apply new tools within the tight time and resource constraints. Theoretical advancements and the development of software tools by both commercial vendors and by the government are not enough for applications in a production environment. The tools and methodology must be integrated in the existing engineering procedures effectively, without causing abrupt disturbances to the organizational structure. Often, these optimization methods, especially the large scale, interdisciplinary tools, require some modifications to the existing engineering processes. Overcoming tradition and inertia under production schedule restraints is a very difficult task. Nonetheless, these methods, and the tools that embody them, are beginning to be used.

Experiences gained in optimization tool development in the '70s and early '80s led to the recognition of the fundamental differences between the implementation of analysis and

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design capabilities. In creating an analysis model, we reduce a wide variety of objects into simple concepts so that the differential or integral equations can be solved conveniently. Frequently, objects irrelevant to the responses are over-simplified or even discarded in this abstraction process. In design, on the other hand, we move in a different direction, selecting appropriate concepts, components, materials, sizing, etc. from a large number of varieties, to achieve desirable characteristics in the final structural system. Factors that provide direction in this selection process include: company tradition, product lines, design manuals or standards, inputs from production, maintenance or sales departments and the background of responsible engineers. For these reasons, a computerized design process must be tailored to the specific environment of each company.

Currently, the two most important aspects of this tailoring are seamless incorporation of structural optimization in the overall aerospace design/production process and multi-disciplinary integration aimed at ultimate performance optimization of the final products. Notable and subtle differences among companies are observed in the integration of structural optimization into the engineering process, and each form is justified in its own right. In fact, there may not be one best implementation plan universally applicable to every company; instead each organization has had to be creative in finding an approach to satisfy their specific requirements. In each case, responsible engineers have had to take some risks to open up new frontiers.

The material compiled in this report represents some, but by no means all, such endeavors. The examples both provide insight into the individual philosophies and stimulation for more widespread applications of structural optimization. Even though the cases cited in this report may look similar, careful readers would notice subtle but important differences in their basic philosophy as well as in their technical approaches. This report was loosely divided into six sections:

I. Modern and Innovative Applications of FASTOP and TSO
II. Integration of Conventional and New Technology
III. Aggressive Applications of New Tools
IV. Structural optimization in a Multidisciplinary Design System
V. Other Developments
VI. Concluding Remarks

The boundaries of the first four sections are fuzzy and may not even be labeled correctly, but cases are categorized into groups simply to make this report readable.

I. Modern and Innovative Applications of FASTOP and TSO

I.1. Grumman's COGS and Applications

The most notable contribution made by Grumman in structural optimization is the development of the FASTOP (Flutter and Strength Optimization Program) computer code under the support of USAF during 1973-1981. Based on the structural design tradition accumulated previously, Grumman used the experiences of FASTOP development and its applications to build an integrated structural design system.[2] Development of COGS (COmprehensive Graphics System), an in-house structural design/analysis system, began in 1975 and continued throughout the 1980s. The three primary components of COGS are:

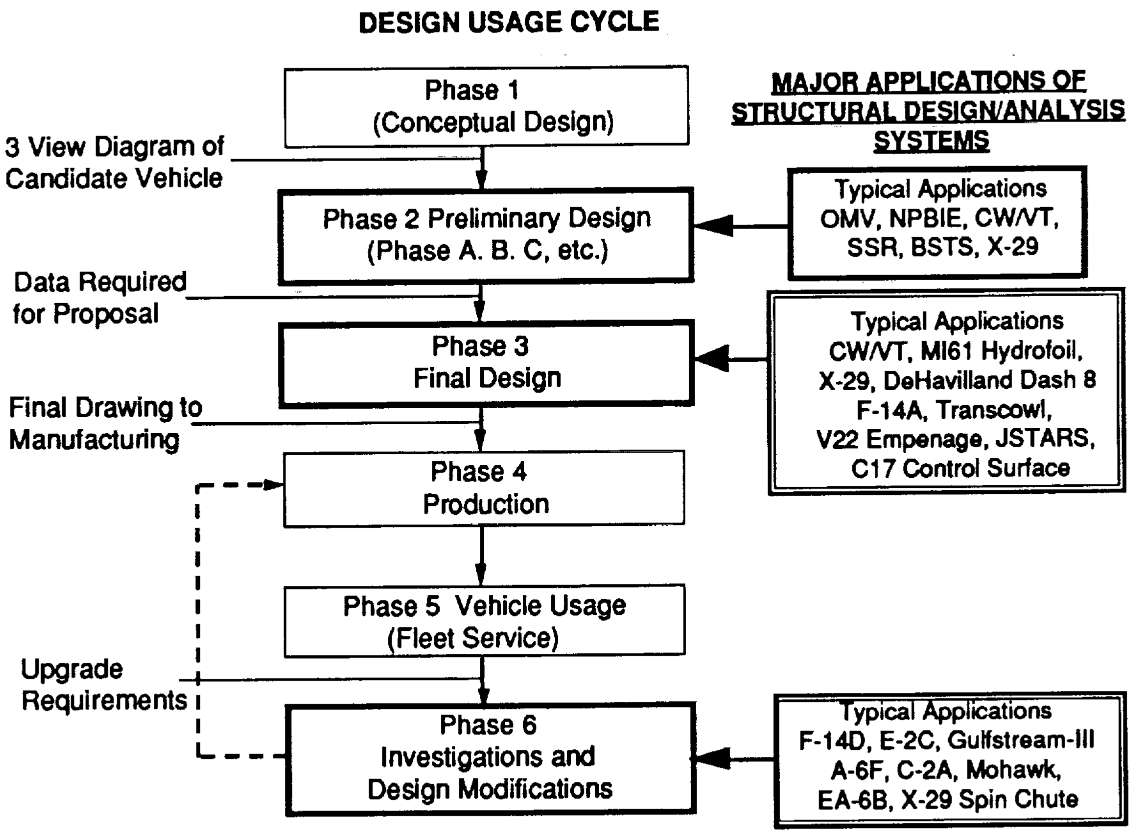


Figure 1 Six Phases in the Design-Evolution Cycle

ASTRAL (a finite element analysis program), COMAP (a matrix manipulation language) and a suite of interactive graphics packages. Important portions of FASTOP were incorporated into COGS by 1983. To provide practical support in the production environment, COGS was fully integrated with interactive computer graphics tools such as CADAM, CATIA and PATRAN. The roles of COGS in the product development cycle is outlined in Figure 1. For the overall, system-level sizing, COGS uses an optimality criteria approach to work with control effectiveness, divergence avoidance, deflection constraints, frequency constraints, flutter constraints and some combinations of these requirements. For strength requirements, internal loads obtained by the finite element analysis are provided to the resizing procedure that recognizes detailed design parameters pertinent to the type of construction employed. This process is schematically shown in Figure 2.

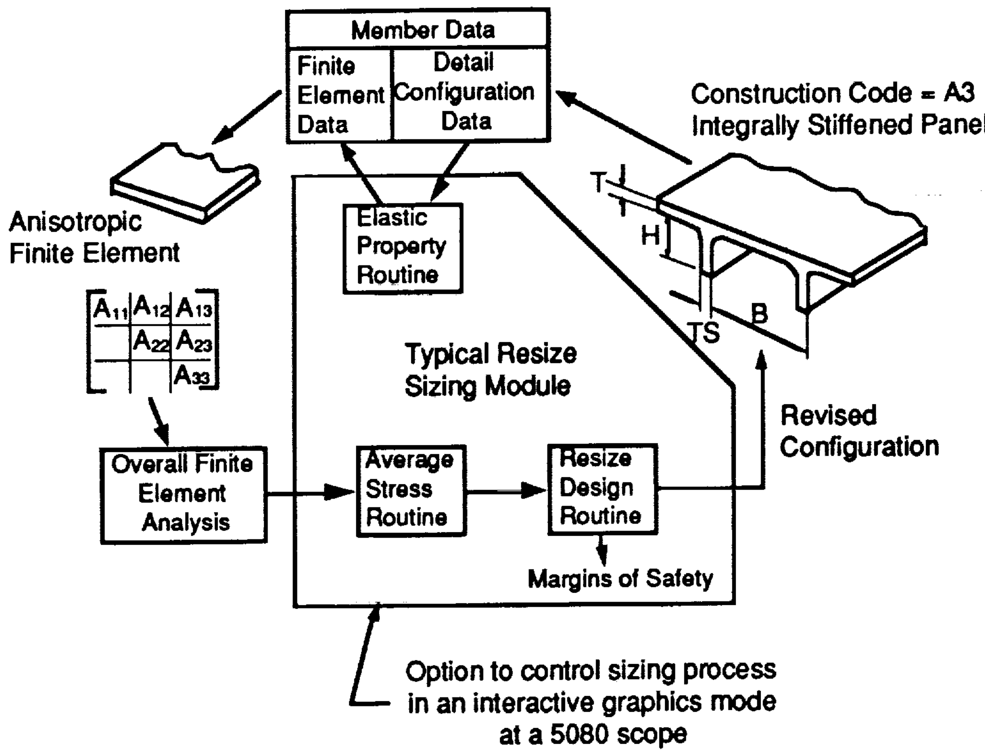


Figure 2 Structural Component Resizing Process

The finite element analysis and resizing cycle normally converges in three to five cycles. Since the resizing scheme utilizes the detailed properties to perform sophisticated component sizing, this scheme results in a realistic and usable final design.

Regarding the organizational impacts of multidisciplinary design optimization (MDO), Grumman recognizes that the software tool is not sufficient in a production environment. Other important factors come into play when an MDO tool is applied. These factors include the control of the (now multidisciplinary) analytical models and the proper representation of manufacturing and production requirements within those models. To facilitate this difficult extension to the traditional engineering design process, necessitated by the use of MDO methodologies, Grumman plans to collocate integrated product teams including analysts, designers and manufacturing engineers.

•Application 1: X-29 Forward-Swept-Wing Demonstrator Aircraft

In 1977, DARPA initiated several Air Force-monitored studies into forward swept wing technology. Interest in the high maneuverability provided by forward swept wings for modern fighter aircraft had been rekindled by Krone's study[3] in 1975, in which he showed that the divergence requirements could be met with substantially lower weights than would be required in aluminum designs by properly tailoring the stiffness using composite materials. Grumman took this opportunity to utilize its newly developed structural optimization technology in the design of a minimum weight, forward swept wing.[4]

Essentially, this effort entailed a parametric study to find optimal kick angles through a series of sizing optimizations to satisfy critical divergence requirements. Preliminary studies covered a pivoted, vairable sweep wing of balanced and unbalanced laminates of ambitious materials including graphite/epoxy, boron/epoxy and hybrids. The optimum kick angle was sought by calculating the minimum weight of the wing while rotating the spanwise ply forward by finite increments. The basic approach was to add materials to the fully stressed design by selecting the most favorable plies for divergence suppression.

As the design process proceeded from feasibility study to the preliminary design, selection of a fixed configuration with lower aspect ratio wing substantially changed the design requirements. The weight penalty to satisfy divergence requirements became much smaller and a more conventional balanced 0/90/±45 degree laminates of graphite/epoxy was adopted and the entire laminate was rotated by 9 degrees based on the results of the parametric study presented in Figure 3. The weight increment to be added to the strength design to satisfy 912 knots divergence-velocity requirement represented only 4% of the wing structural weight, while decreasing the tip rib washin angle from 5.2 degrees to 3.9 degrees.

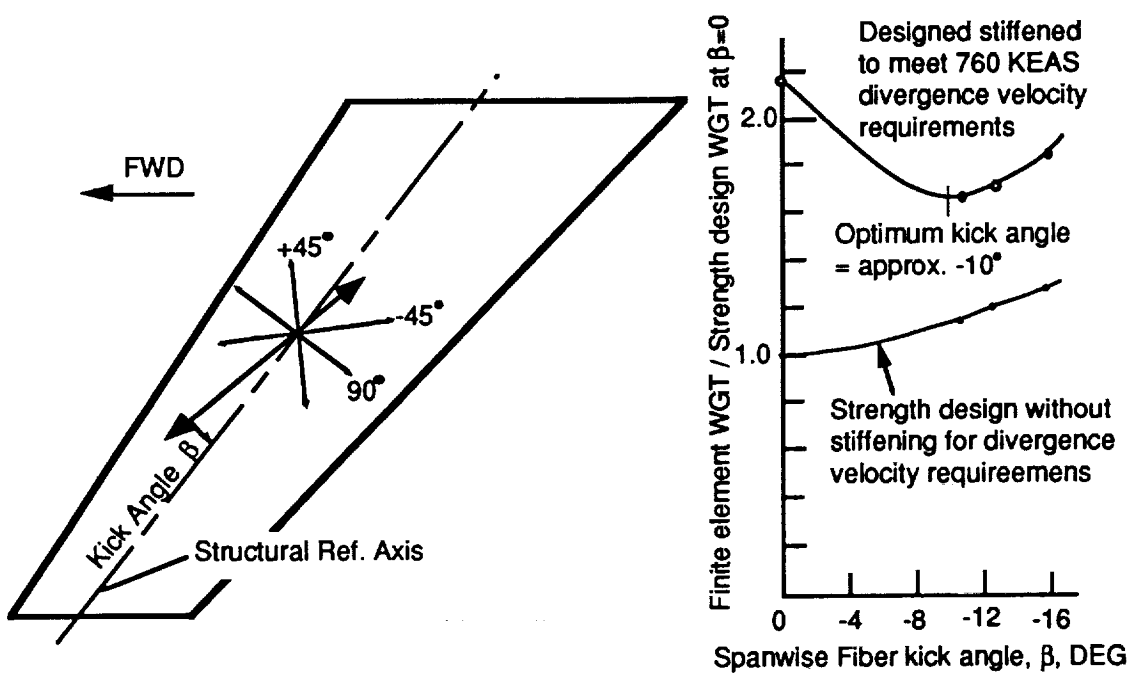


Figure 3 Variations of Structural Model Weight with Spanwise Fiber Kick Angle

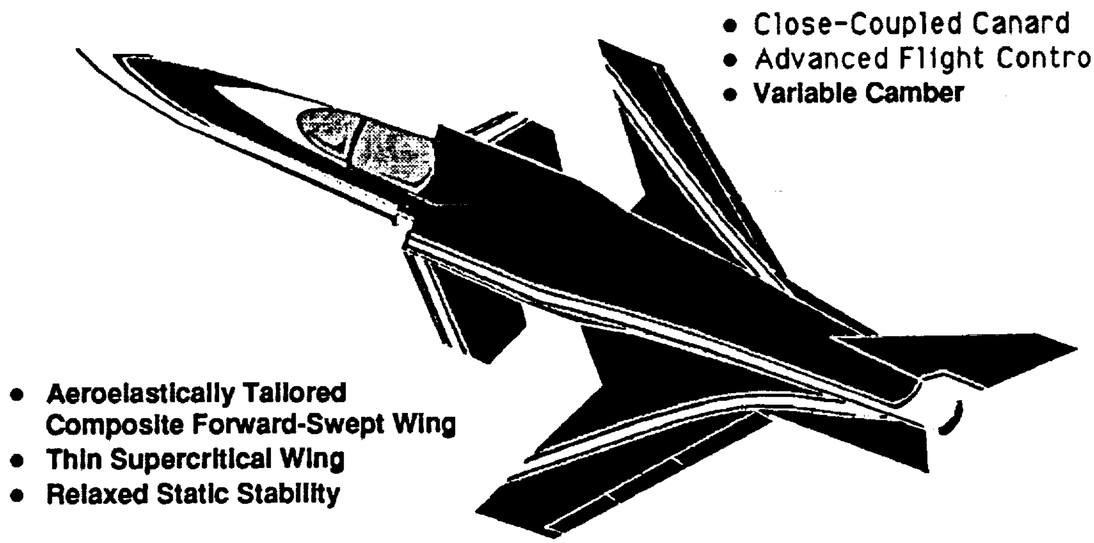


Figure 4 Grumman/DARPA X-29A Advanced Technology Demonstrator

While detailed changes were made in the configuration and in material allowables, the smoothed version of the upper- and lower-skin laminates obtained in this study served as the starting point for the final wing design. Two X-29 aircraft (fig. 4) have been built and put into a series of highly successful flight tests at NASA Ames Dryden Flight research Center.

