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MULTIDISCIPLINARY OPTIMIZATION APPLIED TO A TRANSPORT AIRCRAFT

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INTRODUCTION

Decomposition of a large optimization problem into several smaller subproblems has been proposed as an approach to making large-scale optimization problems tractable. To date, the characteristics of this approach have been tested on problems of limited complexity (e.g., reference 1). The objective of the effort described in this paper is to demonstrate the application of this multilevel optimization method on a large-scale design study using analytical models comparable to those currently being used in the aircraft industry. The purpose of the design study which is underway to provide this demonstration is to generate a wing design for a transport aircraft which will perform a specified mission with minimum block fuel. This paper includes (1) a definition of the problem, (2) a discussion of the multilevel decomposition which is used for an aircraft wing, (3) descriptions of analysis and optimization procedures used at each level, and (4) numerical results obtained to date. Computational times required to perform various steps in the process are also given. Finally, a summary of the current status and plans for continuation of this development effort are given (fig. 1).

OBJECTIVE: TO DEMONSTRATE THE APPLICATION OF MULTILEVEL OPTIMIZATION METHOD IN A LARGE SCALE DESIGN STUDY.

APPLICATION: TO GENERATE A WING DESIGN FOR A TRANSPORT AIRCRAFT TO PERFORM A SPECIFIED MISSION WITH MINIMUM BLOCK FUEL.

PRESENTATION OUTLINE:

- PROBLEM DEFINITION
- MULTILEVEL DECOMPOSITION
- ANALYSIS AND OPTIMIZATION PROCEDURES
- NUMERICAL RESULTS
- OBSERVATIONS

Figure 1

MULTILEVEL OPTIMIZATION APPLICATION

The multilevel optimization procedure is being applied to an L-1011 derivative transport aircraft which is being studied by the Lockheed-California Company as discussed in reference 2. The focus of this particular study is to design a new wing to give minimum fuel consumption for a specified flight profile. Design variables include overall wing geometric shape defined by aspect ratio, sweep, total area, taper ratio and thickness ratio. In addition, variables describing the wing structure within that shape are determined down to the level of cross-sectional dimensions of stiffened-skin wing cover panels. As overall wing geometry changes are made, the structure is reoptimized and the static aeroelastic effects on aerodynamics are calculated but no aerodynamic optimization of wing airfoil shape is performed. (See fig. 2.)

