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Final Technical Report

OPTIMIATION OF AEROSPACE STRUCTURES

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Research carried out is grouped under two topics:
1. Design Optimization
2. Integrated Force Method of Analysis

1. Design Optimization: Research Topics:

a) Singularity alleviation enhances structural optimization methods

b) Computer based design capability extended through substructure synthesis

c) Optimality criteria provides optimum design for a select class of structural problems

2. Integrated Force Method of Analysis: Research Topic:

d) Boundary compatibility formulation improves stress analysis of shell structures

Brief descriptions of the four topics are appended.

Publications:

1) A.S. Gendy, S. N. Patnaik, D.A. Hopkins and L. Berke, "Preliminsry Analysis and Design Optimization of the Short Spacer Truss of Space Station Freedom"
NASA TM 4470, August 1993

2) L. Berke, S.N. Patnaik, and PLN Murthy, "Application of Artificial Neural Networks to the Design Optimization of Aerospace Structural Components"
NASA TM 4389, March 1993

3) S.N. Patnaik, J.D. Guptill, and L. Berke, "Merits and Limitations of Optimality Criteria Method for Structural Optimization"
NASA TP 3373, August 1993

4) S.N. Patnaik, J.D. Guptill and L. Berke, "Singularity in Structural Optimization"
International Jnl for Numerical Methods in Engineering, Vol 36,6, pp931-944, 1993

5) L. Berke, S.N. Patnaik and PLN Murthy, "Optimum Design of Aerospace Structural Components using Neural Networks"
Jnl Computers and Structures, Vol.48,6, pp1001-1010, 1993

Singularity Alleviation Enhances Structural Optimization Methods

Singularity conditions that arise during structural optimization can seriously degrade the performance of the optimizer. Singularity can arise because of linear functional dependence among active stress and displacement constraints. These conditions can be local or global in nature. Local singularities can occur more frequently than global singularities. Linear functional dependence can be seen among sets of constraints containing very small percentages of the prescribed behavior constraints.

The presence of linear functional dependence can best be determined by an examination of the equations of the integrated force method (IFM) of analysis. If the active constraint set is comprised of stress constraints only, then an examination of the IFM compatibility conditions is sufficient. When the active set includes both stress and displacement constraints, then either stress-displacement relations, or a combination of displacement-stress relations and the compatibility conditions need to be examined. A singular value decomposition technique can also be used to separate the active constraints into independent and dependent sets. In structural optimization, consideration of the independent set of active constraints, (especially during the generation of search direction), will avoid the occurrence of the singularity condition. The alleviation of singularity can greatly enhances the performance of structural optimization methods.

The advantage in structural optimization when singularity condition is alleviated is illustrated by considering a simple three bar truss as an example. The problem is solved twice, first disregarding the occurrence of singularity as is the current practice, and next by solving the same problem when singularity condition has been alleviated. For this problem it is observed that the alleviation of the singularity condition produced monotonic convergence and reduced the number of design iterations to less than 10 from 40 that is, when alleviation of the singularity condition is disregarded.