• Application 2: Composite Wing and Vertical Tail (CW/VT) Program

The CW/VT wing is a multi-spar configuration having graphite-epoxy covers and metallic substructure. This design was implemented into the production flight hardware. The structural and design models shown in Figure 5 contain about 3,100 members, 3,400 DOFs and 6,000 design variables. First, the composite components were sized for maximum fibre strain and for panel buckling criteria with 102 load conditions. Resizing for control effectiveness then followed to satisfy pitch and roll effectiveness, ratios of pitch moment and hinge moments and ratios of roll and hinge moments at Mach numbers 0.9 and 1.2. The resultant design was checked against buckling requirements by an external program and minimum gauges were modified to satisfy buckling requirements. Finally, resizing for control effectiveness and strength requirements was repeated prior to sending out the design for postprocessing and smoothing for the final sizing decision.

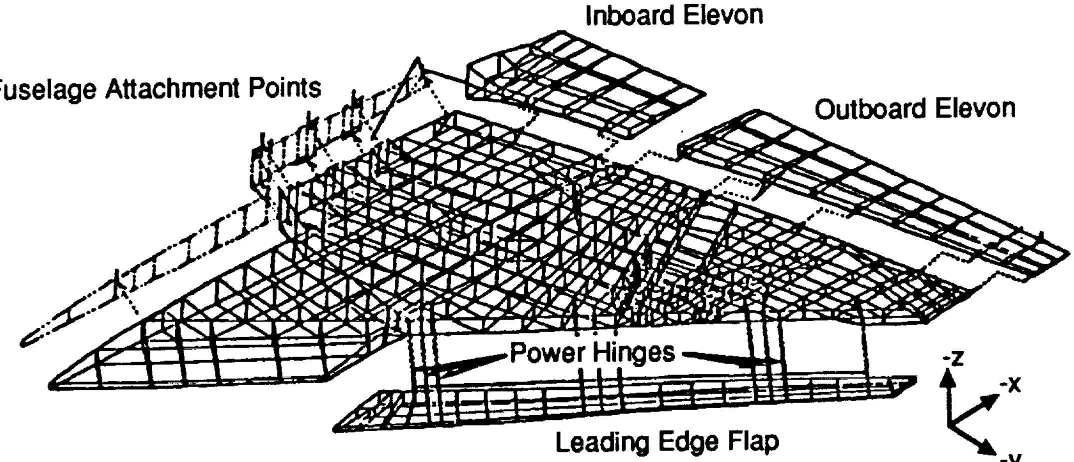


Figure 5 CW/VT Wing Finite Element Model

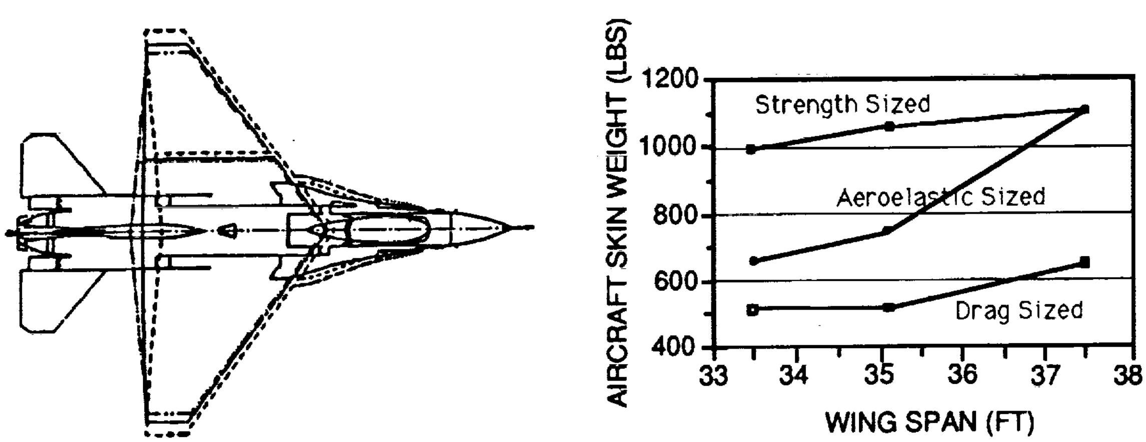
I.2 Modern Applications of TSO for Aeroelastic Tailoring at General Dynamics

General Dynamics spearheaded development of an ambitious aircraft wing design optimization code, TSO, under a series of contracts with Air Force in early 1970s. The structural analysis model for TSO is not finite element-based because this code was intended for use in the conceptual design phase where sufficient data to build finite element models are not yet available. This method for structural analysis proved itself extremely valuable in performing trade studies on many alternative configurations in time to have realistic impacts on the ongoing design projects. Even today, finite element structural analysis models tend to lag behind the design cycle evolutions. Therefore, structural optimization based on finite element analysis methods cannot expect to be a critical component in the conceptual design phase, unless a breakthrough is made in the automatic generation of finite element models for geometrical and topological variations. While TSO sacrifices modeling details of structural arrangements, it has critical features incorporating aeroelastic responses in the structural optimization of composite wings. For this reason, TSO has been updated and widely used in the U.S. aerospace industry throughout the 1980s.

At General Dynamics Fort Worth, an upgraded TSO is integrated in the conceptual design phase of an airplane design process that is followed by more detailed analyses in the preliminary and production phases.[5,6] TSO facilitates the simultaneous consideration of strength, stiffness, frequency, divergence, flutter speed and control surface effectiveness in conjunction with structural weight minimization. Accumulated experiences of development and applications of TSO to various projects allowed General Dynamics to master the effective use of this tool in a production environment. While the structural models are relatively simple, skillful and aggressive use of TSO requires a good understanding of practical structural design considerations. The two most significant factors in practice are the prescription of material parameters and of production requirements. Selection of material allowables must be set by durability and damage tolerance requirements and must include concern for practical structural certification of typical stress concentrations such as cutouts and bolted joints. Selection of practical fibre orientation angles, limitations on the ratio of 0^o angle plies and symmetric laminate configurations, etc. may also be important requirements for the resultant design to be usable. It is interesting to recognize that applications of tools such as TSO can explicitly provide sensitivity of aircraft performance with respect to the material properties, and thus could direct the materials R & D.

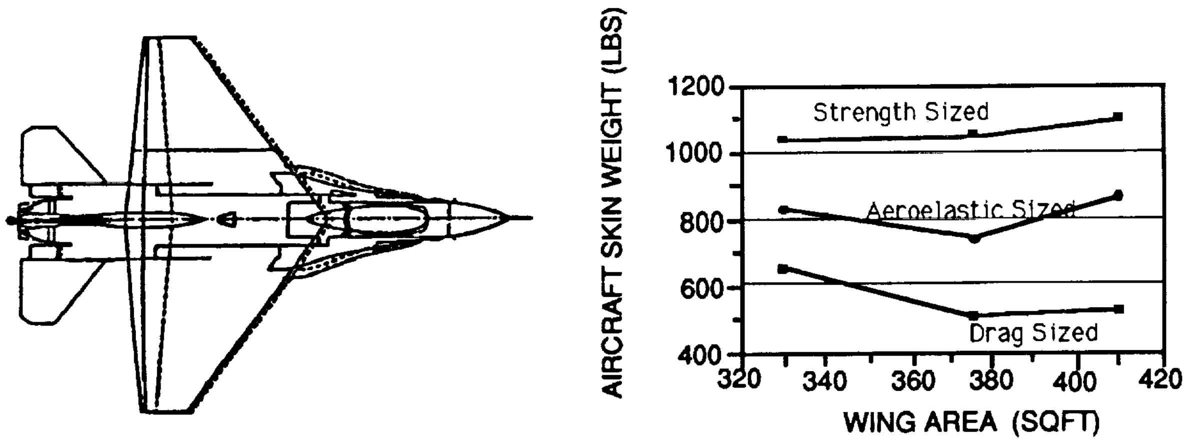
• Application: Fighter Wing Redesign Evaluations by TSO

A fighter composite wing study was performed to establish structural sensitivities in a parametric fashion that included the optimized effects of various aeroelastic tailoring criteria.[6] A matrix of seven wings was defined considering wing span, wing area and leading edge sweep as parameters. Composite skins were constrained to be symmetric by linking thicknesses of +45 deg and -45 deg layers and a manufacturing constraint was imposed such that no one layer exceeds 55% of the total skin thickness. A strength constraint was also imposed for maximum strains not to exceed 3,000 microinch/inch. In addition, aeroelastic constraints to ensure that Flaperon roll effectiveness exceeds 0.5 at M = 0.9, 10,000 ft altitude and to ensure that flutter speed exceeds 1,000 kt at M = 0.9, sea level are imposed as necessary. Note that each data point given in Figure 6 represents a complete design optimization with the corresponding values assigned to the parameters.

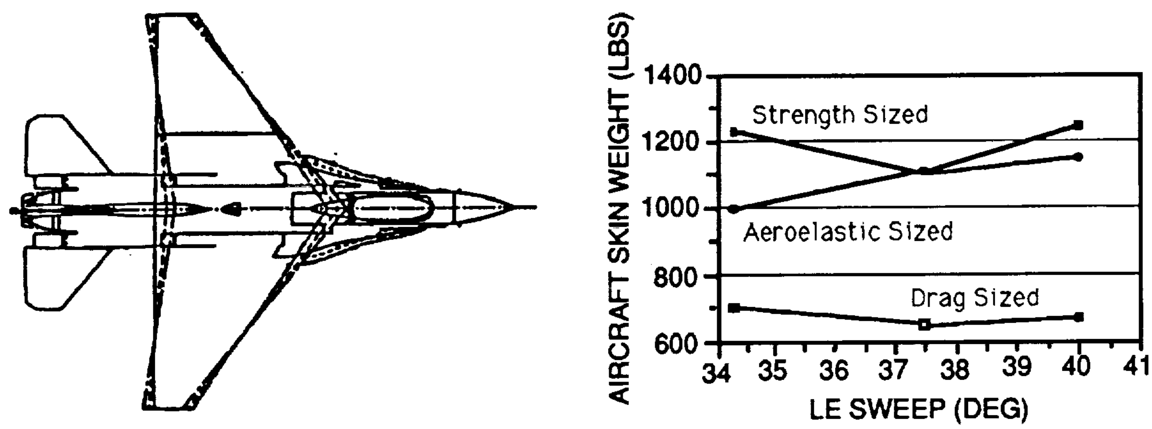


(a) Span Trade

Figure 6 Fighter Wing Redesign Evaluation Study



(b) Area Trade



(c) Sweep Trade

Figure 6 (concluded)

II. Integration of Conventional and New Technology

II.1 Lockheed Aeroelastic Structural Design Program

Lockheed Aeronautical Systems started development of PADS (Preliminary Aeroelastic Design of Structures) in 1976. By that time, Lockheed had a set of well established computer programs to perform final aeroelastic analyses. They included:

A user-friendly matrix-algebra-based computer system
A grid transformation program
A finite element based structural analysis program
Steady and unsteady aerodynamic programs
Weight estimation and distribution programs

Steady maneuver aeroelastic load programs
A transient maneuver aeroelastic load program
A ground handling load program
A dynamic loads (gust, Taxi, landing) program
Flutter analysis programs
Structural resizing programs
Structural sizing programs for stress and fatigue
Feedback control functions synthesis programs for load relief and flutter
Database management programs
Structural finite element model generator programs
Plotting programs
General utility programs known as pre- and postprocessors

These programs were readily available at any design stage, but computer access and job preparation problems prevented them from being used on quick design studies in the early design phases. For conceptual configuration evaluations, Lockheed had the ASSET (Advanced Systems Synthesis and Evaluation Technique) program, but the weight then had to be based on semi-analytical and statistical data. The goal of the development of PADS was to update the weight database during the configuration trade studies with ASSET as well as to perform general aeroelastic analysis and design in a highly computerized environment. The relative positioning of ASSET and PADS is shown schematically in Fig. 7.