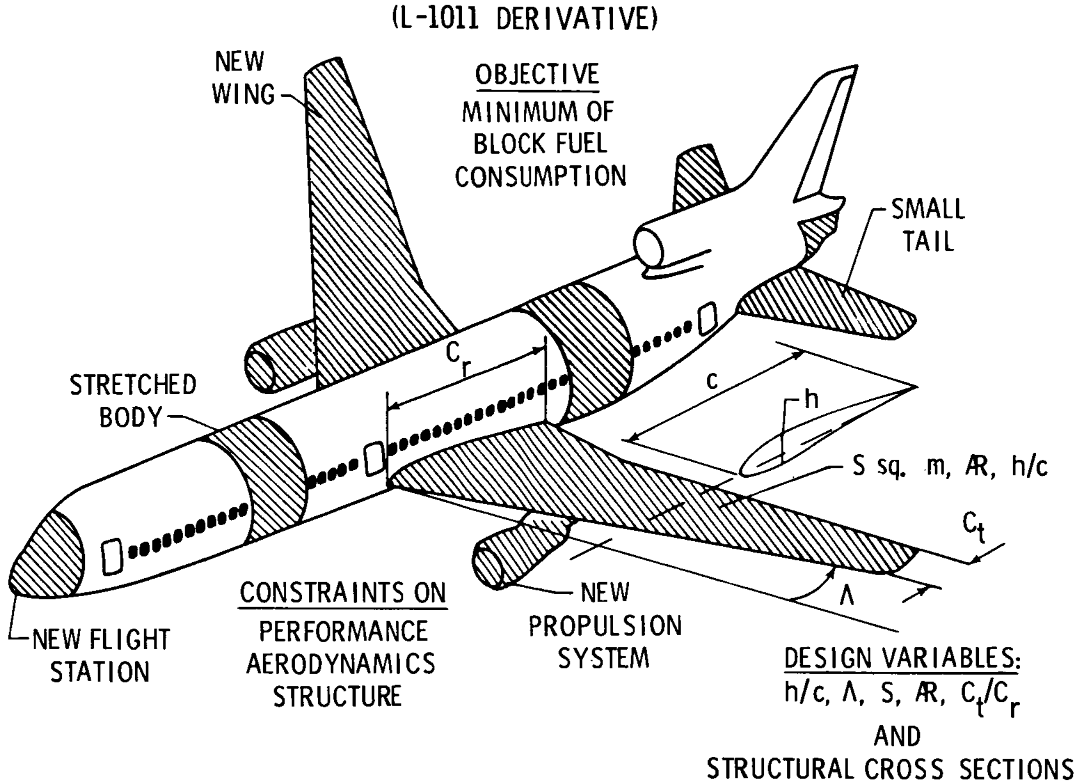

Figure 2

COOPERATIVE VENTURE WITH LOCKHEED

The study of the transport aircraft wing is being performed as a joint venture with the Lockheed-California Company. Lockheed is using their integrated structural design system which computerizes their conventional design methods to perform such studies (reference 2). Parametric studies are used to calibrate weight equations to perform overall configuration trade studies. Structural sizing for this calibration is based on fully stressed design with stiffened wing cover panels selected from design charts representing predesigned cross sections. Aeroelastic considerations such as flutter and gust are included in the Lockheed procedures. Multilevel optimization is being applied at NASA Langley, initially to get the procedure implemented at all levels for strength design and subsequently to include aeroelastic considerations. Lockheed is under contract to provide sufficient design data from their studies to allow NASA personnel to study the same configuration at the same level of detail. (See fig. 3.)

LOCKHEED - CALIF.	NASA LANGLEY
CONVENTIONAL PARAMETRIC STUDIES	SYSTEMATIC MATHEMATICAL OPTIMIZATION
• STRUCTURES: INTEGRATED ANALYSIS FULLY STRESSED DESIGN PREDESIGNED CROSS SECTIONS	• MULTILEVEL APPROACH FROM CONFIGURATION LEVEL DOWN TO STRUCTURAL SIZING LEVEL
• AEROELASTIC CONSIDERATIONS	• DISCIPLINARY ANALYSES COMPARABLE TO LOCKHEED'S AS TO THEIR DEGREE OF DETAIL

Figure 3

FINITE-ELEMENT STRUCTURAL MODEL

The finite-element representation of the structure was developed by Lockheed personnel for analysis by the NASTRAN program used in their PADS system (reference 3). Since the focus was on wing design, a fairly detailed model is used for the wing structure and the regions of the fuselage necessary to get proper representation of the wing-body intersection. The wing and wing-body intersection structure is modeled primarily with rod and membrane panel elements. The remainder of the structure (fore and aft fuselage, empennage, engine, and landing gear) is modeled using beam elements. This NASTRAN model was converted to be compatible with the Engineering Analysis Language (EAL) system (reference 4) for analysis at NASA Langley. The resulting model has 641 joints for a symmetric half model. During design studies, only the cover panels in the upper and lower surfaces of the main wing box (216 elements) were resized (fig. 4).

