Recent Developments in Large–Scale Structural Optimization *

V.B. Venkayya

Flight Dynamics Laboratory
Air Force Wright Aeronautical Laboratories †
Wright-Patterson AFB, Ohio

ABSTRACT

This paper presents a brief discussion of mathematical optimization and the motivation for the development of more recent numerical search procedures. A review of recent developments and issues in multidisciplinary optimization are also presented. These development are discussed in the context of the preliminary design of aircraft structures. A capability description of programs FASTOP, TSO, STARS, LAGRANGE, ELFINI and ASTROS is included.

INTRODUCTION

The notion of an optimum solution to an engineering problem is intriguing and has been investigated for a long time. The strongest cantilever.beam in bending and constant shear as formulated by Galileo Galilei was also an optimum design for minimum weight under a uniform stress constraint. Galileo's problem was probably one of the earliest structural optimization problems. However, the roots for the development of mathematical optimization started after the introduction of calculus by Newton and/or Leibniz during the latter part of the 17th Century. The min-max conditions (from calculus) as defined by the gradients of the function with respect to the independent variables provided the necessary conditions for optimal solutions. The function itself represented a measure of the performance of the system, while the independent variables spanned the design space. The min-max conditions. in their original form, are only of limited, interest because they addressed only the unconstrained optimization problems, which are of little interest in true engineering optimization. The extension of simple mini-max conditions to constrained optimization problems is through the formulation of an augumented Lagrangian function which consists of both the objective and constraint functions with additional variables called Lagrangian multipliers. There are as many Lagrangian multipliers as there are

constraint functions. The Lagrangian multipliers serve two purposes: a) they are weighting factors in establishing the importance of the various constraints at different regions of the design space; b) they are also a link between the objective and the constraint functions in the augumented Lagrangian function. One way of looking at this latter connection is the dimensional compatibility of the objective function and the constraint functions in an augmented Lagrangian function. The Lagrangian multipliers are the dual variables, while the original variables in the objective and constraint functions are the primal variables. Determination of both these variables constitutes the solution of the optimization problem.

The emergence of the calculus of variations (attributed to Bernoulli, Euler and Lagrange during the 17th/18th Century) represents the beginning of the golden age of mathematical optimization. The brachistochrone problem and its many variations provided an intellectual challenge to such great mathematicians as the Bernoulli brothers, Leibniz, L'Hôpital and Newton. Variational calculus is basically a generalization of the elementary theory of minima and maxima. However, variational methods deal with the extremum of a function of functions. The resulting solution is not an extremum point but one or more functions, and they are represented by differential equations. The solution of these differential equations represents the optimal path or all the optimal points in the domain of definition.

Variational methods have applications in many disciplines such as solid mechanics, fluid mechanics, fluid-structure interaction, optics, flight mechanics, optimal controls and general engineering optimization problems. The formulation of the Euler-Lagrange equations in the 18th Century represented the most far reaching advance in variational calculus. Most of the field equations of rational mechanics can be derived from the Euler-Lagrange equations. The next major advance in variational methods was the "principle of least action" as originally derived by Euler and later improved and expanded to a wider class of forces by Hamilton. It is subsequently known as Hamilton's principle. Most of the dynamic system equations based on Newton's Laws can be derived from Hamilton's principle of least action. A further extension of the principle of least action is the formulation of Lagrange's equation which is the basis for an elegant description of Newtonian dynamics. Reference 1 provides a lucid description of the development of variational methods with details of the mathematical formulation.

Even though variational methods are the basis for all optimization problems, they present numerous difficulties in practical applications. The Euler-Lagrange equations

which express the extremum conditions yield one or more differential equations for solution. Most often they are nonlinear differential equations. The solution of nonlinear differential equations in closed form is difficult except in the case of very simple problems. Even when there are solutions, the continuity and differentiability requirements severely restrict the range of their application. A numerical approach to the solution of variational equations involves an approximation of derivatives by differences and integrals by sums. The accuracy, time steps and convergence become serious impediments to a reliable solution. Multidisciplinary design as an optimization problem becomes even more intractable in the context of variational calculus. Each discipline generates different orders and characteristics of the differential equations, and their interface is often difficult because the requirements of differentiability and continuity cannot be satisfied easily. Moreover modern digital computers are geared for the direct solution of algebraic equations rather than differential equations. The solution of differential equations on a digital computer involves an additional step of converting them into algebraic equations through approximations which do not always guarantee the desired accuracy or the stability of convergence.