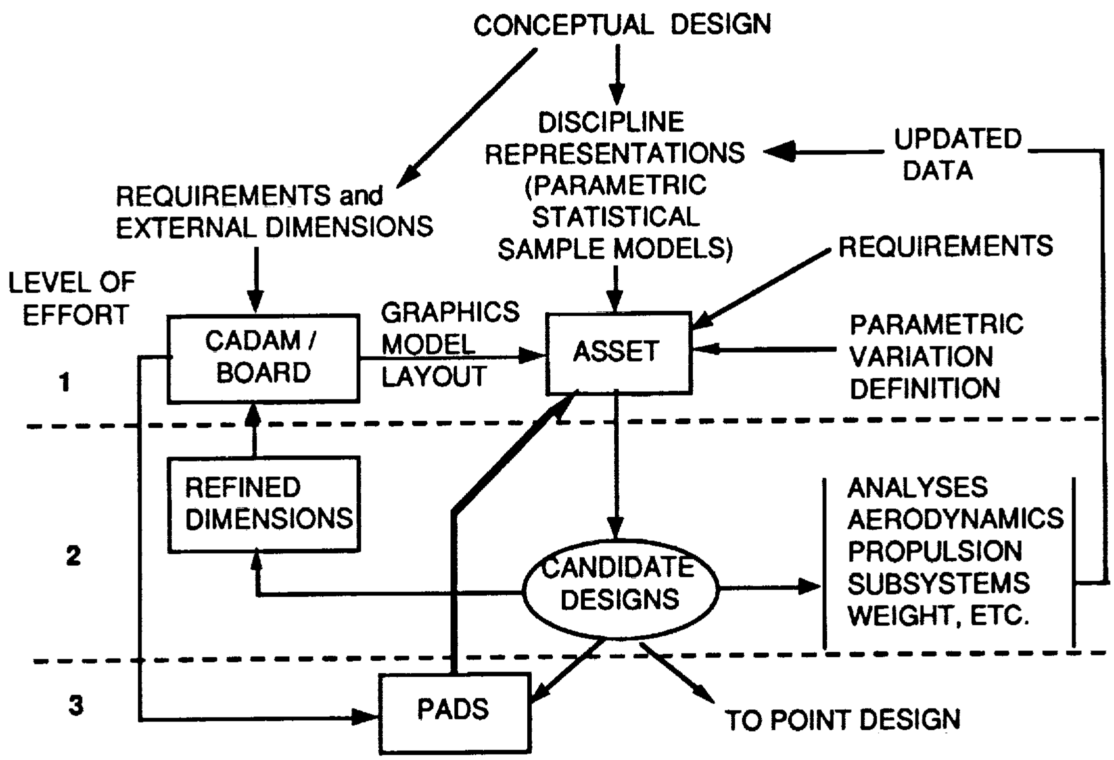


Figure 7 PADS and ASSET Interface

In the development of PADS, Lockheed recognized two critical technical issues to be addressed. The first was that the structural modeling effort was by far the most time consuming of any aeroelastic modeling task. This led to the major engineering development and coding of computer programs for the rapid generation of principal ingredients of the finite element model using relatively few input variables. The second issue was data- and program-flow management to seam through the many modules incorporated into PADS. To facilitate this capability, CBUS (Continuous Batch User Specification) was developed. CBUS is written in the UNIX command language and manages data and program execution and provides a user interface through a high level command language.

The structural design scheme implemented in PADS is visualized in Figure 8.[7] As shown therein, sizing with converged flexible loads was considered to be important for calculating the margins of safety with reasonable accuracy for production sizing. For strength sizing, finite element analysis is used to predict internal force distributions, which are then used for individual panel sizing to meet the desired margins of safety as well as for computing stress allowables for system level sizing, if required. Flutter sizing is performed using approximation concepts that require sensitivity data computed by perturbing the system matrices. For optimization with respect to the approximate models, a nonlinear programming package, ADS,[8] was used.

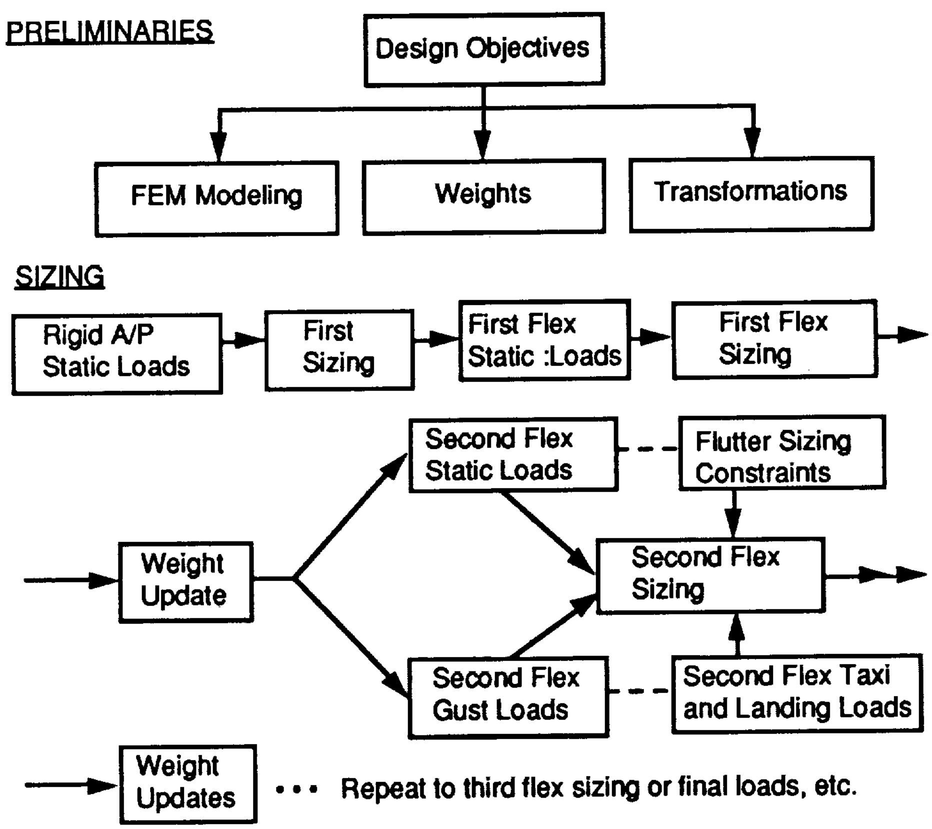


Figure 8 Design Process Overview

• Application: Transport Wing Design Exercise

From 1981 to 1985, Lockheed, under a NASA Langley contract, exercised PADS on a known design: the wing design for the L1011 wide body transport.[9-11] The baseline aircraft was selected to be the L1011-500 with a maximum gross takeoff weight of 504,000 pounds, a maximum design zero fuel weight of 338,000 pounds, an operating empty weight of 252,000 pounds, a range of 5,200 nautical miles, a payload of 40,000 pounds and a cruise condition of 39,000 ft at Mach number 0.83. This baseline aircraft wing had a span of 164 ft 4 in., a 25% chord sweep angle of 35 deg. and an aspect ratio 7.64.

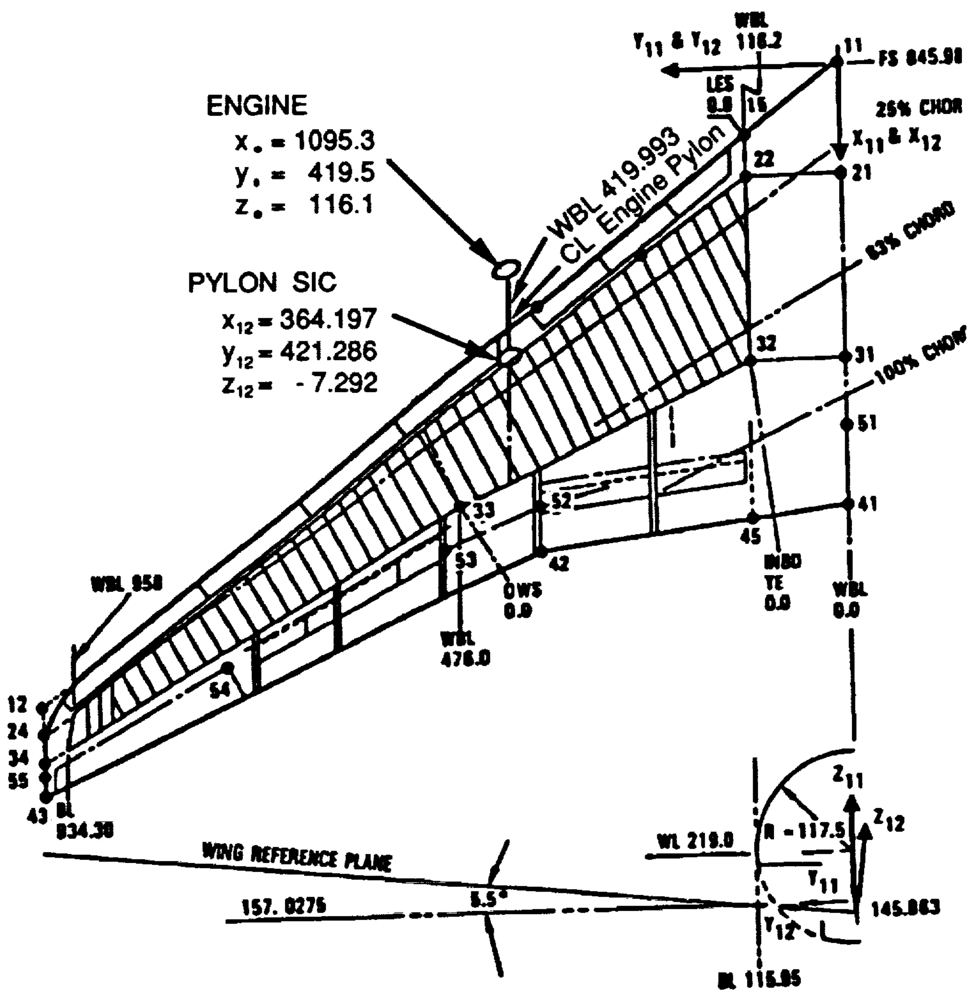


Figure 9 Wide Body Transport Wing Configuration

Application of PADS to this wing design considering about 25 static load conditions revealed several interesting features. The effects of flexibility were important enough to be incorporated in the preliminary wing weight estimation process. Sizing for rigid wing loads and flexible wing loads could differ as much as 20% depending on the location of the panels. However, the convergence seemed to be very fast, requiring no more than two to three flexible loading iterations. Two types of weight factors were identified. The first is the effect that the finite element model is not accounting for details. Those details accounted for about 12% additional weight to the resized structural weight. The second was the nonstructural weight to account for sealants, rivets, paints, etc. and was about 20% of the model weight. For this wing, flutter was not an active constraint.

This planform was originally designed for cruising at Mach 0.88 reflecting the fuel cost prior to the oil crisis. Preliminary performance calculations by ASSET suggested an increase in the aspect ratio to 12.0 and a change of the quarter chord sweep angle from 35 deg to 25 deg if the realistic fuel cost in early 1980s was taken into consideration. However, this result had to be verified with more reliable wing weight data, because the database of ASSET did not have data in this aspect ratio range. The problem to fill this gap was assigned to PADS.

This was a large deviation from the baseline configuration and provided a challenge to test if PADS could work well for configurations that are substantially different from that of the baseline. Two aerodynamic planforms corresponding to the 25% chord sweep of 35 degrees and of 25 degrees were created while keeping the wing area identical to the baseline design of 3,552 square feet. For these two models, the automated finite element model generation program created both structural analysis and design models. Structural resizing was then performed by PADS.

For an aspect ratio of 12, the flutter velocity of the optimized wing was 430 KEAS, which was close to the dive velocity of 418 KEAS. The structural weight penalty to increase the flutter velocity to 1.2 times the dive velocity and the weight penalty to install active flutter alleviation were evaluated and recommended for consideration in the subsequent system analysis and optimization by ASSET. Results of this series of studies are summarized in Table 1.

A series of "follow-on works" have been performed at NASA Langley Research Center to test the multilevel design strategy on this problem.[10,11,12] Refs. 10 and 12 used a different set of software from those of the Lockheed studies in all three levels of the design process. These follow-on studies are not intended to compare the final results side by side with the results obtained by Lockheed, instead they tested feasibility of the multi-level system optimization scheme based on optimal sensitivity proposed originally by Sobieski[13] taking advantage of the large practical structural design problem with a well documented finite element model. There were over 1,300 design variables in the third level subsystems in Ref. 13, although each sub-optimization handled much smaller number of design variables. The finite element analysis model in NASTRAN data format for the baseline wing is available for qualified organizations as an excellent testbed for a large scale structural optimization.

	Point Design			Optimal Design for Minimum Block Fuel	
	Baseline	AR=12 Sweep=35	AR=12 Sweep=25	Baseline*	With PADS weight inputs
Aspect Ratio	7.64	12.0	12.0	12.0	14.0**
1/4 C Sweep (deg)	35.0	35.0	25.0	35.0	35.0
Taper Ratio	0.259	0.259	0.259	0.298	0.301
Wing Area (ft^2)	3,541.0	3,541.0	3,541.0	3,650.0	3,528.0
Wing Loading (lb/ft^2)	142.3	148.0	146.9	142.3	140.9
Thickness Ratio	10.13	10.03	10.03	11.0	11.0
Cruise Mach No.	0.83	0.83	0.76†	0.83	0.83
Radius (NM)	4,778.0	4,749.0	4,786.0	4,780.0	4,778.0
GTOW (1000 lbs)	504.0	524.0	520.3		497.1
OWE (1000 lbs)	252.0	288.8	278.6		272.7

* Base line aircraft was optimized without reliable wing weight estimation data.

** At this aspect ratio, the flutter speed is below VD, not acceptable for FAR-25. Active flutter alleviation required.

† Severe drag rise for a cruise Mach number 0.83. Minimum block fuel Mach number for 25 degree sweep was 0.76.

Table 1 Summary of Wide Body Transport Aircraft Wing Design Exercise

II.2 <u>Applications to High Speed Aircraft Design</u>

Recent emergence of high speed aircraft development programs such as the NASP (National AeroSpace Plane) or the HSCT (High Speed Civil Transport) provided unprecedented opportunities for structural optimization technology to demonstrate its effectiveness. Various aerospace companies have been working with applications of structural optimization to this type of aircraft. This is motivated by : (1) a lack of historical data to predict the first order effects and (2) the knowledge that conventional structural design, using known materials, cannot satisfy basic mission requirements. There will be more information published in the future, but the capabilities of the system developed at McDonnell Douglas[14] for a NASP-type vehicle are summarized here.