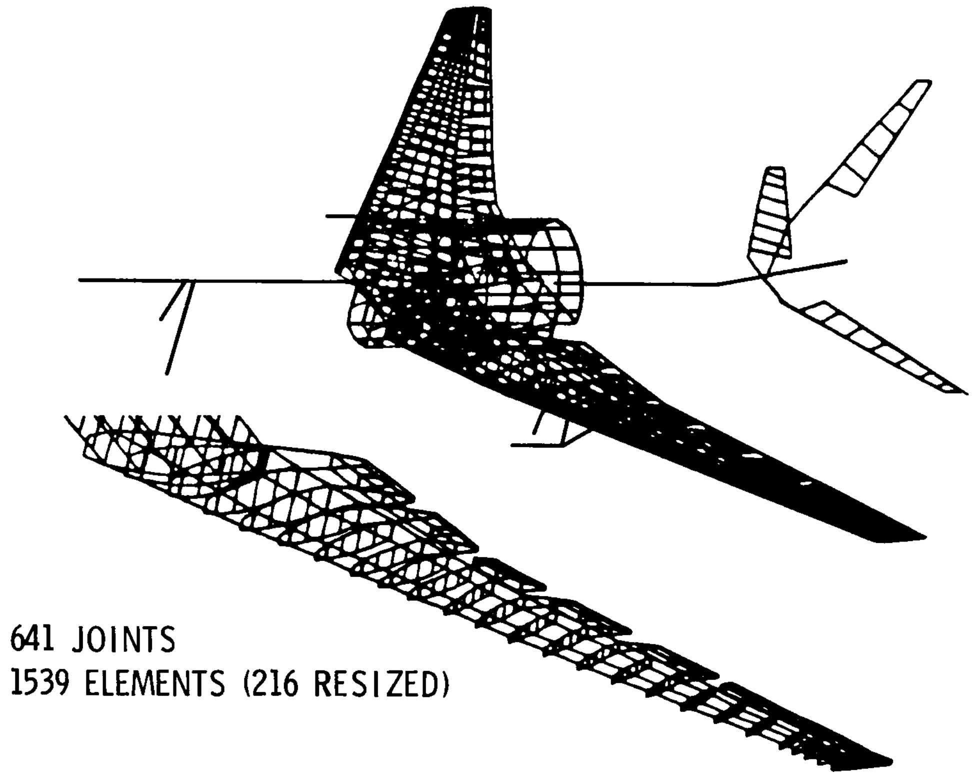

Figure 4

THREE-LEVEL DECOMPOSITION

The decomposition for wing design is a particular case of the general multilevel decomposition methodology described in reference 5. The wing design process is decomposed into three separate optimization problems, as shown in figure 5. At the top level, design variables such as wing structural weight, aspect ratio, and sweep are used to minimize fuel consumption subject to performance constraints. The optimum values of these variables are then passed to the middle level as fixed parameters where the distribution of wing box cover skin material is determined which will give a minimum measure of constraint violation. Next, these optimum distributions are passed to the bottom level where the optimum cross-sectional dimensions of each of the stiffened panels are calculated. The optimization procedures at the middle and bottom levels are used to minimize a single cumulative constraint violation associated with that level. This cumulative constraint is a differentiable envelope function of all individual constraints. The particular envelope function used is the Kresselmeir-Steinhauser function (reference 6). The cumulative constraints and their derivatives are passed upward between levels. Iteration between the three levels is performed until all constraints are satisfied. Analysis and optimization procedures used at each level are discussed next.