It became apparent in the 1950's that high speed digital computers can provide unprecedented opportunities for the solution of complex engineering problems. The result is the development of finite element, finite difference and other discrete methods for the analysis and numerical search techniques for optimization problems. A common feature of these new methods is that they reduce the field equations to algebraic form instead of ingro-differential form. The algebraic equations are readily amenable to solution on high speed digital computers.

The basic concept of numerical search techniques for optimization problems is very simple. It involves a point by point search for the optimum in an n-dimensional design space. In its simplest form a numerical search procedure consists of four steps when applied to unconstrained minimization problems:

i.   Selection of an initial design in the n-dimensional space where n is the number of variables.

ii. A procedure for the evaluation of the function (objective function) at a given point in the design space.

iii. Comparison of the current design with all the preceding designs.

iv. A rational way to select a new design and repeat the process.

The constrained minimization requires an additional step for the evaluation of the constraints. This step is for determining whether the design is feasible (does not violate the constraints).

The numerical search procedure as outlined here appears deceptively simple. However, actual implementation to practical design problems poses many difficult questions which cannot be answered easily. Even a cursory examination of the procedure reveals a number of uncertainties. For example, how is the initial design selected and what effect will it have on the outcome of the search? If there is a unique optimum, the intial design should not effect the final result. However, it is well known that most nonlinear optimization problems will have multiple optimums, and the initial design would only guarantee the nearest optimum. Even if there is a unique optimum, the initial design will certainly effect the number of points to be searched. The next pertinent question is what is a rational way to select the new designs and how does it effect the final outcome. This is the most serious issue and incites more passion than a rational discussion among the algorithm developers. The simplest, but probably a mindless way, is to select new design points at random. This procedure may be acceptable when the dimensionality of the design space is small and the objective and constraint functions evaluation is simple and computationally inexpensive. A more rational approach to the search strategy is to take advantage of the gradient information of the objective and constraint functions to reach the optimum. The next question is where to stop the search. The obvious answer is when the optimality conditions are satisfied. In the case of unconstrained minimization, the necessary conditions for the optimum are the standard min-max criterion of calculus. For constrained minimization problems the same min-max conditions are also valid with the augumented Lagrangian function. In the presence of multiple optimums this procedure can only guarantee the local optimum. The only way to investigate other solutions is by starting at different initial points and hope to cover the rest of the design space. Even though the numerical search procedures lack the elegance of variational methods, they are simple in concept and flexible in implementation in multidisciplinary design.

ISSUES IN MULTIDISCIPLINARY DESIGN OPTIMIZATION

Design optimization in an interdisciplinary setting is one of the most promising fields at present both in basic research and exploratory development. As systems become more and more complex, a creative designer needs to supplement intuition with computational tools in order to verify the validity of new concepts. Recent developments in computer

hardware and related software offer great opportunities for integration of the relevant disciplines to simulate the true environment of aerospace vehicles. The goal of modern design is to optimize the total system rather than the individual components. The conflicting requirements of the subsystems can be handled much more effectively in an integrated design.

As lofty as this goal might be, progress has been very slow in achieving the objectives of interdisciplinary design. The obvious difficulty is the vast scope of individual disciplines and the inability to comprehend complex interactions. For example, a typical aircraft design encompasses at least aerodynamics, structures, controls and propulsion.

Each of the disciplines presents numerous computational issues on their own. When combined, their interaction further compounds the problem. Even the definition of a simple merit function, the constraints, and the variables that respond to the requirements of all the disciplines is not an easy matter. The weight of the structure may be the most appealing merit function for a structural designer. The lift and/or drag may be the concern of an aerodynamicist. Some stability or performance criterion may be a suitable merit function for a control designer, while the thrust to weight ratio may be the interest of the propulsion designer. The definition of the constraints and the variables similarly add to the complexity.

A closer examination of the design process in the context of an aircraft wing (and other lifting surfaces) optimization can lead to a better appreciation of the complex interactions. In particular the coupling between aerodynamics, structures, and controls is very strong in high peformance aircraft. The elements of structural optimization with due consideration to this coupling are shown schematically in Fig. 1. It is assumed that a structural concept definition preceded this discussion, and a reasonable mathematical model of the structure is available for preliminary design.