The NASP is an experimental research aircraft that is capable of performing multiple single-stage-to-orbit and hypersonic cruising missions. Use of cryogenic hydrogen as the fuel makes the volume of the aircraft one of the critical design parameters and thereby necessitates extremely efficient shell structures to enclose the volume while serving as the heatshield against severe aerodynamic heating. Shell structure/thermal protection system configurations are variable depending on the location, but a typical panel subject to a relatively high heat flux is shown in Fig. 10. McDonnell Douglas assembled a system to estimate panel weight using existing engineering methods as shown in Fig. 11. Aerodynamic loads, thermal loads and structural responses are coupled together to calculate internal loads

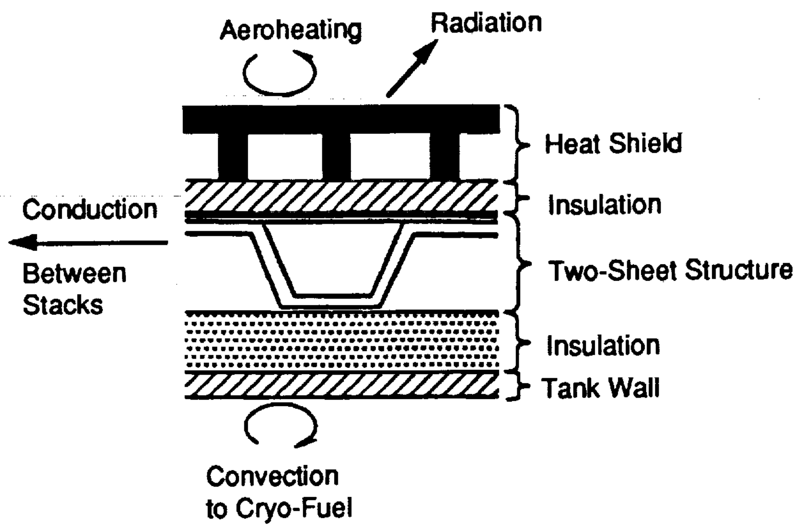


Figure 10 Thermal Stack Definitions

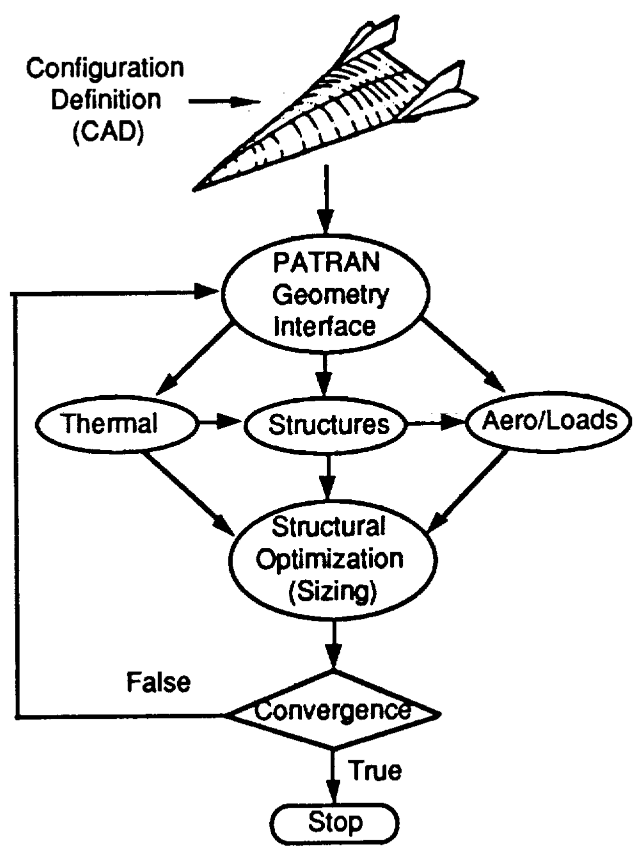


Figure 11 Design System Flow Diagram

of the flexible aircraft. The geometry data are transferred among disciplines by mapping software. Structural analysis for internal load distributions is performed by finite element analysis, which separately calculates internal loads due to mechanical and thermal loads. The basic philosophy for structural design is that the internal forces (not stresses) are nearly invariant through the sizing process. This assumption for the NASP-type aircraft was confirmed when convergence was achieved in three or four iterations. Each structural design cycle includes resizing each designed panel considering strength, stability and thermal stress, aiming at optimization of the section geometry as shown in Fig. 12. Analysis methods were validated against other codes such as PANDA and against test measurements.

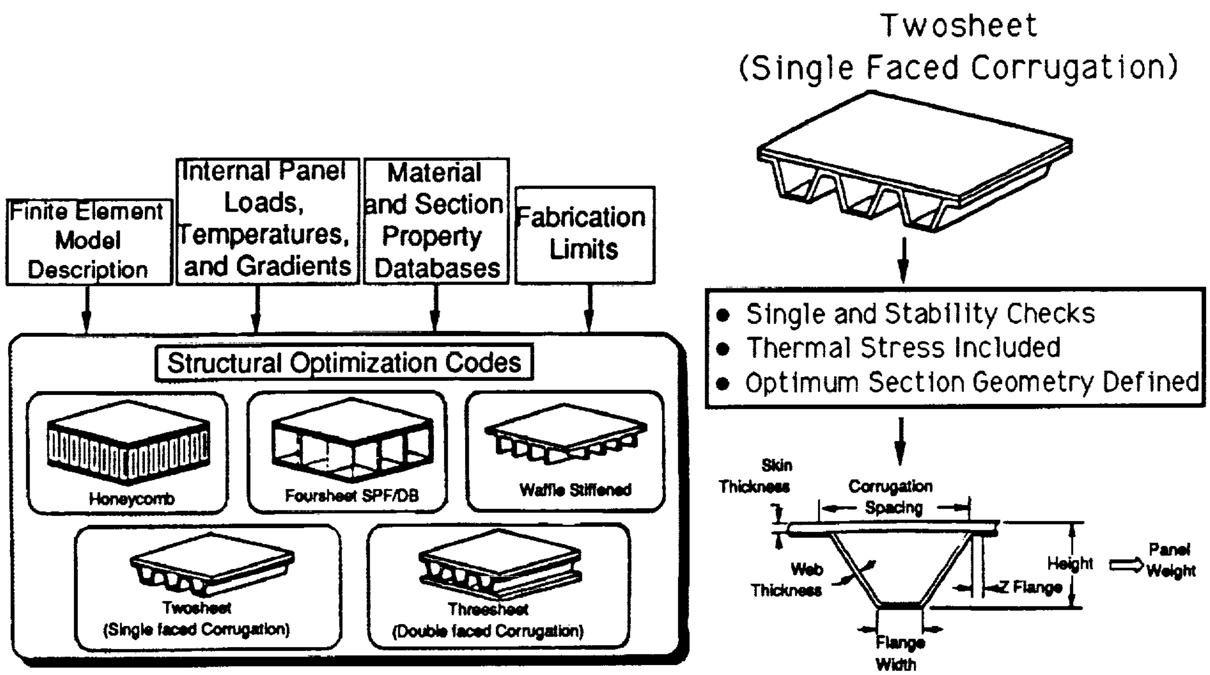


Figure 12 Structural Sizing Codes

Guidance for manufacturing, producibility and supportability are incorporated into the specifications of sizing limits. Consideration of these types of local panel design details in the conceptual/preliminary design phases is recognized to be important in practice, because of the high level of confidence that sized sections are less likely to change significantly as the configuration matures.

As previously described, the new challenges associated with hypersonic aircraft are linked to tight synergy among aerodynamics, propulsion, thermoaerodynamics and structures. Configuration management, to ensure all disciplines work with consistent data, is increasingly difficult without appropriate analysis/design tools. It is likely that this area must make substantial progresses in 1990s for the U.S. aerospace industry to meet the challenges of development of unprecedentedly high performance aircraft.

III Aggressive Applications of New Tools

In the last half of 1980s, we saw availability of structural optimization features installed in well recognized commercial finite element analysis programs such as MSC/NASTRAN and ANSYS. Also, the availability of excellent numerical search programs and of super computers that can process a large volume of data within reasonable turnaround time provided opportunities that were not previously feasible.

III.1 Strength and Stiffness Design of Transport Aircraft Wing

McDonnell Douglas at Long Beach recently came very close to setting a world record in terms of the number of design variables for structural optimization based on a general nonlinear programming optimization algorithm.[15] It is significant to know that commercially supported software can be applied to the problem of this scale. At the same time, we need to realize the substantial amount of peripheral work required to make best use of such capability in a production environment.

An analysis/design model for an MD12X wing (Fig. 13) was created for structural weight minimization with strength, tip deflection and tip twist constraints. The attributes of structural analysis/design model are shown in Table 2. The initial, approximate, skin thickness distribution was obtained using TSO. The thickness distribution was then converted to the format of MSC/NASTRAN. A special FORTRAN program was written to create design model data automatically for MSC/NASTRAN. This was necessary because PATRAN (which was used to create the analysis model) did not then have any capability to create design models In fact, there are no finite element analysis preprocessors that can create design model data for a problem of this size. The design variables are sizing properties for skins and stringers.

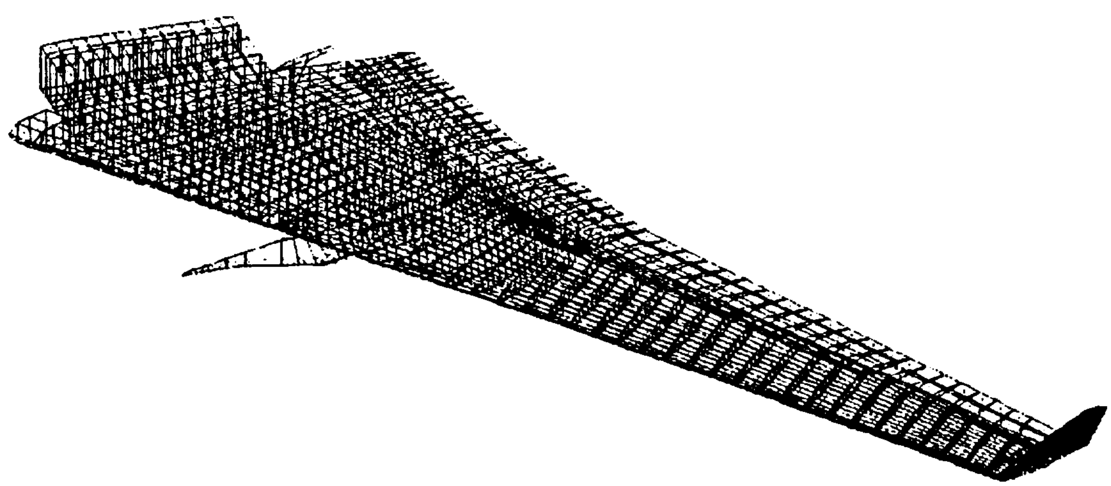


Fig. 13 MD-12X Wing Structural Analysis Model

Number of Elements	9,479
Number of Grids	2,851
Number of Free DOF	9,945
Number of Load Cases	1 to 3
Total number of Design Variables	2,192
Number of Independent Design Variables	1,168
Number of Constraints	5,314

Table 2 Attributes of MD12X Wing Analysis/design Model

MSC/NASTRAN Solution sequence 200 was run on a CRAY X-MP with only the strength constraints. The design converged in five cycles expending 3 hrs and 37 minutes of CPU time (16 hours of clock time). This run required six static analyses, five sensitivity analyses and five optimizations with respect to approximate models. Since independent static analysis on Solution 24 required 3 minutes 27 seconds of CPU time, it appears that significant amount of computational effort was required in sensitivity analysis and approximate optimization, which is not surprising for the large number of design variables and large number of active strength constraints toward the end of the design process.

The sizing results of this optimization may not be the production sizing, since the allowables that take the compression-shear interaction are sizing dependent. A second external FORTRAN program was developed to process the sizing and stress data from the final design of MSC/NASTRAN optimization. This program makes adjustments to member sizes so that all components have adequate margins of safety using a stress interaction equation with corresponding size-dependent allowables. The results of this program automatically update the MSC/NASTRAN analysis/design model data for additional design optimization or for verification analysis. The final design thus obtained was optimal for allowable stresses while maintaining desirable ratios of stringer area to skin panel end area for crack prevention and adequate torsion stiffness.

Next, stiffness design was attempted to reduce the tip deflection to 50% of the strength design and the tip twist to 27% of the strength design. After five design cycles, the tip deflection was decreased to 65% and tip twist to 36.4%, while the structural weight was increased as much as 30%. This weight increase was not acceptable and verified that the stringent stiffness requirements cannot be satisfied with this particular wing configuration simply by adjusting the material distribution.

III.2 TRW ASOS - Applications to Space Structures

TRW Space and Technology Group in Redondo Beach, California is one of the most successful organizations in incorporating critical ingredients of modern structural optimization techniques as an essential part of the day-to-day operational tools in the design of space structures.[16] An Automated Structural Optimization System (ASOS) computer software was developed beginning in 1983. The group that developed ASOS was thoroughly familiar with approximation concepts and various new techniques were added to enhance the efficiency of ASOS and to facilitate its applications in a production environment. Structural design of space structures has to perform extremely strict weight minimization while maintaining severe static and dynamic design requirements for safe and reliable operation. It is estimated that the cost to lift a payload to a low earth orbit is several thousand dollars per pound but, at the same time, the payloads are very expensive hardware that may not be replaceable.

To avoid duplication in creating and calibrating finite element analysis models for design optimization, response analysis and design sensitivity analysis capabilities implemented in MSC/NASTRAN were selected to be the key components of ASOS. This choice, together with the incorporation of approximation concepts in the basic architecture, made it feasible for ASOS to handle relatively large design problems. The design model data for sensitivity analysis are generated semi-automatically by a separate program. For both strength and stiffness sizing, ASOS makes full use of its beam cross section library (currently more than 20 cross sections are stored). Generation of beam properties and determination of detailed sizing are performed by ASOS taking specific characteristics of cross sections into account. This is done both for accuracy of analysis and for detailed design and fabrication requirements. As is often the case with aerospace applications, the mass matrix is generated separately from the structural model. To consider the structural mass as the objective function or as a constraint dependent on the design variables, 1% of the real density is assigned to the designed beams and checks are performed to ensure that this additional fictitious mass has no appreciable effects on the key responses affecting the final design.

• Application: Gamma Ray Observatory (GRO) Platform Structural Design Optimization

ASOS was successfully applied to the basic structural design of the GRO that was lifted to the orbit by the space shuttle in April 1991.[17] During the initial design phase, the weight of the GRO had grown and the GRO Office decided it was necessary to conduct a weight reduction study for the GRO platform. The primary structure and the finite element model are shown in Figures 14 and 15.