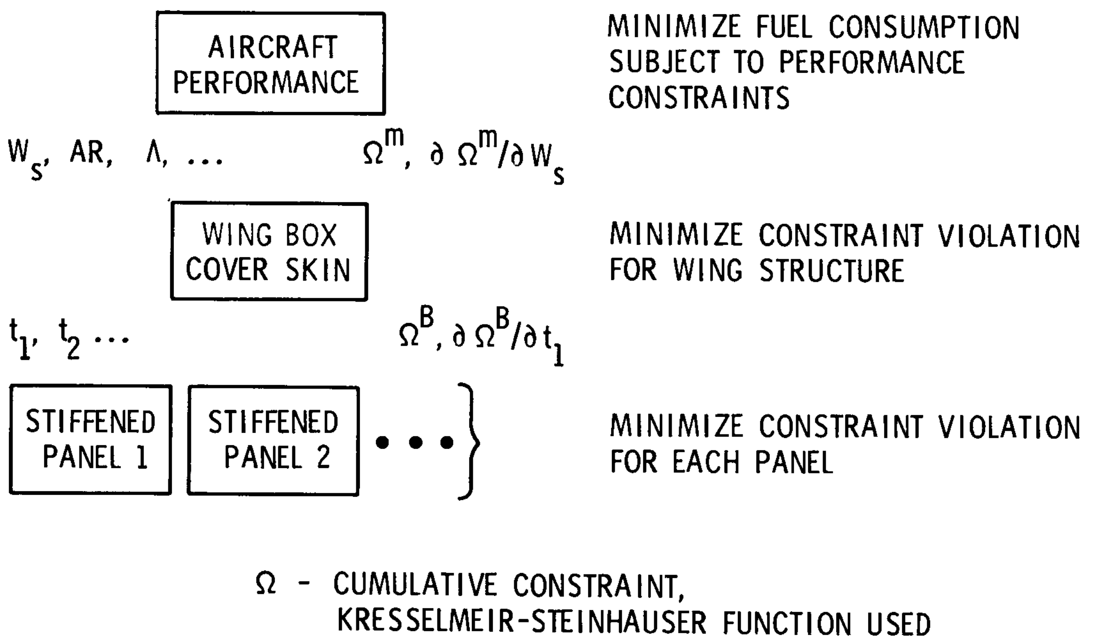

Figure 5

TOP LEVEL PROCEDURES

The Flight Optimization System (FLOPS) (reference 7) is used to perform overall optimization at the top level. The objective is to determine the aircraft wing configuration which minimizes block fuel consumption for a specified mission. Performance constraints include limits on approach speed, field length, and climb gradient thrust. Cumulative constraints from the lower levels must also be satisfied. The standard version of FLOPS uses statistical equations to calculate wing weight as a function of wing geometry. Modifications have been made so that the program can be implemented in the multilevel optimization procedure by including wing structural weight as a design variable and adding the cumulative constraint from the lower levels. (See fig. 6.)

- FLOPS MISSION PERFORMANCE PROGRAM USED (REF 7)

- MODIFICATIONS TO FLOPS NECESSARY FOR MULTILEVEL IMPLEMENTATION
  - WEIGHT OF WING STRUCTURE INCLUDED AS A DESIGN VARIABLE
  - ADD A CONSTRAINT: CUMULATIVE CONSTRAINT FROM BOTTOM AND MIDDLE LEVELS

Figure 6

MIDDLE LEVEL PROCEDURES

The optimum distribution of material in the wing box cover skins is calculated by the middle-level procedures. Displacements and stresses are calculated using the model in figure 4 as input to the EAL system. Analytical derivatives of these quantities are calculated using the procedures described in reference 8 which are implemented as sequences of input statements to EAL. The design variables used in optimization are coefficients in a polynomial expression for the cover thickness distribution. The distribution currently being used is illustrated in figure 7. As indicated on figure 5, the objective function is a cumulative constraint from the middle and bottom levels with a fixed weight of the wing box covers from the top level specified as a constraint. Optimization is performed using CONMIN (reference 9) in a sequence of steps in which the results from the structural analysis are approximated by linear extrapolation.

- EAL USED FOR STATIC ANALYSIS AND DERIVATIVES
  - ANALYTICAL DERIVATIVES USED FOR THICKNESS VARIABLES
- DESIGN VARIABLES = COEFFICIENTS IN EXPRESSION FOR COVER THICKNESS DISTRIBUTION

  $$TSKIN = C_0 + C_1 (1-\beta) + C_2 (1-\beta)^2$$
- OBJECTIVE FUNCTION = MINIMUM CUMULATIVE CONSTRAINT FROM:

  MIDDLE LEVEL - WING TIP DISPLACEMENT
  BOTTOM LEVEL - PANEL CUMULATIVE CONSTRAINTS
- CONSTRAINT = FIXED WEIGHT OF WING BOX COVERS
- PIECEWISE LINEAR OPTIMIZATION PROCEDURE USING CONMIN