The loads definition is a complex process in an aircraft design. This information can be derived from knowledge of the expected maneuvers. The maneuver loads have generally two components: The inertia loads from the aircraft acceleration and the lift and drag forces from the aerodynamics. They are calculated at the peak condition of each maneuver and used as static airloads. These loads are used in conjunction with the static and dynamic aeroelastic conditions in optimization. The airloads are computed on the entire lifting surface (aerodynamic model). The structural box normally constitutes only a fraction of the lifting surface, and the two models (the aero model and the structural model)

Interdisciplinary Design

Mass Properties →	**Inertia Loads** →	**Maneuver Loads** ←	**Flexible Air Loads**
Steady Aero Model →	**Rigid Air Loads** →	**Transformation Forces** →	**Aeroelastic Corrections**

Controls ← **Normal Modes** ←

Structural Model

[M] [K] [C] {Q}

SIC

Eigenvalue Analysis

Stress Analysis

Transform Displacements

Transform AIC

ASE ← **Aeroelastic** →

Unsteady Aero Model

Sensitivity Analysis

Objective Gradients

Constraint Gradients

Optimization

Search Directon

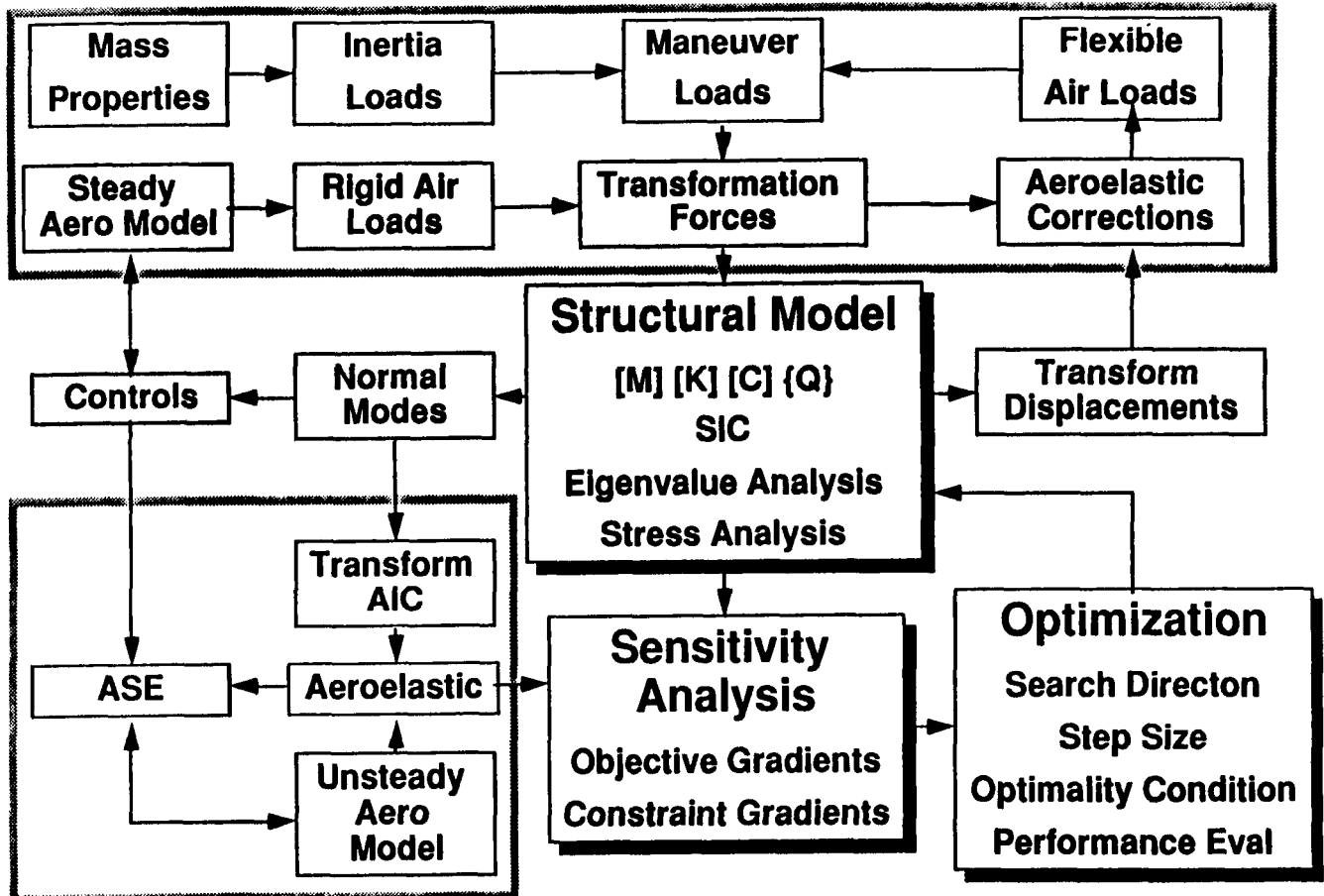Step Size

Optimality Condition

Performance Eval

FIGURE 1

are not the same. To make the two models compatible, two types of transformations (one preceding and one after the analysis) must be devised. One transformation involves the generation of an equivalent load system from the airloads to the structual grid loads. The theoretical basis of this transformation is somewhat nebulous and open to controversy. The assumptions made in deriving this transformation can adversely effect the local behavior of the structure. Optimization can further aggravate the situation by propagating the errors. The second transformation involves an interpolation/extrapolation of the displacements from the structural box to the aerodynamic surface. The purpose of this extrapolation is to determine the change in angle of attack (due to deformation) which effects the air flow on the wing. Many software systems such as NASTRAN and ASTROS use a spline extrapolation for this purpose. In many instances the approximations in this extrapolation seem to break down and produce spurious results. Even though the loads and the displacement transformations appear to be innocuous, they are one of the serious impediments to integration. The technology of maneuver loads calculation is one of the major stumbling blocks. This is particularly so in the supersonic range. Aeroelasticity and aeroservoelasticity are emerging technologies, and they need further validation. Dimensionality is a serious limitation in optimization algorithms. This limitation is of particular significance in the optimization of composites where the number of design variables increases rapidly. These are some of the issues which need further resolution for an effective application of multidisciplinary optimization.

STATUS OF MULTIDISCIPLINARY OPTIMIZATION

Interest in multidisciplinary design has been widespread for over 20 years. A number of optimization programs for the preliminary design of aircraft structures were developed in the past and are being developed at present. A brief review of these optimization systems is provided in the remainder of this paper. A list of programs reviewed in this paper is as follows:

- ASOP-FASTOP[2,3]

- TSO[4,5]

- STARS[6,7]

- LAGRANGE[8,9]

- ELFINI[10]

- ASTROS[11,12]

ASOP-FASTOP PROGRAM