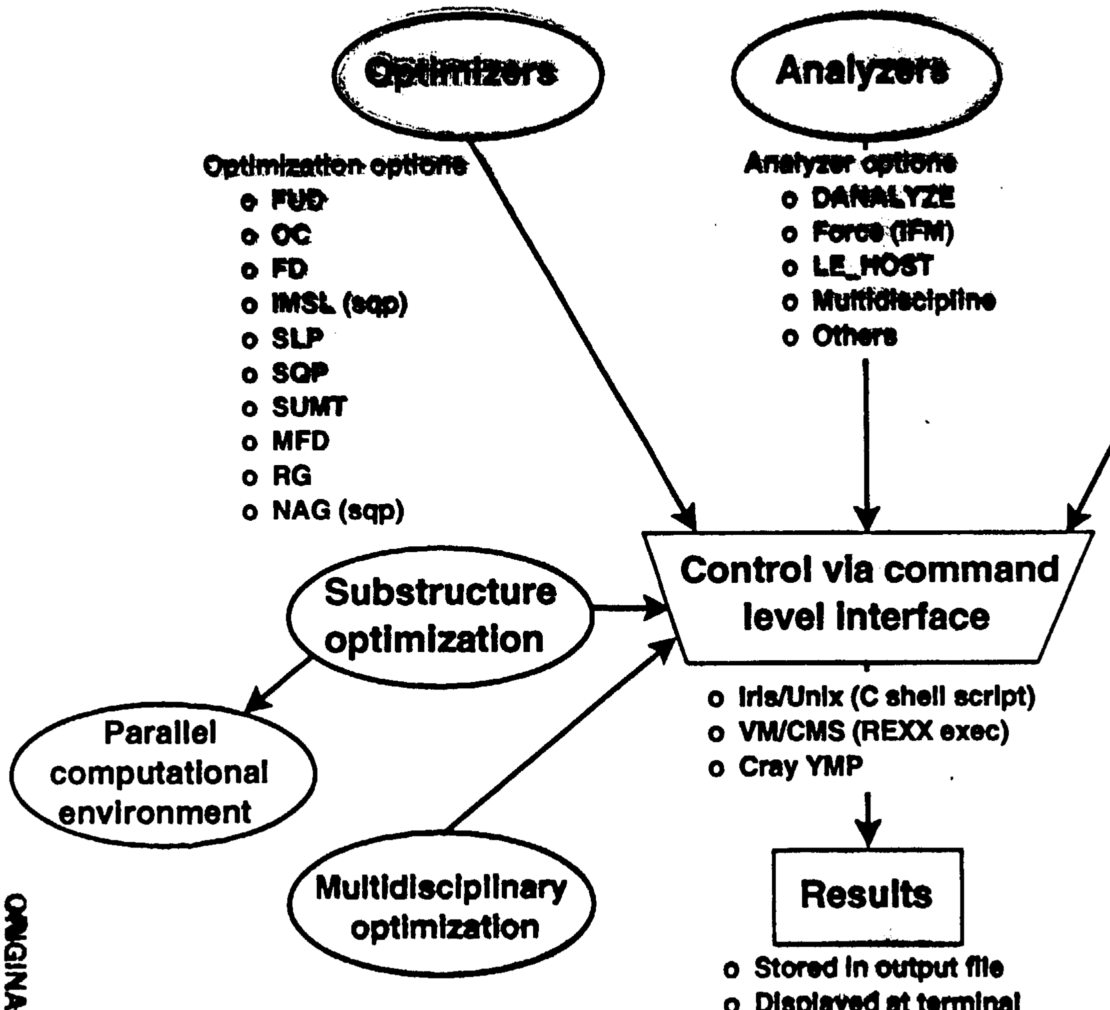
Computer Based Design Capability
Extended by Substructure Synthesis

Design optimization of a large structural system with many design variables and a large number of implicit nonlinear behavior constraints can become intractable, computationally expensive and it can easily saturate most advanced computer systems. Design optimization of such structures can be attempted through a substructure synthesis technique. In this technique, the given large structure is divided into several small substructures. Each substructure can have few active design variables and a small number of behavior constraints. The design optimization of an individual substructure becomes a smaller problem, whose optimum design can be obtained using available design tools without difficulty. The optimum design of the original large structure can be attempted through repeated design optimization of, each of the substructures separately, until convergence occurs. In the substructure technique, several factors such as adequate design variable coupling, common behavior constraints between substructures, rules to update intermediate initial designs, etc have to be considered to assist/ensure convergency to a global optimum. The substructure synthesis concepts have been incorporated into NASA LeRC design optimization capability CometBoards_2.0, which is an acronym for Comparative Evaluation Test Bed of Optimization and Analysis Routines for Design of Structures. CometBoard_2.0 design capability with substructure technique can provide optimum design for a large structural system, which may otherwise be difficult to obtain when the design of the entire structure is attempted in a single step.