Figure 7

INITIAL SKIN PANEL DESIGN VARIABLE LINKING

The thickness properties of the finite elements representing the wing box cover skins are described in the spanwise direction by the quadratic expression in terms of the nondimensional parameter "β" (β=0 at the wing root and β=1 at the tip) shown on figure 8. Two quadratic segments are used, one inboard of the engine pylon and the other outboard. A constant thickness is specified in the chordwise direction. The upper and lower wing box cover skin properties are taken to be symmetric with respect to the wing middle surface. The six coefficients of the two quadratic expressions are the design variables used during optimization. This linking scheme is used to reduce the number of design variables during initial testing of the multilevel optimization procedure. It is recognized that this simplified linking restricts the possible distributions available for optimization and these restrictions will have to be removed after the initial testing phase.

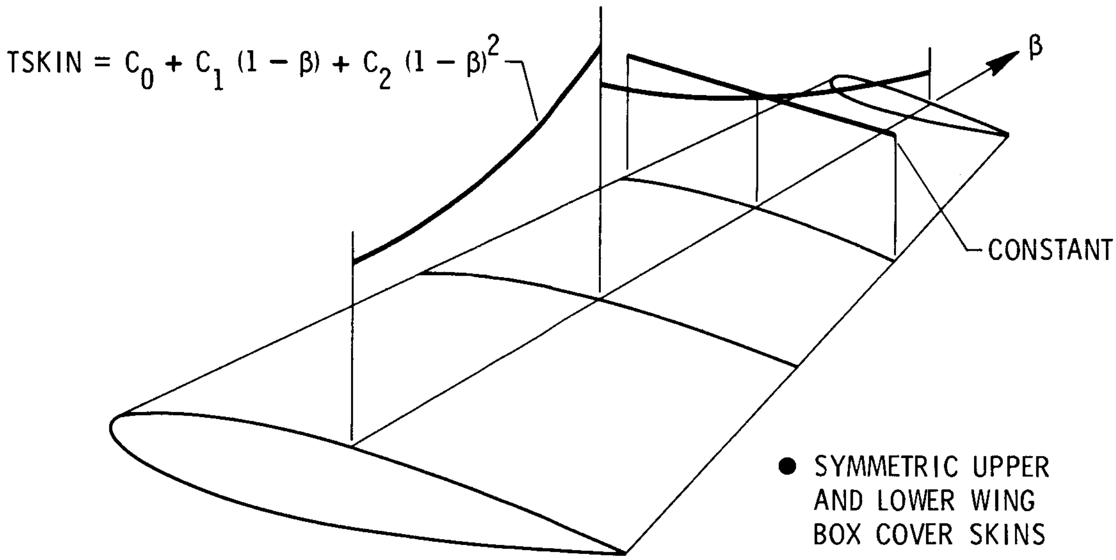

Figure 8

BOTTOM LEVEL PROCEDURES

Each of the 216 wing box cover panels is optimized by the bottom level procedures. Although properties of corresponding panels on the upper and lower surfaces are taken to be the same, the panel loads are not the same. Therefore, each pair of panels is optimized in order to assure consideration of the panels with the critical loadings. The design variables are the cross-sectional dimensions of a stiffened panel, as shown in figure 9. The objective function is a cumulative constraint composed of contributions from five stress constraints and eight buckling constraints that are considered. The CONMIN program is used for optimization. After each panel is optimized, an optimum sensitivity analysis is performed to get derivatives of the cumulative constraint with respect to parameters such as panel length, width and stress resultants which are passed down from the middle level. The algorithm described in reference 10 is used for these calculations. Finally, these optimum sensitivity derivatives are combined wih structural response derivatives from the middle level to form cumulative constraint derivatives which are subsequently used in the middle-level optimization process.