The ASOP (*A*utomated *S*tructural *O*ptimization *P*rogram) and FASTOP (*F*lutter *A*nd *S*trength *O*ptimization *P*rogram) programs were the earliest attempts to automate the preliminary design function of lifting surfaces. These programs were originally intended for the modest integration of structures, aerodynamics and optimization. The original objectives of these programs were very ambitious but with very limited resources for development. However, these programs were very effective and established the feasibility of integrating the three disciplines. They are the forerunners for the more recent systems. The objectives of even recent systems are not significantly different from those of FASTOP. A summary of FASTOP capabilities and shortcomings is provided here.

- Structural Model
    - Elements
        - Membrane Quadrilateral
        - Membrane Triangle
        - Shear Panel
        - Rod
        - Bar
    - Materials
        - Isotropic and Layered Composites
- Air Loads
    - Steady Aerodynamics
    - Distribution of Vortices - Subsonic
    - Distribution of Sources - Supersonic
- Inertia Loads
    - Maneuver Defined by
    - Vehicle Load Factors
    - Angular Accelerations and Velocities
- Aerodynamics and Structure Interface
    - A beaming procedure to the structural grid points nearest to the panel center of pressure.
- Aeroelasticity
    - Unsteady Aerodynamics

Kernel Function - Subsonic

Doublet-Lattice - Subsonic

Mach-Box - Supersonic

Flutter Solution

K-Method

P-K Method

- Optimization

  Stress-Ratio Type

- Objective Function

  Weight

- Constraints

  Strength, Stiffness and Aeroelasticity

The major contribution of FASTOP is that it established the feasibility of integrating structures, aerodynamics and aeroelasticity. It is a relatively unsophisticated program from the point of view of software design. It is a difficult program to adapt to changes in computer operating systems. A number of aerospace companies have used the FASTOP system, and even today it is considered to be a very good capability.

TSO PROGRAM

The TSO (Tailored Structural Optimization) program was developed for the tailoring of composites for aircraft wing type structures. It is intended primarily for making rapid design trades in order to establish performance trends while optimizing the composite layup. Structures, aerodynamics, aeroelasticity (with the capability to model multiple control surfaces), sensitivity analysis and optimization are the disciplines integrated in this program.

SPECIFIC DETAILS

- Structural Model

  Smeared Plate and Raleigh-Ritz Procedure

  Single Trapezoidal Surface

  Polynomial Variation of Thickness

- Materials

  Isotropic and Layered Composites

- Air Loads

A Finite Element Lifting Surface Procedure - ROT

- Inertia Loads

    Maneuver Specified

- Aeroelasticity

    Assumed Downwash Pressure Distributions

- Optimization

    Unconstrained Minimization with Penalty

    Davidson-Fletcher-Powell Modification for Search

- Objective Function

    Weight

- Constraints

    Strength

    Stiffness

    Static and Dynamic

    Aeroelasticity

TSO is one of the most widely used programs for the aeroelastic tailoring of lifting surfaces with layered composites. One of the serious deficiencies of TSO is the structures model. Equivalent plate idealization does not fully capture the internal behavior of a wing structure. It needs extensive lumping before optimization and unlumping after optimization. Nevertheless, it is an extremely good capability for establishing overall design trends.