This model had about 6,000 static and 500 dynamic degrees of freedom. Weight minimization was the objective, while the three lowest natural vibration frequencies and minimum gauge requirements were imposed. The minimum gauges were predetermined to represent strength, buckling and fabrication requirements.

TRW performed two parallel weight reduction efforts simultaneously: one was to use the conventional trial-and-error approach based on engineering judgements, and the other was to apply ASOS. The performance of ASOS was satisfactory since a converged design was usually obtained within a few design cycles. It turned out that automated structural optimization achieved significantly more weight savings at less than half the cost required in the conventional approach. It was determined that the conventional approach (based on intuitive engineering judgements) had to compromise in system responses for this level of complex interaction of design variables and system responses. In particular, it was extremely interesting that ASOS added mass to certain portions of the system even if the objective was weight minimization. These small additions of mass to one part, however, permitted it to take away more mass at other places. This type of adjustment is hard to perceive intuitively, while the numerical optimization algorithm had no difficulty in grasping the global picture to manipulate large number of variables simultaneously.

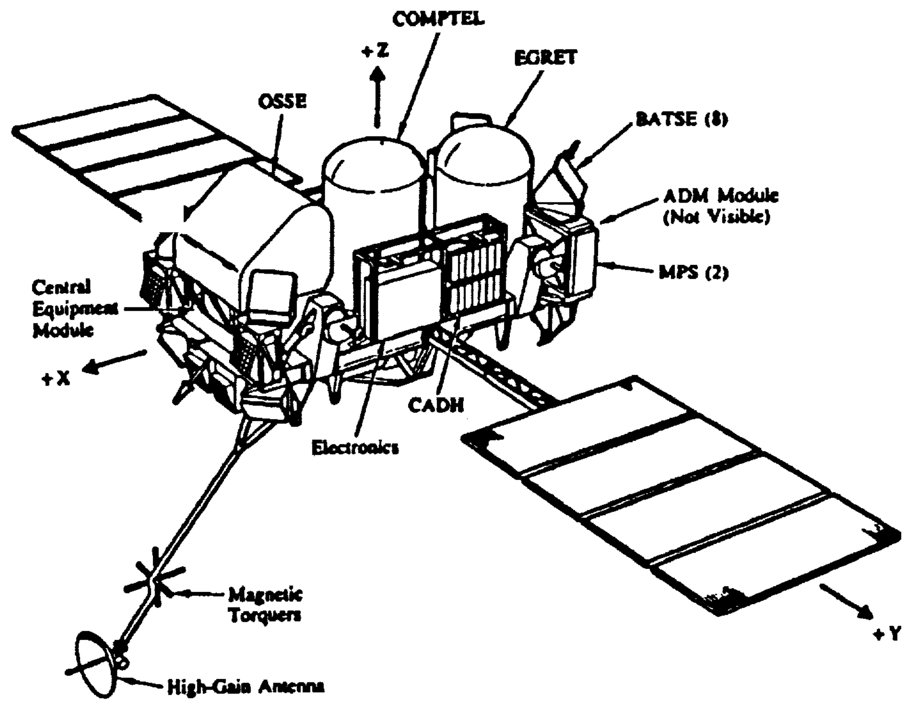


Figure 14 Gamma Ray Observatory

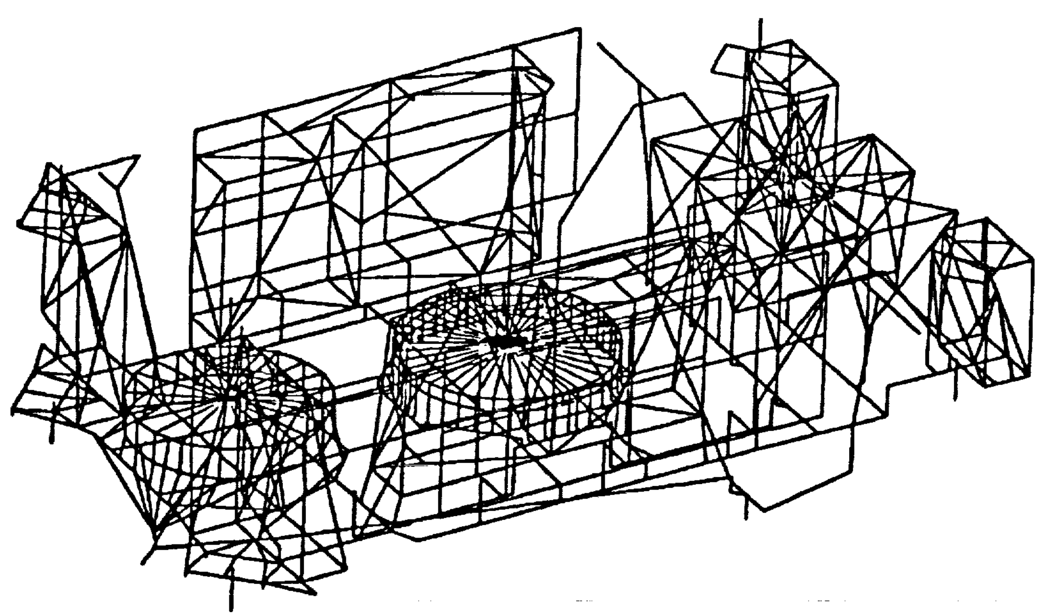


Figure 15 GRO Primary Structures (w/o instruments)

TRW has been upgrading ASOS and has integrated it in the spacecraft structural design process. Following its success on the GRO, ASOS has been used in various projects, including the payload support structure of the Orbital Maneuvering Vehicle (OMV).

IV. Structural Optimization in a Multidisciplinary Design System

IV.1 Northrop Advanced STOVL Preliminary Design-- (Applications of ASTROS)

Short takeoff and/or vertical landing (STOVL) capabilities for future fighter aircraft are becoming increasingly important to meet the demands of landing on damaged or improvised runways, to operate from remote and austere sites in challenging environments and to perform multiple sorties effectively. To achieve STOVL capabilities, fully optimized structural concepts are required utilizing advanced materials and innovative manufacturing technologies.

The Northrop N382-20 STOVL fighter is a descendent of a family of horizontal attitude take-off and landing (HATOL) and vertical/short take-off and landing (V/STOL) aircraft. Predecessors to the N382-20, such as the -12 and -18, were developed to meet basic mission and point performance goals, with the exception of supercruise in dry power. The -20 version incorporates configuration changes to satisfy the supercruise through shortening the fuselage.

As part of the "Ultralightweight Structures" program, the N382-20 STOVL fighter was chosen as one application to assist in the development of ultralightweight structural design concepts and advanced materials.[18] In looking to "reduce the weight" to the maximum extent possible, formal numerical structural optimization techniques were an intrinsic part of the study. The Automated STRuctural Optimization System, ASTROS was chosen as the principal multidisciplinary optimization tool with other subsidiary optimization tools used for component design.

ASTROS is intended to provide quantitative information to the designer for making decisions regarding the arrangement of large and intermediate structural components. For example, the relative weights for optimal designs with either multispar or multirib wing constructions, or the weight tradeoffs associated with a carry-through wing versus a side-tie wing. For this study, preliminary choices for these items were made to demonstrate one step in the preliminary design cycle using optimization. ASTROS, then, determines the optimal vehicle with a given structural arrangement (optimal being defined as lightest). Further cycles would then allow the designer to compare optimized arrangements.

The baseline STOVL fighter (Figure 16) is a single engine aircraft that takes off conventionally (with the addition of vectored thrust) in 600 feet, and can land vertically at the conclusion of the mission. It employs a Remote Augmented Lift System (RALS) turbofan propulsion system with vectorable nozzles to provide the thrust needed for take-off, vertical landing, and for control during transition and hover. The fighter is a 28,000 lb class aircraft that carries two AMRAAMs and two ASRAAMs in an under fuselage conformal pod and carries a 20mm gun with 500 rounds of ammunition. Basic dimensional data and significant characteristics of the STOVL fighter are presented in Table 3. The N382-20 has a canard-delta planform composed of four major structural assemblies constructed primarily from advanced graphite reinforced composites: multi-rib wings, shoulder mounted to the fuselage;

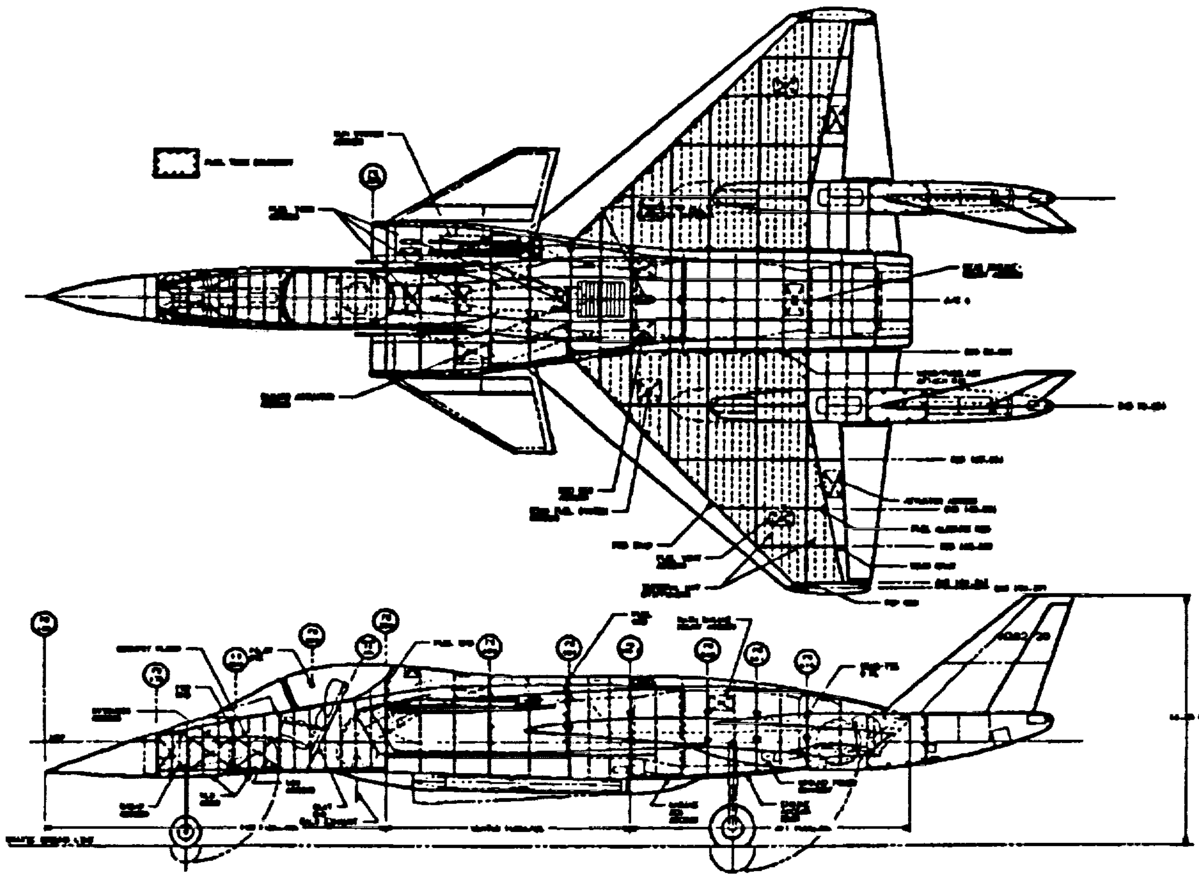


Figure 16 Advanced STOVL Finite element Model

BASIC SURFACES	UNITS	WING	CANARD	VTAIL
AREA (Projected)	FT^2	495.3	145.9	52.4
ASPECT RATIO	-	2.1	2.0	1.4
TAPER RATIO	-	0.18	0.15	0.28
THICKNESS RATIO, ROOT	-	0.04	0.04	0.04
THICKNESS RATIO, TIP	-	0.04	0.04	0.04
LEADING EDGE SWEEP	DEG	50.0	60.0	47.5
QUARTER CHORD SWEEP	DEG	40.8	53.74	41.5
DIHEDRAL/CANT ANGLE	DEG	-5.0	4.0	15.0
INCIDENCE ANGLE	DEG	0.0	0.0	0.0
TWIST ANGLE	DEG	0.0	0.0	0.0
SPAN (Projected)	FT	32.4	16.9	8.5
ROOT CHORD	FT	25.9	14.9	9.7
TIP CHORD	FT	4.7	2.3	2.7
MEAN AERO. CHORD	FT	17.7	10.2	6.9

Table 3 STOVL FIGHTER BASIC DIMENSIONAL DATA

semimonocoque fuselage; fully movable canards; and two wing-mounted nacelles that accommodate the landing gear, contain fuel and support the vertical stabilizers.

The ASTROS procedure provides a multidisciplinary analysis and design capability for aerospace (and other) structures. The engineering analysis capabilities of the system include finite element structural analysis (static and dynamic), aeroelastic analysis (static and dynamic), and automated design within a single software tool. The design variables within ASTROS are the thicknesses of membrane plate elements and the areas of BARs and RODs. The design constraints available in ASTROS include:

1. Stresses and strains (within the strength allowables)
2. Deflections (maximum and minimum)
3. Natural frequencies (maximum and minimum for each mode)
4. Aileron and lift effectiveness for the static aeroelastic performance (maximum and minimum)
5. Flutter damping (maximum)
6. Thickness/area (maximum and minimum).

The principal strength of ASTROS is that these constraints can be applied over a range of boundary conditions (e.g., symmetric and antisymmetric), flight conditions and load conditions. Once applied, ASTROS attempts to find the minimum weight structure that can simultaneously satisfy ALL applied constraints. Hence, the optimum structure does not represent a point optimum, but one that is feasible throughout the flight envelope. A sampling of loads was chosen for this ASTROS application covering the broad spectrum critical for major portions of the structure. The selected conditions were:

1. Maneuver loads on wing, fuselage, and canard for symmetric 9g pull-up and 3g push-over with aeroelastic correction.
2. Antisymmetric maneuver for 360 degrees/sec steady state roll with aeroelastic correction.
3. Rigid aero 9g symmetric pull-up load.
4. Quasi-static landing impacts on the nose landing gear and the main landing gear.
5. Flutter at Mach 1.5 at 15,000 ft for fuselage and wing combined. Canard and vertical local flutter were not included since these portions represent undesigned structure.