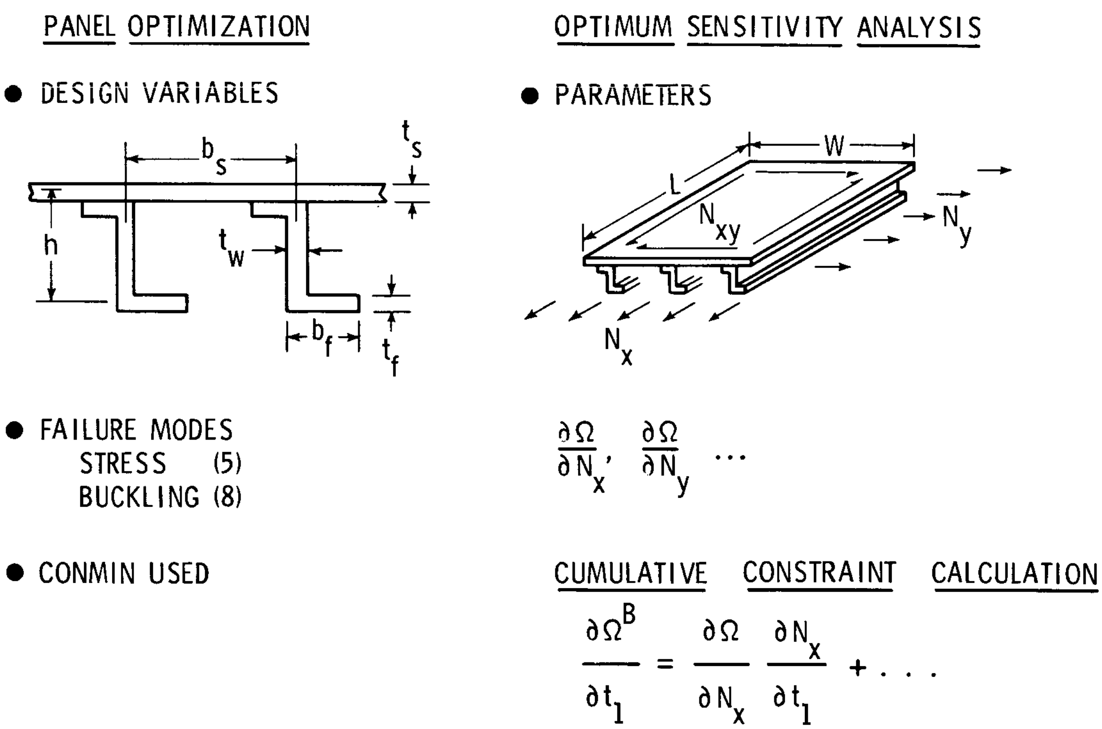

Figure 9

MULTILEVEL OPTIMIZATION IMPLEMENTATION FOR L-1011 DERIVATIVE WING

The general characteristics of the computer programs used in each of the three levels have been described in the previous discussions of the levels. The original intent was to transfer all data between levels via the Relational Information Management (RIM) system (reference 11). Since the procedures in the middle level are all related to the EAL structural analysis system, its data base was used for all data communication within the middle level. It was found that the bottom level was tightly coupled to the middle level in terms of types and quantities of data that had to be shared. Consequently, the bottom level was implemented as an EAL processor and utilities described in reference 12 were used to provide data communication to the EAL data base. The relatively small amount of data communication required between the middle level and top level is handled using the RIM system. (See fig. 10.)