STARS PROGRAM

STARS - (_ST_ructural _A_nalysis and _R_edesign _S_ystem) is a structural optimization system originally developed at RAE. Later development was transfered to SCICON Ltd. This program is of interest to aircraft companies in Europe, in particular, British Aerospace in England and MBB in Germany. The original STARS was primarily a structural optimization program. It was intended for structural weight minimization with strength, stiffness and frequency constraints. The program has limited structural analysis internally (RAE analysis) but depends on programs like NASTRAN for large scale applications. Versions of the program at MBB and British Aerospace include a flutter optimization capability. To the author's knowledge the program does not have the capability to calculate static air loads.

SPECIFIC DETAILS

- Stuctural Model
  - Elements

    When used in conjunction with NASTRAN, it has access to all the NASTRAN elements. RAE analysis consists of the following elements:

    Membrane Quadrilateral - Bending

    Rod

    Bar-Box Beam

    Shear Panel

    Triangular Elements

- Materials

  Isotropic, Anisotropic and Layered Composites

- Air Loads

  The author is not aware of air loads capabilities.

- Aeroelasticity

  Versions at British Aerospace and MBB have aeroelasticity.

- Optimization

  Stress Ratio Module

  Pseudo-Newton Module

  Optimality Criterion Module

- Objective Function

  Weight

- Constraints

  Strength

  Stiffness

  Frequency

  Flutter (British Aerospace and MBB)

The STARS system will continue to be and further develop into a sophisticated structural optimization system if British Aerospace enhances the aerodynamics capability. It is also being used by MBB-civilian division.

LAGRANGE PROGRAM

Messer Schmitt-Bolkow-Blohm in Germany has invested considerable resources in the

development of LAGRANGE, a structrual optimization system. It contains most of the capabilities necessary for the integration of aerodynamics, structures and controls in an optimization setting. It appears that the system has been operational at MBB for over a year. However, it is not clear from the two references, 6 and 7, whether LAGRANGE is an integrated (structures, aerodynamics, optimization, etc.) system or an interface between programs such as NASTRAN, TSO (modified at MBB), ASAT (modified FASTOP) etc. These references contain excellent design studies, and they can be the basis for comparison with the designs obtained from other multidisciplinary optimization systems.

SPECIFIC DETAILS
- Structural Model

  It is not clear if the structural analysis module is external to the system. If NASTRAN is the main driver for the structural analysis, then the system has access to all the elements necessary for the optimization of aircraft structures.
- Materials

  Isotropic

  Anisotropic

  Layered Composites
- Air Loads

  Similar to FASTOP and TSO with signficant enhancements.
- Inertia Loads

  Maneuvers defined by

  Vehicle Load Factors

  Angular Accelerations and Velocities
- Aerodynamics and Structure Interface

  A beaming procedure similar to FASTOP (assumption).
- Aeroelasticity

  It is assumed that it is similar to FASTOP with significant enhancements.
- Optimization

  Sequential Quadratic Programming

  Generalized Reduced Gradients
- Objective Function

Weight
- Constraints
    Strength

    Displacements

    Frequencies

    Static Aeroelastic Efficiencies

The LAGRANGE program is expected to have a significant impact on future multidisciplinary optimization developments. This judgment is based on published design studies using the program.

ELFINI - STRUCTURAL OPTIMIZATION SYSTEM AT DASSAULT

ELFINI is an integrated finite element analysis and optimization system under development at Dassault for over a decade. It is an excellent example of what a sustained long term investment can do to design productivity. It appears that ELFINI's interface is not limited to finite element pre and post processing systems. The Three-D graphics system CATIA with extensive mesh generation capability can be used in conjunction with the finite element pre and post processors to generate a data stream for analysis and optimization. ELFINI integrates the structures, aerodynamics and controls for aircraft structures design. ELFINI has the most extensive applications history starting with its use in the design of Dassault's mirage series fighters to more recent systems like RAFALE (the most recent DASSAULT fighter with extensive use of composites) and HERMES (European Space Shuttle). Both military and civilian applications are cited.