These conditions were considered to be adequate for an initial sizing of the STOVL vehicle with the intent of adding additional cases as our knowledge of the vehicle behavior increased. The following primary structural components of the vehicle were modeled: skins, longerons, bulkheads, spars, ribs and inlet ducting.

Multidisciplinary optimization of aerospace systems always requires accurate mass as well as stiffness modeling. A key modeling parameter for structural optimization is the non-optimum material density. The value chosen for the STOVL fighter was 1.5 times the true density. This quantity must account for the extra weight associated with splices, joints, fasteners, and anything else which is not modeled in detail but is felt to be dependent on the element thicknesses. Little historical data is available to guide the analyst in this determination. Some studies at Northrop using an internally developed program REVWING on the F-18 wing, indicate a factor of 2.0 for the skins and spars, and 5.0 for the ribs. The value 1.5 was chosen because the REVWING results were seen as case specific and not applicable to this vehicle. This remains, however, an area for active research (for example see Sec. V.1). In addition to the structural mass, several hundred concentrated masses were included in the model to represent the nonstructural mass of equipment, payload, crew, and fuel.

The "design model" consists of two critical parts: the definition of the local design variables (those elements to be sized) and the definition of constraints. The static design constraints consist of strength allowables for each element in the finite element model. Other constraints applied were for the aerodynamic behavior of the STOVL. The static aeroelastic roll performance at Mach 0.70 at sea level (SL) was constrained to exceed 360 deg/s and the vehicle was required to be free of flutter at Mach 1.5/15,000 ft.

For this study, as much of the N382 structure as possible was represented as eligible for redesign. The parts not sized by ASTROS were the vertical stabilizer, the canard, and the landing gear. The engines and other internal equipment were taken as fixed in size and mass. The thicknesses of plies for all other structural elements were linked using shape functions and were therefore being sized by ASTROS. The wing structure had 74 design variables and included 4 ply directions on each of the upper and lower skins (0/+45/-45/90). The substructure was modeled using "single ply" composite elements as were used on the fuselage.

All portions of the fuselage were modeled with just 2 shell/plate element properties: quasi-isotropic top and bottom skins, bulkheads, and frames; and 100% 45 degree "Fabric" side skins (primary shear structure). Note that our fabric was cross-plied unidirectional tape rather than a true fabric. Fuselage skins tend to be buckling critical, so minimum gauge limits were expected to be critical. Buckled skins would not carry their fair share of the bending loads, so the 45 degree "fabric" side skins were intended to minimize their contribution to the fuselage bending moment of inertia in lieu of true buckling constraints. The quasi-isotropic assumption for top and bottom skins represent skins of primarily ±45 degree plies with integral fore/aft stiffeners. As a result, the elements in the fuselage were all "single ply" composite layups represented by a total of 92 design variables.

A feasible design (one that satisfies all the imposed constraints) was achieved with a resultant weight of 4230 lbs of designed structural weight. The undesigned structure and nonstructural weight was 21,989 lbs for a total "optimal" weight of 26,219 lbs. The weight target from the mission analysis was 28,133 lbs. Of that, 6,144 lbs is the structural weight not including the landing gear. Figures 17 and 18 show some of the final thicknesses of the skin and substructure at the converged optimum. The critical constraint for the STOVL was the flutter constraint. The STOVL model represents a poor configuration for flutter in that the wing pods, which carry both fuel and avionics (approximately 800 lbs/side), provide mass aft of the wing's elastic axis to excite a flutter mode. The flutter mode observed in the STOVL was a coupling of the first fuselage bending (with the pod following along since the delta wing has significant chordwise bending) and the first wing torsion mode. Notice, that the term weight savings is not used in relation to our final design. Since there was no baseline version to compare to, and only one feasible design solution was sought, there can be no "weight savings." Only one design is available which satisfies all the multidisciplinary constraints.

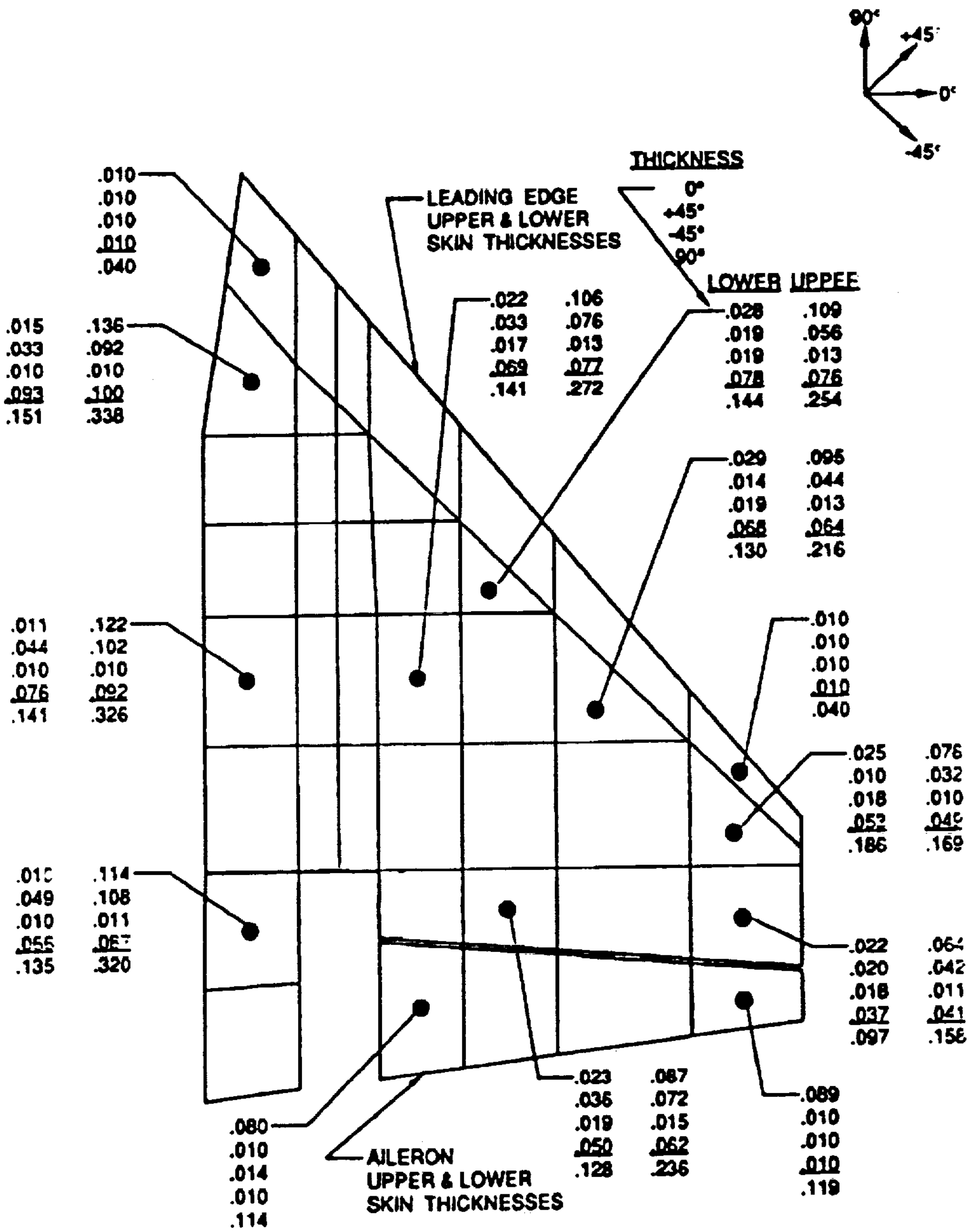


Figure 17 Composite Wing Panel Thickness Distribution

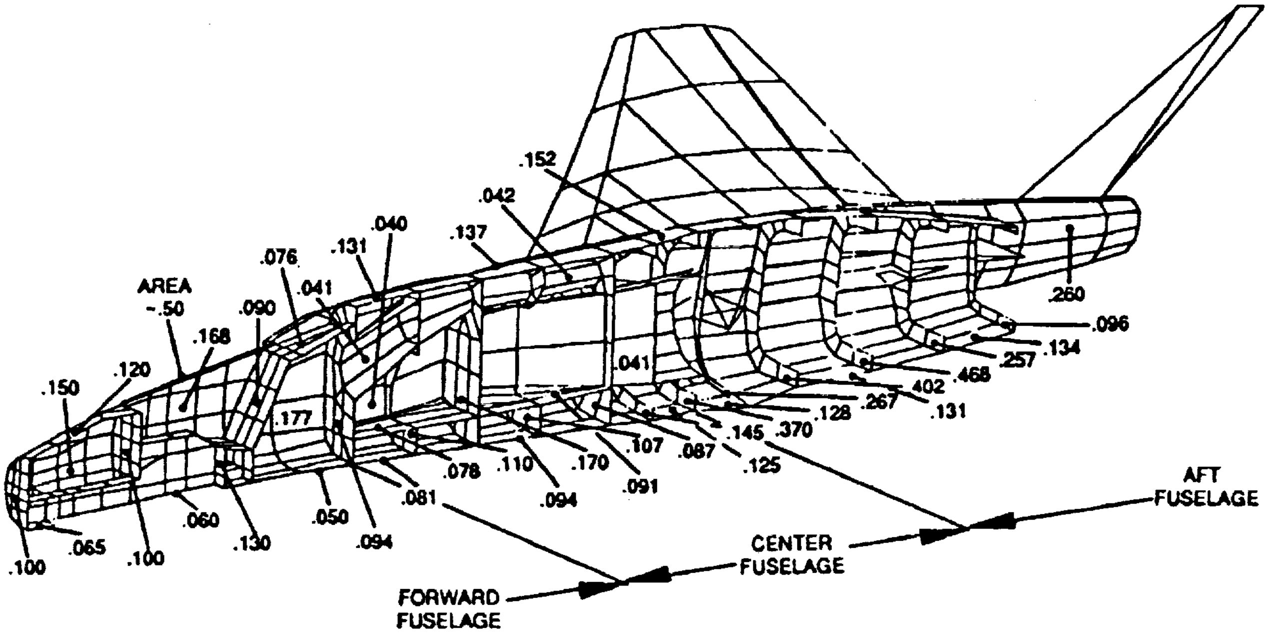


Figure 18 Fuselage Sizing Results

Other constraints that were near critical at the optimum and which strongly influenced the early design iterations were the stress constraints due to the landing impact loads and the 9g symmetric pull-up. These constraints influenced such regions as the main and nose landing gear pickups, and the canard support structure. Conspicuously absent are the wing skin stresses. They are not critical at the optimum since the flutter requirement forced a general thickening of these elements to increase the wing stiffness.

Other gauge results are worthy of some discussion. For example, the upper wing skin at the optimum is more than twice the thickness of the lower skin (0.33 inch vs 0.14 inch) and is thicker at the leading edge than the trailing edge. The reasons for this are not completely clear. Certainly, the different compression and tension allowables play some role, but cannot account for a factor of two. The balance is probably driven by the stiffness requirements of the flutter constraint. Conventional wisdom is not sufficient to separate the effects of competing constraints in driving the design. This is one example of a non-intuitive solution to the multidisciplinary design problem.

The results of ASTROS static aeroelastic analyses indicate that the N382-20 does not have enough canard effectiveness to trim the aircraft for level flight without excessive drag (Canard deflection = 15 degrees). Moving the canard forward enough to fix the situation is not acceptable. This forward center of gravity challenge is often encountered in STOVLs with RALS systems. To limit necessary bleed for vertical flight using the RALS nozzle and deflected main engine thrust, however, the engine position must remain forward, close to the aircraft center of gravity. The pods have already been used to move the c.g. aft to compensate, therefore, no ready means are available to move the c.g. further aft.

Another important result of the STOVL study was the development of a multidisciplinary design cycle including ASTROS. Even with the simplifications made for the STOVL preliminary design, the issues of finite element modeling, weights, design flight conditions, aerodynamic modeling, flutter modeling, design variable selection and optimization proved to be fairly complex. The level of detail in the ASTROS STOVL model is adequate for preliminary design, more detailed that is typical for conceptual design and crude relative to final design work. As a modeling decision, both the fuselage and the wing structures were modeled at a moderate level of detail rather than focusing on any one component. This was important since the fuselage flexibility contributed to the critical flutter instability which drove the design. This is considered to be the proper approach to multidisciplinary airframe design since it makes no a priori assumptions about the nature of fuselage/wing interactions.

Buckling also plays a role in interpreting the validity of our optimal structural sizes and computed structural weight. The absence of buckling constraints may or may not profoundly influence the optimal thicknesses. There is a weight trade-off that was not fully investigated in this study in which stiffeners are used for panel breakers, thus reducing the required skin thickness. Obviously, it is desirable to have the means to perform this trade within the multidisciplinary design tool. Since the results presented in Reference 18 were obtained, Northrop has further developed ASTROS to include local panel buckling and some composite manufacturing constraints.

ASTROS clearly provides an advance in formal optimization tools for aircraft design. The conventional design methods where dynamics, aeroelasticity, and flight controls are treated independently as "weight penalties" to the optimal strength design will no longer suffice. As aircraft become lighter and more flexible, multidisciplinary design optimization is required to develop design concepts, structural arrangements, and structural sizes that reconcile conflicting design requirements. ASTROS has demonstrated promise in providing feedback to the designer on the quality of various concepts early in the design cycle. Originally conceived as a preliminary structural design tool, it can also serve to quantify the relative merits of different configurations or structural concepts.