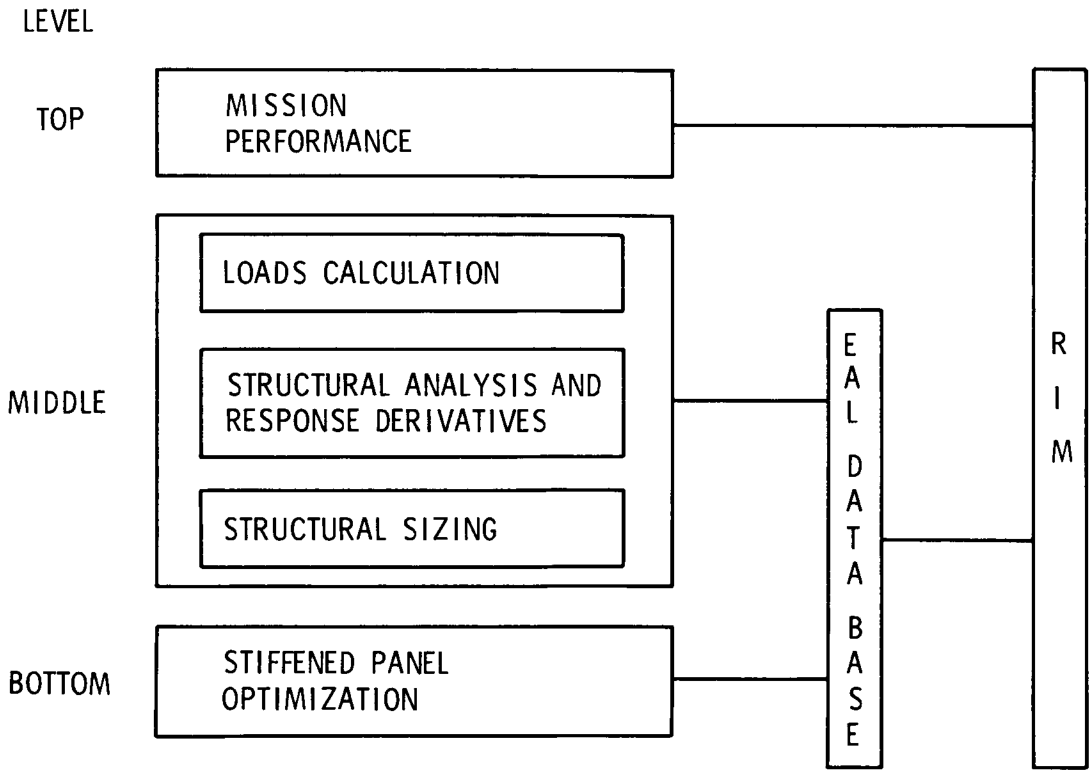

Figure 10

MINIMUM WEIGHT SIZING BY INDIRECT METHOD

To assess the results being produced by the bottom two levels, an indirect method of calculating a minimum weight design was employed. The middle and bottom levels were used to calculate minimum values of the middle-level cumulative constraint for four values of wing box cover weight. These optimized designs are indicated by the circular symbols on figure 11. The point above the horizontal axis is infeasible since the cumulative constraint has a positive value and the three points below the axis satisfy all constraints but are overdesigned. The minimum weight design is located where a line through these points intersects the horizontal axis as shown on the figure. This design is heavier than the minimum weight design produced in the Lockheed studies. The difference is attributed to the restrictions imposed by the initial design variable linking scheme, figure 8, that is being used for testing purposes.