SPECIFIC DETAILS
- Structural Model
    Rod

    Bar

    Membrane Triangle

    Membrane Quadrilateral

    Shear Panel

    Buckling Plate - Triangle and Quadrilateral.

    There are additional elements but they are not relevant in optimization.
- Material
    Isotropic

Anisotropic

Layered Composites

- Aerodynamics

    Extensive Aeroelasticity Capability

    Not clear about integrated air loads capability.

- Optimization

    Conjugate Projected Gradient

- Objective Function

    Weight

- Constraints

    Strength

    Displacements

    Frequencies

    Buckling of the Elements

    Buckling of the Structure

    Static and Dynamic Aeroelastic Constraints

- Graphics Interface

    Extensive graphics interface in pre and post processing and geometric modeling.

Like the program LAGRANGE, ELFINI is expected to play an important role in the development of integrated design systems by providing an applications data base. The most impressive features of ELFINI are its extensive graphics interface and its applications in a practical design environment.

ASTROS - AUTOMATED STRUCTURAL OPTIMIZATION SYSTEM

This program was developed over the past five years. The program was released to industry in July 1988. This program is a follow-up of a series of optimization programs (ASOP-FASTOP-TSO-ASTROS) sponsored by the Flight Dynamics Laboratory at Wright-Patterson AFB. Development of software standards for integrated design systems is one of the significant contributions of ASTROS. This is in the tradition of the development of NASTRAN. ASTROS' "MAPOL" executive system and Computer Aided Design Data Base (CADDB) are supported by six engineering modules which are important in the integrated design of aircraft structures. Figs. 2-4 show the schema, the architecture and the engineering modules.

SPECIFIC DETAILS

- Structures Model

  Rod

  Bar

  Membrane Triangle

  Membrane Quadrilateral

  Shear Panel

  QUAD4 - Bending and Membrane Quadrilateral

- Materials

  Isotropic

  Anisotropic

  Layered Composites

- Aerodynamics

  Air Loads - Steady Aerodynamics

  USSAERO - Woodward Aerodynamics

  Aeroelasticity - Unsteady Aerodynamics integrated into ASTROS

  Doublet Lattice - Subsonic

  CPM - Supersonic

- Optimization

  ADS

  Optimality Criterion (Planned)

- Objective Function

  Weight

- Constraints

  Strength

  Stiffness

  Frequencies

  Static and Dynamic Aeroelastic Constraints

- Graphics Interface

  Data input and output similar to NASTRAN.

  Pre and post processors for NASTRAN are applicable.

With the ASTROS program release to industry, a number of applications and results are expected in the near future. The program is being updated for new releases after quality assurance testing. The formulation of a users group and procedures for submitting an SPR
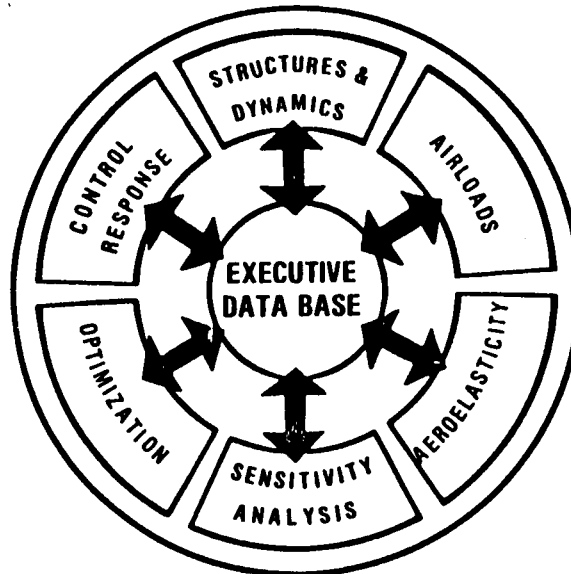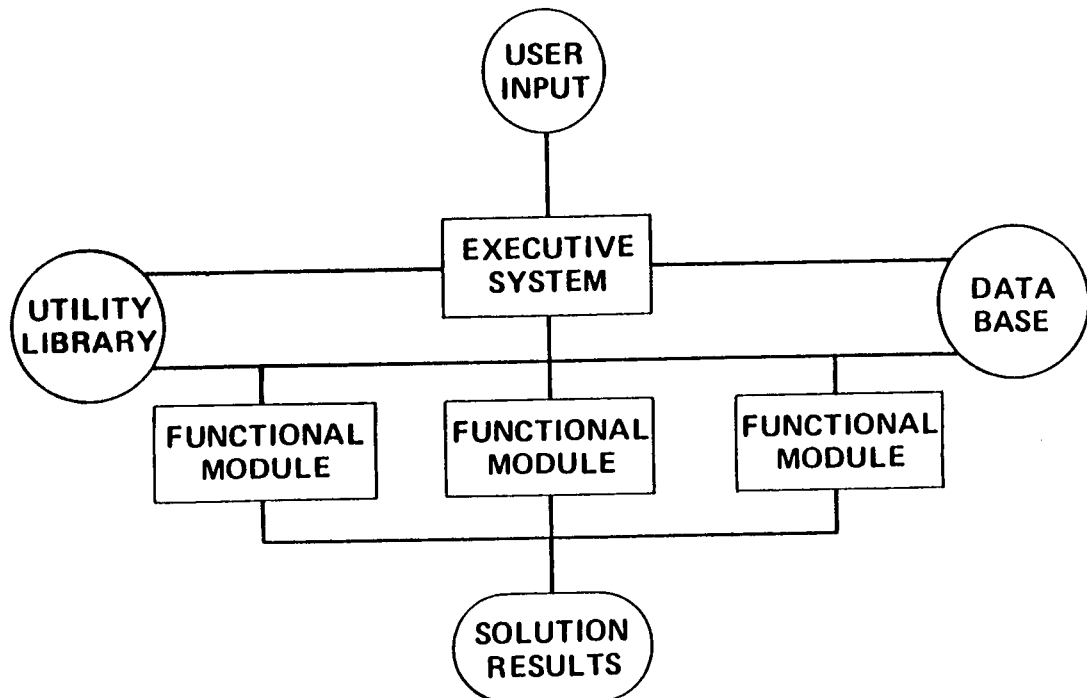
FIGURE 2