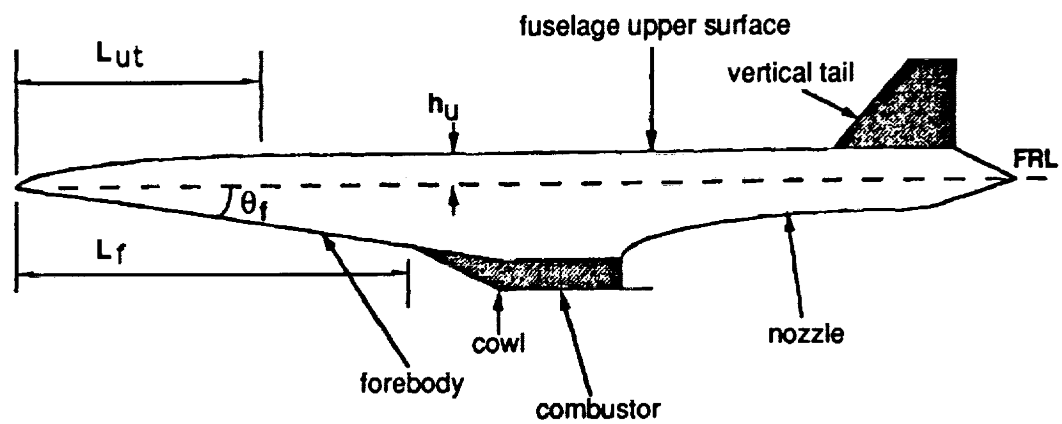
IV.2 High Speed Aircraft Design by Rockwell ASO

With the advent of high supersonic to hypersonic aircraft development programs during the 1980s, various companies responded to the need to work with the complex synergistic nature of the design problems. Rockwell developed a program, RSOP[19] (Rapid Structural Optimization Program), addressing the following issues:

- Reduced iteration cycle time through automated data exchange between disciplines
- Timely analysis and optimization of advanced airframes based on finite element models
- Provision for interdisciplinary interactions using mathematical optimization
- Estimation of the structural weight early in the design process.

It was recognized that updating structural analysis/design models at the same pace as the aircraft design cycle is extremely difficult using conventional tools and practice. RSOP responds to this specific need as a collection of independent programs working with a common executive controller program and a database (which is nothing but shared files at this moment). The primary structural optimization module is called SAOM (Structural Analysis and Optimization Module) and a second program for panel buckling is called BUCKOP (panel BUCKling analysis and OPtimization module). SAOM implements optimality criteria design capability for strength and deformation with finite element structural analysis. BUCKOP resizes element gauges in the structural model for biaxial panel buckling using the element stresses saved from SAOM module. As support modules, RSOP contains external, fully integrated, loads generation modules for linear and nonlinear aerodynamic analyses and a program called CDS (Configuration Design System) that defines vehicle moldline geometry on the basis of quadratic splines. CDS then passes the data to the FEM preprocessor. Another significant support module, RCADS (Rockwell Computer Aided Design System) is a FEM pre/post processor that has the ability to prepare analysis as well as design models for structural optimization and also is capable of creating geometry models for thermal analysis. The overall aircraft system design optimization is performed under the Executive Controller by the ADS optimizer[10] based on the global sensitivity.[20]

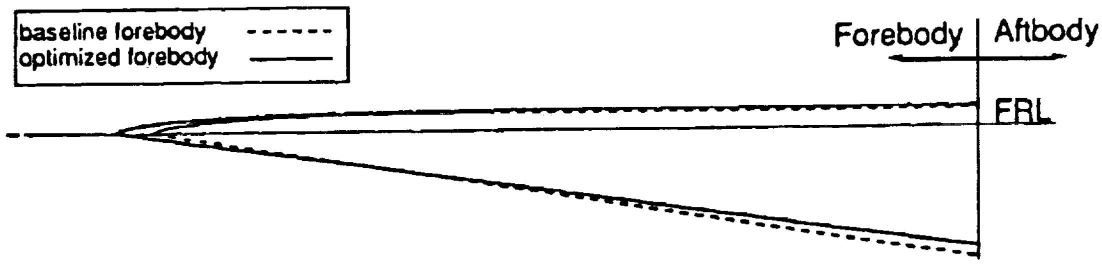
The most significant results obtained by RSOP and open to the public is the forebody geometry design of the single stage to orbit hypersonic aircraft shown in Figure 19.
This is a truly multidisciplinary design problem involving structures, aerodynamics, thermal analysis and mission analysis, but structural design was one of the critical components since it is necessary to have a very low structural weight fraction.



L_f	=	Forebody Length
θ_f	=	Forebody Mean Cone Angle
h_u	=	Fuselage Upper Surface Height
L_{ut}	=	Upper Surface Transition Length

Figure 19 Baseline Space Plane Configuration

The forebody configuration was represented by the four parameters given in Figure 19. The objective was maximization of the trimmed specific impulse, I_{SP}, at a hypersonic speed. I_{SP} is the ratio of thrust to fuel flow and is a critical measure of propulsion efficiency of the vehicle. This I_{SP} depends on the total air mass flow captured by the inlet of the engine. The flow under the forebody is sensitive to the geometry of the forebody. In this design, 3D Euler CFD, 2D Navier-Stokes CFD, engine cycle/nozzle analysis and finite element structural analysis odes were coupled via the global sensitivity scheme[20] to capture the interaction between the aerodynamic geometry and the flexibility of optimized structures. One of the typical results is shown in Figure 20. If the body is assumed to be rigid, the optimizer is driving the vehicle shape to become a slender cone shape by stretching the forebody while reducing the cone angle. Inclusion of structural flexibility reduced this stretching by 50%.



Optimization Parameter	Baseline Value	Optimization Results
Design Variable		
1 - Forebody length	1.000	1.0209
2 - Cone angle	1.000	0.9693
3 - Upper surface height	1.000	1.0029
4 - Geometric transition length	1.000	1.0760
5 - Elevon deflection	1.000	0.8620
6 - Bodyflap deflection	1.000	1.0320
Objective		
Effective trimmed Isp	1.000	1.1259

Figure 20 Optimization of Space Plane Forebody Geometry

As shown in this example, structural analysis/design capabilities are recognized to be critical components of multidisciplinary aircraft design systems. But structural optimization is not working as an isolated program. Instead, it is interacting with other modules through constraints and loads. This trend seems to attract a great deal of attention of the research community as well as the industrial developers. A variety of other applications of the system developed at Rockwell are also found in References 21 and 22.

V Other Developments

The items compiled in this section represent some very practical and innovative applications related to structural optimization. They differ from the preceding examples in that they represent insight into the details of optimization rather than its application to a single specific case.

V.1 Weight Evaluation of a Wing based on Optimized Structural Design

Finite element structural analysis models are generally only skeletal representation of the primary load carrying members and may represent less than half the mass of the actual as built structures. Additional materials are needed for padding-up for fasteners, stiffening, access holes and other penetrations, primers, paints or other protective coatings, etc. A single factor and/or normal parametric multipliers obtained by the statistical data may or may not be adequate, but are especially questionable when extrapolating the data to unconventional new designs. For airframe structures, the additional factor ranges from 40 to 80% for conventional metal structures and 30 to 60% for sandwich and composite structures. This level of uncertainty could wipe out all the effort of structural optimization and is unacceptable even in the conceptual design stage since selection of incorrect values for the factor may lead to poor design decisions.

In the early '80s, an innovative concept was developed by a group at Boeing Military Aircraft to address this critical issue.[23] The key is to recognize that structural optimization is a powerful tool to establish the most efficient loadpaths and that the load envelope, applied to the finite elements, is reflected in its optimum sizing. The observation that the theoretical optimal size contains the critical information to estimate the weight of the as-built structure is very profound.

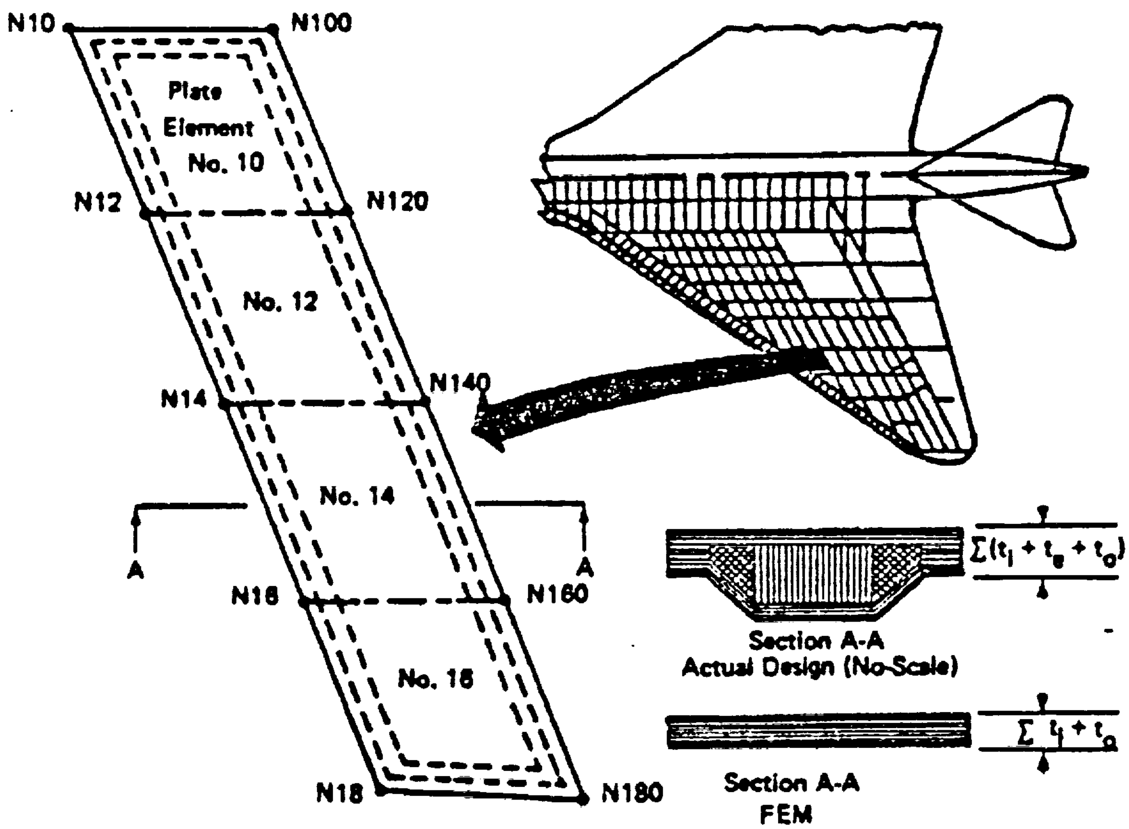


Figure 21 Sandwich Wing Panel

To properly account for these weight items in a visible and traceable manner, one must break down the structure into small enough components; for instance, one structural panel modelled by one finite element. For each component, a theoretical optimal weight is obtained from the results of structural optimization and additional items are then defined by increments controlled by multiple factors reflecting design and manufacturing methods.

For example, consider a sandwich panel as shown in Fig. 21. The finite element model may not account for any of the core materials, or for the padup for the edges where it would be fastened to the substructure. Also, the core may require an adhesive layer for good bonding to the laminate skin, etc. The critical factor to make the weight estimation method usable in preliminary design stage is the capability to come up with reasonably accurate weight estimates based on the limited information available before detailed drawings exist. The algorithm developed computes incremental weights to account for known omissions and add them to the theoretical weight. A particular element would typically use from 3 to 10 algorithms off the shopping list. Hence, the total weight of each element would be:

$$W^{e}_{Total} = W^{e}_{Optimal} + \Delta W^{e}_{1} + \Delta W^{e}_{2} + \cdots + \Delta W^{e}_{n} \tag{1}$$

As an example, the list of available algorithms for a plate element includes:

1. Load offset	2. Major splice
3. Stepped gauge	4. Surface finish(outer)
5. Surface finish(inner)	6. Fasteners
7. Manhole	8. Missing lamina
9. Edgeband pad-up	10. Stiffeners
11. Hole out	12. Small Hole pad-up
13. Fillets	14. Septum
15. Honeycomb core	16. Tapered core
17. Extra skin over taper	18. Skin/core adhesive
19. Core filler	20. Transition doublers
21. Positive margin increments	22. S/V hardening
23. Manufacturing tolerance and practical penalties.	24. Special considerations

An incremental weight computation algorithm was developed for each of these items for aluminum, composite laminate and sandwich constructions. Each algorithm uses a small number of control parameters specified by the user, but automatically estimates necessary sizes of additional weight components based on the theoretical (optimal) size. Therefore, the user of the computer program, FEM/SOAP, has freedom to select particular design concepts, but does not have to work out detailed design information.

The benefits of this type of program in the preliminary design include:

1. Accurate weight data of as-built structures in time to give sufficient impacts on the preliminary design decisions. For example, weight evaluation of a structure with 5,000 elements can be completed in 24-26 man hours and each revision may be completed in less than 8 man hours.
2. Additional weights to the optimized structures are justified with complete visibility of "how much, where and why."

V.2 Engine Mount Design for Cabin Noise and Vibration Control

As shown schematically in Fig. 22, each engine of this twin engine transport is mounted on the under-wing strut via the isolator mounts. Unbalance of the fan and low pressure turbine (LPT) causes vibration which is transmitted through the structure to appear as noise within the cabin. The purpose of the isolation mounts is to reduce the cabin noise. Generally, soft mounts are desirable for noise reduction but stiff mounts are desired for flutter and wear considerations. Therefore, the design of engine mount stiffnesses is, in essence, reduced to seeking the best compromises of these conflicting requirements.[24]

The complete system is composed of three subsystems: engine [C], mounts [K], and airplane [A] as shown in Fig. 23. On the engine side, NASTRAN direct frequency response is used to compute engine compliance defined at the rotor unbalance degrees of freedom and at the engine mounts. The engine mount compliance $[K]^{-1}$ is a diagonal matrix of reciprocal stiffness. On the airplane side, a harmonic shake test at the engine mount attach points is used to measure the airplane compliance [A] and cabin noise [B].