Substructure synthesis strategy available in CometBoards_2.0 is illustrated considering the design optimization of a support system of the large spacer structure of the Space Station Freedom. The support system is made up of an assemblage of plates and beams and it transfers loads (arising from space shuttle accelerations and maneuvers etc.) from spacer structure to hard points in the cargo bay of the shuttle. For finite element analysis, the structure is modelled using a four node isoparametric shell element (SH_75) and a two node nonprismatic beam element (BE_98). For the purpose of design optimization, the support system is divided into four substructures. Each substructure contains approximately one fourth of the number of design variables of the original structure and similar number of behavior constraints. The design optimization incorporates, design variable formulation (with adequate overlaps) and constraint grouping schemes at substructure level. The optimum design is obtained through substructure synthesis and the convergence of the design is shown in the figure. Convergence is achieved in three cycles. Each cycle includes optimization of the four substructures. In other words, generation of the final design of the spacer structure required 12 separate substructure optimizations.

CometBoards

Comparative Evaluation Test Bed of Optimization and Analysis Routines for the Design of Structures



Development of CometBoards

Phase	Description	Status
1	Comparative evaluation of optimizers and analyzers	Completed
2	Space Station and EPM Project • Component synthesis • Design variable formulation • Constraint formualation	Completed
3	• Substructure optimization • Parallel processing in Cray YMP	Completed
4	Multi-discipline optimization • Strategy • Objective function formulation	Progress

Optimality Criteria Provides
Optimum Design For Select Class of Structural Problems

The performance of the optimality criteria method, for the minimum weight design of structures subjected to multiple load conditions under stress, displacement and frequency constraints, has been investigated by examining several numerical examples. The examples were solved utilizing the optimality criteria design code that was developed for the purpose at NASA LeRC. The design code incorporates optimality criteria methods available in the literature with generalization for stress, displacement and frequency constraints, fully stressed design concepts, and hybrid methods that combined both techniques. The design code also includes multiple choices for the calculation of Lagrangian multipliers and several design variable update rules, strategies for different constraint combinations, variable linking, displacement and integrated force method analyzers, and analytical and numerical sensitivities, etc.

On the basis of the numerical examples solved, it is observed that when, only displacement, or only frequency constraints are used, the optimality criteria method is satisfactory even for large structural systems with many design variables. The monotonic convergence characteristics of an optimality criteria method, is observed for a large structure with 1027 design variables under displacement constraints only. When extended for general application (with stress, displacement and frequency constraints), the optimality criteria method satisfactorily provided optimal design for small problems. For problems with large number of behavior constraints and design variables, the method appears to follow a subset of active constraints that can result in a heavier non optimal design. The fully utilized design methodology was found adequate when stress constraints dominated the design. Hybrid methods, as formulated, were unsatisfactory, but further research could be fruitful. The computational efficiency of the optimality criteria method is found to be similar to some nonlinear mathematical programming techniques.

Optimality criteria can be an useful tool to design or modify an existing design of a structure for displacement or frequency constraints.

Boundary Compatibility Formulation
Improves Stress Analysis of Shell Structures

The equilibrium equations and the compatibility conditions are fundamental to the analysis of structures. However, anyone who undertakes even a cursory generic study of the compatibility conditions can discover with little effort that, historically, this facet of structural mechanics has not been adequately researched by the profession. Now the compatibility conditions have been understood to a great extent. For a class of shell structures, the compatibility conditions on the boundary which were missing for over a century have been derived from the stationary condition of the variational functional of the integrated force method. Augmentation of these novel boundary compatibility conditions completes the classical Beltrami-Michell stress formulation for shell structures. The completed Beltrami Michell Formulation (CBMF) is a force method of analysis and it is as general as the Navier's displacement method. The CBMF is applicable for the analysis of all three types of, (stress, displacement and mixed) boundary value problems of elasticity. It is worth noting that the classical Beltrami-Michell stress formulation has limited use because this formulation could solve only stress or first boundary value problem but not the more prevalent and practical displacement and mixed boundary value problems.

The versatility of the completed Beltrami-Michell formulation is illustrated considering, a composite cylindrical shell made of two different materials, as an example. The shell which is made of aluminum and steel, is an example of a mixed boundary value problem with elastic interface transition conditions between the two components. The structure is subjected to both thermal and mechanical loads. Due to the mixed nature of the boundary conditions, the problem can not be solved by the classical Beltrami Michell's stress formulation. The problem however is amenable for solution by the CBMF due to the boundary compatibility formulation. The composite shell is solved for stress parameters (forces and moments) using the completed Beltrami Michell's stress formulation. Force and moment distributions, were obtained as a solution of the CBMF for the problem.