ASTROS ARCHITECTURE

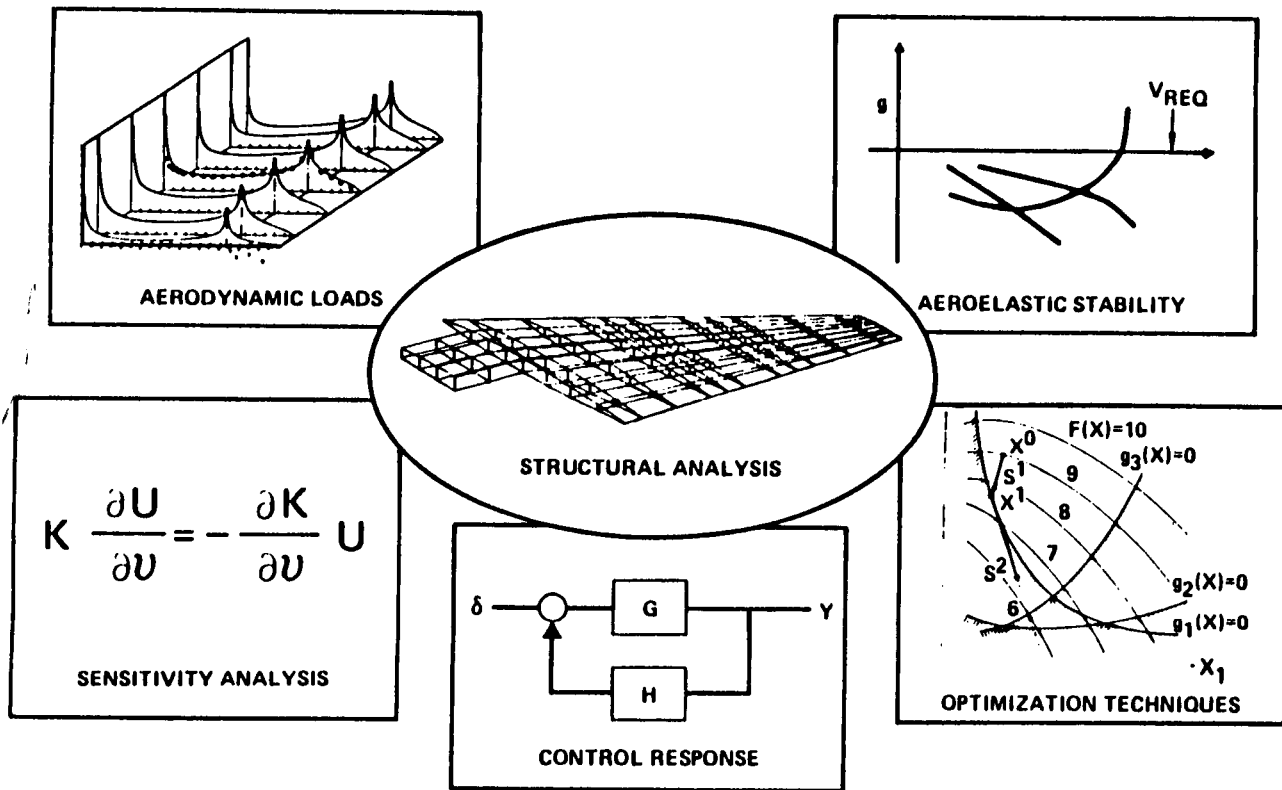

FIGURE 3

ENGINEERING DISCIPLINES

FIGURE 4

(Software Problem Report) and a DER (Documentation Error Report) are being worked out.