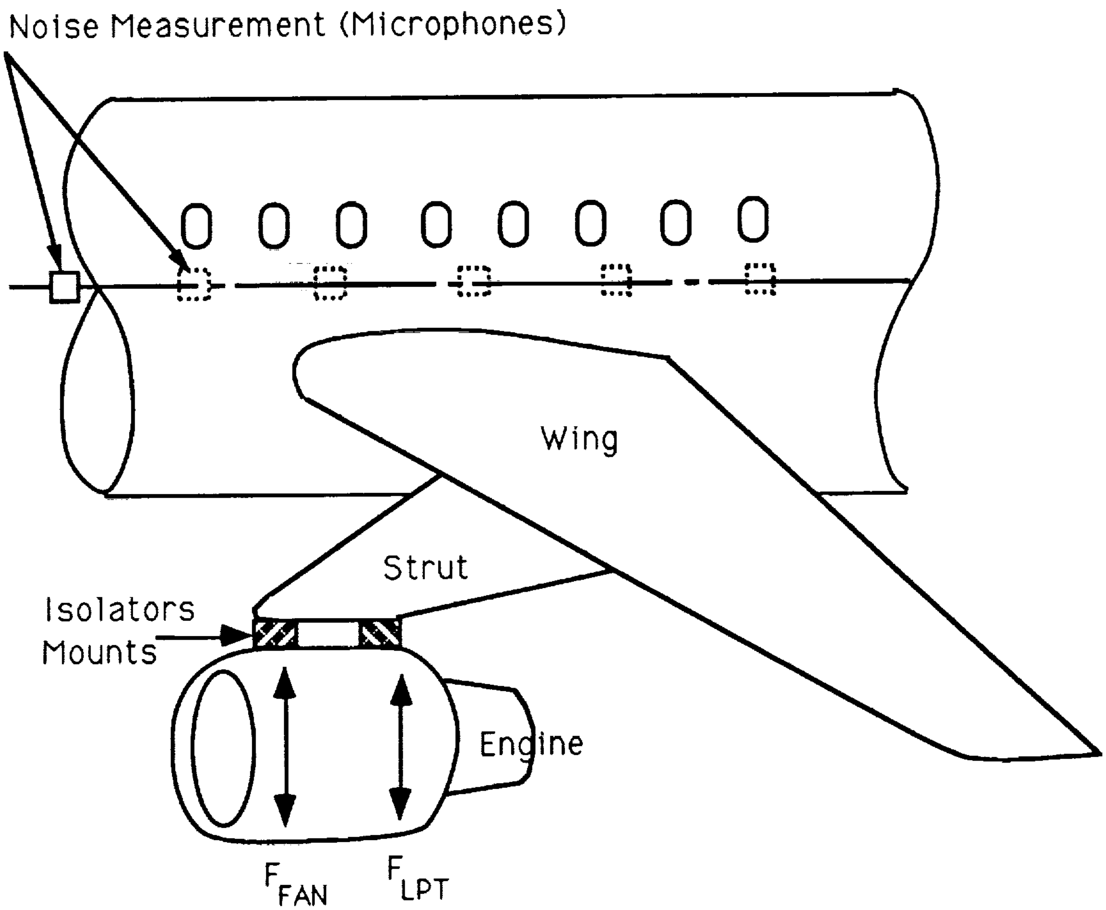


Figure 22 Fuselage, Wing, Strut, Mounts and Engine Assembly

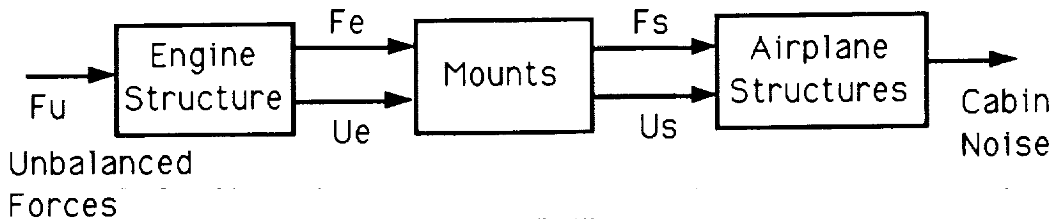


Figure 23 Noise Analysis Block Diagram

The Method of Compliance Merge is used. The subsystem compliance matrices are defined by:

Engine:

$$\begin{Bmatrix} \vec{u}_u \\ \vec{u}_e \end{Bmatrix} = \begin{bmatrix} C_{uu} & C_{ue} \\ C_{eu} & C_{ee} \end{bmatrix} \cdot \begin{Bmatrix} \vec{F}_u \\ \vec{F}_e \end{Bmatrix} \tag{2}$$

Mounts:

$$\begin{gathered} \{\vec{F}_e\} = \{\vec{F}_s\} \\ \{\vec{u}_e - \vec{u}_s\} = [K]^{-1}\{\vec{F}_s\} \end{gathered} \tag{3}$$

Airplane:

$$\begin{gathered} \{\vec{u}_s\} = [A]\cdot\{\vec{F}_s\} \\ \{\vec{n}\} = [B]\cdot\{\vec{F}_s\} \end{gathered} \tag{4}$$

Elimination of $\{\vec{u}_s\}$ and $\{\vec{F}_e\}$ gives the system compliance equation for finding the unknown forces $\{\vec{F}_s\}$ due to the prescribed engine unbalance $\{\vec{F}_u\}$:

$$\{\vec{F}_s\} = -\left[A + C_{ee} + K^{-1}\right]^{-1}[C_{eu}]\{\vec{F}_u\} \tag{5}$$

Then, displacements $\{\vec{u}_e\}$ and noise

$$\begin{gathered} \{\vec{u}_e\} = \left[A + K^{-1}\right]\{\vec{F}_s\} \\ \{\vec{n}\} = [B]\{\vec{F}_s\} \end{gathered} \tag{6}$$

The objective function to be minimized is the RMS of the noise components subject to constraints on the engine displacements. The design variables are the mount stiffness [K]. Other design variables could be included in this design procedure. The optimizer used in this study was COPES/CONMIN.[25]

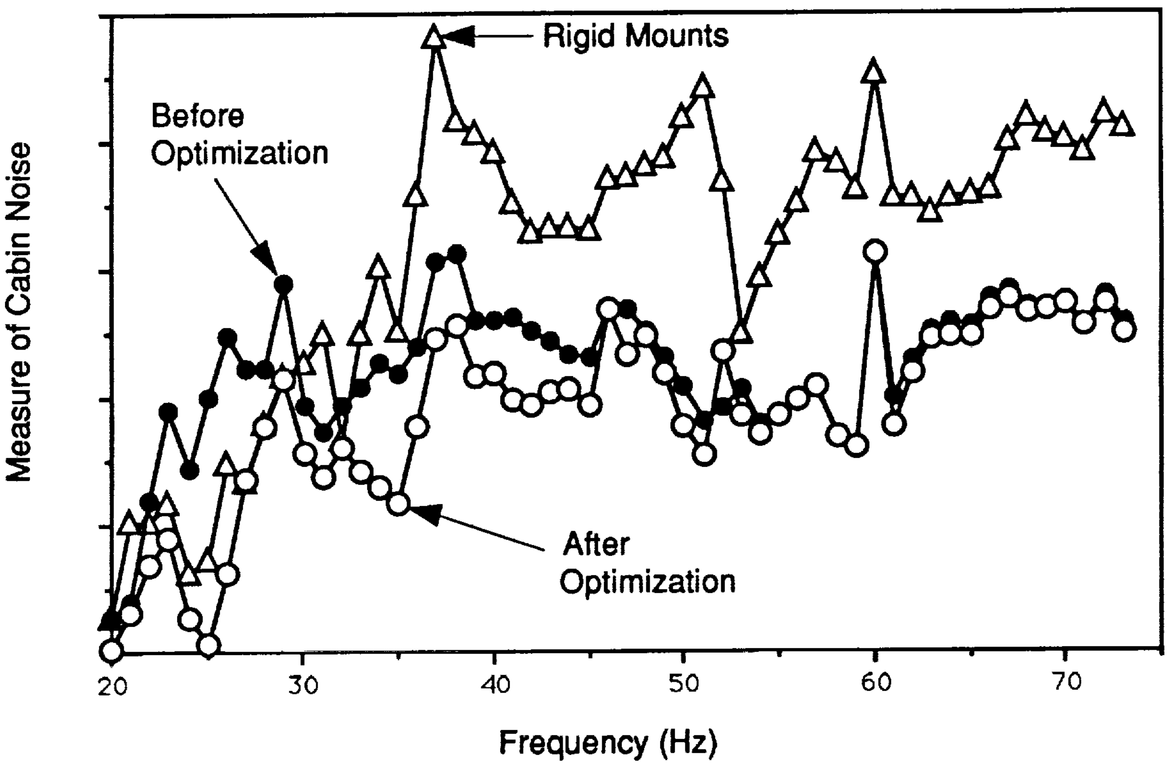


Figure 24 Computed Measure of Cabin Noise for Three Engine Mounts

Typical results are given in Figure 24, where the RMS cabin noise vs. excitation frequency are plotted for rigid, initial and optimal mount stiffnesses in the frequency range, 20 to 73 Hz. The initial design before optimization was already well tuned to isolate the vibration in this frequency range, thus any additional reduction of cabin noise has practical significance. For the example given above, a significant reduction in noise level in the frequency range 20 - 45 Hz without degrading noise suppression in the higher frequency range is considered to be important.

Since it is not desirable to permit excessive deformation, adequate constraints are imposed on all components of the deformation vector, $\bar{\mathbf{u}}_s - \bar{\mathbf{u}}_e$. Furthermore, relative stiffnesses and their frequency dependence are subject to practical manufacturing constraints of the mounts, which must be quantified and incorporated into the formulation of the optimization problem.

Extensive design studies have been carried out for the improvement of engine mount design of the existing and future transport aircraft . However, verification of the performance of the mounts designed by the structural optimization technique described herein has yet to be done.

V.3 Applications of Design by Experiments

Techniques to plan experiments in such a way that we obtain as much information as possible from a limited number of tests have been the subject of research for a long time.

These same techniques, however, have been applied to engineering design problems only recently. These techniques are called Design By Experiments (DBE) or Response Surface Method(RSM). Among the techniques available, various applications of the Taguchi method[26] started appearing in literature. The Taguchi method is based on statistical theory and is different from mathematical programming algorithms. This approach may be regarded as an effective guideline to search through the discrete combinatorial design space to locate the best combination of design variables using a limited number of experiments. It can take advantage of prior knowledge of the user to narrow the search space. For example, if the user has *a priori* knowledge that there are no interactions among certain sets of variables, the search space is reduced by taking advantage of such specific knowledge. Under the Taguchi method, various combinations of tables called orthogonal arrays are available and the contents of the each table indicate which experiments are to be carried out. Usually the number of experiments to be carried out is only a fraction of the total possible number of combinatorial experiments. The user selects one such table and carries out all the experiments requested. The results of the experiments are used to organize additional tables in such a way that an optimum combination of variable settings can be identified.

An example applied to structural design optimization was the selection of the landing gear configuration for minimum weight.[27] In this example, three joint location variables and two structural member size variables are identified. Each of these five variables may assume three distinct values, thus the total number of possible combinations is 243. Interactions of variables are considered only among the joint location variables. An orthogonal table labeled L_{27} was used requesting 27 experiments. Each experiment requires an estimate of the weight of the landing gear structures for the selected values assigned to the five parameters. The smallest weight found in these 27 experiments was 301.9 pounds. However, after processing the results, the best possible combination of values for five variables was identified, which was not included in the 27 experiments. When the weight of the suggested design was computed, it was found to be 292.42 pounds.

Ref. 28 used the Taguchi method to identify promising regions in the design space based on the regression model obtained from the results of multiple analyses. For example, if the domain of each of five variables is divided into four subregions, there are 4^5 =1,024 possible subregions. The search for the most promising subregion based on the regression analysis model was performed by the Taguchi method which requires a much smaller number of optimizations within specific subregions.

More recently, Ref. 29 reported applications of Taguchi method to aeroelastic tailoring with the TSO program. The purpose of this study was to identify the relative importance of weighting coefficients in the special composite objective function of TSO, so that a measure representing better roll performance combined with lower skin weight is achieved as a side effect of structural optimization by TSO.

These examples suggest various innovative possibilities to exploit integration of the best parts of two approaches, i.e. methods for design by experiments such as the Taguchi method and mathematical programming structural optimization methods.

VI Concluding Remarks

It is obvious that the U.S. aerospace industry substantially increased its use of structural design optimization during 1980s. It is certain that numerous other interesting and important projects employing optimization were carried out during this watershed decade, but the majority of such activities are not available under company proprietary or other strictures. Often, these applications by line engineering sections remained undocumented because the engineers are too busy to write about their excellent engineering practices.

While it remains difficult to say in the '80s that, for example, the wing of a particular airplane was designed by structural optimization, we can say that many of the actual designs or design studies performed during 1980s depended on structural optimization techniques somewhere in the design process. The uses of structural optimization might be varied but such applications must have resulted in practical information useful to the design team. This trend will clearly be accelerating steadily in 1990s.

Actual incorporation of structural optimization in practical design environment is different at each company. In the industrial environment, it is hard to introduce any procedures with which the associated engineers are not completely comfortable. After all, they have to make design decisions and have to live with the decisions. Therefore, each company seems to have started with the available tools in which they have complete confidence or with procedures to which they have become accustomed. Seasoned, skilled applications of FASTOP at Grumman and the extensive use of TSO at General Dynamics are examples of the first category. Detailed panel sizing based on the assumption of small internal force variation through the design variable perturbation has been the standard way of incorporating finite element structural analysis in the design process. Lockheed, McDonnell Douglas and many others took advantage of this well established gauge sizing practice and used structural optimization to adjust multiple sizing variables in each of the local substructures. The designers seem to feel at home with this approach because they can determine relatively detailed structural arrangements in the early design phases, while assuring that the designs they are producing are physically realizable and manufacturable.

Industrial applications of general purpose structural optimization codes have not been well publicized yet, especially in the domain of aerospace design. One of the obvious reasons for slow penetration of the general commercial structural optimization codes is the lack of preprocessor capabilities. With the advent of new generation graphic preprocessors that are capable of creating design models, these programs will find niches in the aerospace industry. However, it is still uncertain if there exists a universal structural design framework that will be accepted by almost all the U.S. aerospace industry.

This decade has been a remarkable period of evolution of the engineering design process, multidisciplinary analysis and, finally, multidisciplinary design optimization. This report has detailed a few applications of these multifaced topics. It is clear that the previously "academic" study into structural optimization has grown into a practical methodology that is giving benefit in the design of aerospace structures. While the tools are still new, and their relationship to the existing management structures, design organizations, engineering and manufacturing processes are not well understood, it is clear they will be integrated into standard engineering practice. Perhaps the '90s will result in sufficient progress so that, like finite element structural analysis, optimization applications will no longer be noteworthy enough to merit a report such as this.

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13. ABSTRACT *(Maximum 200 words)*
This report is the summary of a technical survey on the applications of structural optimization in the U.S. aerospace industry through the 1980s. Since applications to rotary wing aircraft will be covered by other literature, applications to fixed-wing aircraft and spacecraft were considered. It became clear that very significant progress has been made during this decade, indicating this technology is about to become one of the practical tools in computer aided structural design.

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