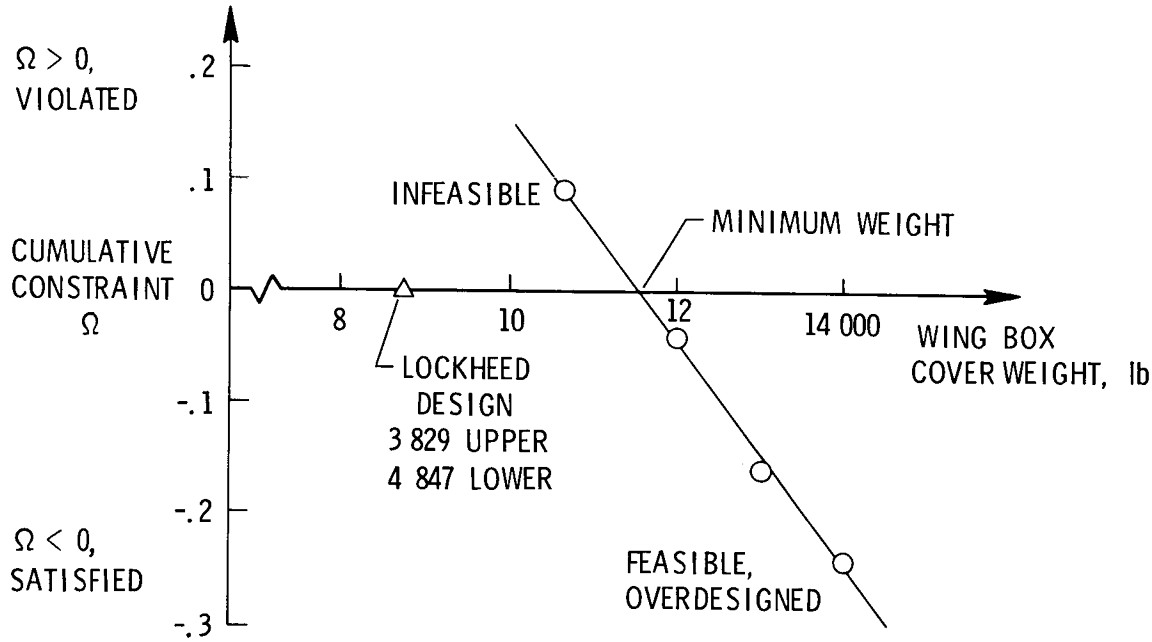

Figure 11

TYPICAL SUMMARY OF COMPUTATIONAL ACTIVITY

A summary of the computational activity for the major tasks involved in the operation of the middle and bottom levels is shown in figure 12. Both normalized CPU time and I/O count are given. Performing a static structural analysis and calculating derivatives of the response quantities involve considerable computational activity. A large portion of CPU time is required for panel optimization at the bottom level where 216 separate optimization runs are made. Only a small amount of I/O activity is required in these calculations. The CPU time required for optimization at the middle level is an order of magnitude less than that required for the structural analysis and derivatives that are used for linear approximation during optimization. Total CPU time, I/O count, and cost are shown at the bottom of the figure for five piecewise linear optimization cycles on a CDC Cyber 175 computer.

TASK	NORMALIZED CPU TIME	NORMALIZED I/O COUNT	
INITIALIZE	.052	.134	
STATIC STRUCTURAL ANALYSIS	.174	.277	
STATIC DERIVATIVES	.137	.243	
PANEL OPTIMIZATION & SENSITIVITY ANALYSIS ($\approx$35 ITERATIONS/PANEL)	.613	.025	← 216 PANELS
LINEAR OPTIMIZATION CYCLE FOR Ω (10 ITERATIONS)	.024	.321	
	1.000	1.000	

FOR 5 PIECEWISE LINEAR CYCLES ON CYBER 175		
	CPU TIME	650 sec
	I/O COUNT	34 000
	COST	$350

Figure 12

CONCLUDING REMARKS

The current status of the implementation of the multilevel optimization procedure is summarized on figure 13. The aircraft wing design process has been decomposed into three levels. The bottom two levels have been implemented using the EAL system and have been successfully tested. This initial testing resulted in the demonstration of an indirect method for minimum weight design which may prove to be an attractive alternative to conventional methods that have been used in the past. The three-level system can be tested when the FLOPS program is incorporated at the top level and efforts to demonstrate the application of the multilevel optimization method on a large-scale design study are continuing.

- AIRCRAFT WING DESIGN DECOMPOSED INTO THREE LEVELS
- INTEGRATION AND TESTING OF BOTTOM TWO LEVELS SUCCESSFULLY COMPLETED
- MINIMUM WEIGHT SIZING BY INDIRECT METHOD DEMONSTRATED
- FLOPS PROGRAM TO BE INCORPORATED AT TOP LEVEL
- STUDY CONTINUING

Figure 13

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