CONCLUSIONS

With the release of all these new systems, the concept of multidisciplinary optimization has the potential to become reality. The growth of an applications data base in the next few years will not only help fine-tune the systems but also will provide valuable lessons for future developments. The expected release of MSC-NASTRAN with optimization will be a significant development in the direction of establishing standards for multidisciplinary optimization. The developments in new computers and the interest in integrated design will provide excellent opportunities for making the computer-aided design a reality. Reference 13 contains a capability summary of many of the systems.

REFERENCES

1. Smith, D. R., "Variational Methods in Optimization," Prentice-Hall Inc., Englewood Cliffs, NJ, 1974.

2. Isakson, G., Pardo, H., Lerner, E., and Venkayya, V., "ASOP-3: A Program for the Optimum Design of Metallic and Composite Structures Subjected to Strength and Deflection Constraints," AIAA Paper 77-378; also published in the Journal of Aircraft, July 1978, pp. 422-428.

3. Wilkinson. K., Markowitz, J., Lerner, E., Chipman, R., George, D., and Schriro, G., "An Automated Procedure for Flutter and Strength Analysis and Optimization of Aerospace Vehicles," Vol. I - Theory, Vol. II - Program User's Manual, Air Force Flight Dynamics Laboratory, AFFDL-TR-75-137, Dec. 1975.

4. McCullers, L. A., and Lynch, R. W., "Dynamics Characteristics of Advanced Filamentary Composite Structures," AFFDL-TR-73-111, Volume II, September 1974.

5. Lynch, R. W., Rogers, W. A., and Brayman, W. W., "Aeroelastic Tailoring of Advanced Composite Structures for Military Aircraft," Vol. I - General Theory, Vol. II - Wing Preliminary Design, Vol. III - Modifications and User's Guide for Procedure TSO: AFFDL-TR-76-100, April 1977.

6. Bartholomew, P., Morris, A. J., "STARS: A Software Package for Structural Optimization," Proceedings of the International Symposium on Optimum Structural Design, Oct 1981, University of Arizona.

7. Wellen. H., and Bartholomew, P., "Structural Optimization in Aircraft Construction," Proceedings of the NATO Advanced Study Institute - Computer Aided Structural and Mechanical Systems - Editor: Carlos A. Mota Soares - Springer-Verlag, 1987, pp 955-970.

8. Sensburg, O., Fullhas, K., and Schmidinger, G., "Interdisciplinary Design of Aircraft Structures for Minimum Weight," A paper presented at AIAA/ASME/ASCE/AHS/ACS 29th Structures, Structural Dynamics and Materials Conference, Williamsburg, VA, April 18-20, 1988.

9. Kneppe, G., Kramer, J., and Winkler, E., "Structural Optimization of Large Scale Problems Using MBB-LAGRANGE," Paper presented at the Fifth World Congrress and Exhibition on Finite Element Methods, Salzburg/Austria, October 5-9, 1987.

10 Lecina, G., and Petian, C., "Advances in Optimal Design with Composite Materials," Proceedings NATO - Advanced Study Institute - Computer Aided Optimal Design - Structural and Mechanical Systems - Editor: Carlos A. Mota Soares - Troia, Portugal, June 29 - July 11, 1986.

11 Neill, D. J., Johnson, E. H., and Canfield, R. A., "ASTROS - A Multidisciplinary Automated Structural Design Tool," Paper presented at AIAA/ASME/ASCE/AHS 28th Structures, Structural Dynamics and Materials Conference, Monterey, CA, April 6-8, 1987.

12. Johnson, E. H., Neill, D. J., and Venkayya, V. B., ASTROS: Theoretical Manual - User's Manual - Applications. AFWAL-TR-88-3028, December, 1988.

13. Hornlein, H. R. E. M., "Take-off in Optimum Structural Design," Proceedings of NATO Advanced Study Institute - Editor: Carlos A. Mota Soares - Troia, Portugal, June 29 - July 11, 1986.