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APPLICATION OF MULTIDISCIPLINARY OPTIMIZATION METHODS TO THE DESIGN OF A SUPERSONIC TRANSPORT

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ABSTRACT[1]

A new optimization-based design method is discussed. This method is based on integrating existing disciplinary analysis and sensitivity analysis techniques by means of generalized sensitivity equations. A generic design system implementing this method is described. The system is being used to design the configuration and internal structure of a supersonic transport wing for optimum performance. This problem combines the disciplines of linear aerodynamics, structures and performance. Initial results which include the disciplines of aerodynamics and structures in a conventional minimum weight design under static aeroelastic constraints are presented.

INTRODUCTION

An effort is underway at the NASA Langley Research Center (LaRC) to improve multidisciplinary interactions in the processes of analysis and optimization of complex engineering systems. As presented by Dollyhigh and Sobieski [1], this effort named HiSAIR (High-Speed Airframe Integration Research) is focused on the HSCT (High-Speed Civil Transport) design activity. This paper describes the component of the HiSAIR effort which researches methodology for optimization and design of complex multidisciplinary engineering systems.

The objective of the research is to develop and demonstrate new mathematical methods for the integrated design of aircraft. The application selected is the optimization of a supersonic transport configuration developed at the NASA LaRC. Ultimately, the aircraft wing shape and structural layout are to be optimized for best overall vehicle performance.

To reach that objective, existing structural, aerodynamic and performance analysis and sensitivity analysis capabilities are first combined to predict the behavior of the aircraft. Since this project is one of demonstration, the level of analysis is deliberately kept low initially; the intent is to include progressively higher level capabilities as the methodology matures. Integration of analysis capabilities is discussed at length by Wrenn and Coen [2]. Second, sensitivity information is integrated using Sobieski's [3] recently introduced generalized sensitivity equations. This methodology has been validated with several different disciplinary and multidisciplinary design problems. It has being applied by Bloebaum *et al.* [4] in simultaneous shape optimization and structural sizing, by Woodward *et al.* [5] to the design of a controlled space structure, by Unger *et al.* [6] to the design of a subsonic transport, and by Levine *et al.* [7], to the design of a hypersonic aircraft. Third, the design itself is carried out with an optimization-based computer system which interacts with a relational database.

The product of this research will be firstly an improved methodology for design integration. Second, the resulting experimental design system will be used to produce trade studies in support of the HiSAIR effort.

In the following sections, the paper presents the formulation of the complete design problem and a brief description of the design model. The generic optimization system used for design is described. Finally, initial design results are presented for an early implementation of the procedure where design constraints are calculated accounting for aeroelastic effects, but derivatives include only structural effects.

DESIGN PROBLEM FORMULATION

The design problem considered is that of a supersonic transport aircraft. The wing internal structure, planform and thickness are varied for optimum performance. Figure 1 presents a schematic representation of the analysis problem. It combines the three disciplines of structures, aerodynamics and performance. Performance estimates for the airplane require knowledge of the flexible lift curves and drag polars and of the wing structural weight. Likewise, aerodynamic calculations depend on aircraft gross weight and wing flexible deflections. Finally, structural analysis is performed for given gross weight and aerodynamic loads.

The problem's independent design variables are manipulated in each discipline to produce a design; they are denoted X_i with i indicating in which discipline they are manipulated (a= aerodynamics, p= performance and s= structure). They include the structural (sizing) variables X_s, the aerodynamic configuration variables X_a and the performance gross weight X_p. The dependent variables are calculated in each discipline and may be needed in other disciplines; they are denoted $Y_{i,j}$, with i indicating the originating discipline and j, the discipline in which it is used. For example,

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[1] Presented at IIIrd Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization , 24–26 Sep. 1990, San Francisco, CA and AGARD Workshop on Integrated Design Analysis and Optimization of Aircraft Structures, 1–2 May 1991,. Bath, UK.

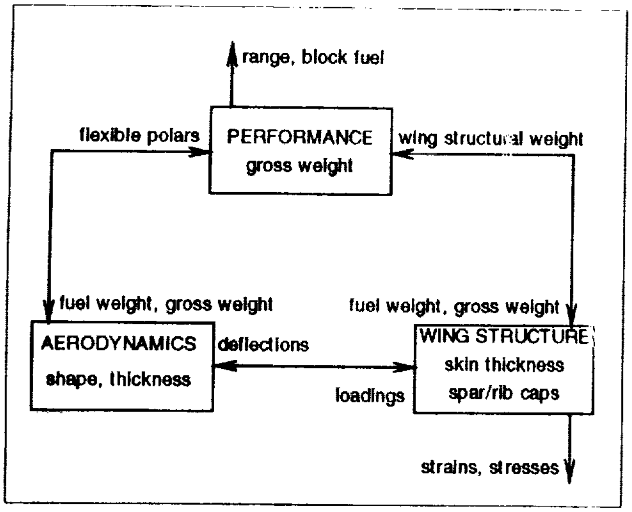

Figure 1 Multidisciplinary problem description

the aerodynamic discipline obtains the aerodynamic loads (Y_{as}) in the different load cases, and the aircraft polar datapoints (Y_{ap}). Likewise, the performance discipline computes performance measures which include gross weight and fuel weights ($Y_{pa} = Y_{ps}$) as well as range and block fuel (Y_{pp}). Finally, the variables calculated by the discipline of structure include the wing static deformations under loads (Y_{sa}) in the different load cases, the structural weight (Y_{sp}), the structural stresses and strains (Y_{ss}).

In formal notation, the following analysis equations result which express the coupled relationships among the different variables

$$\begin{aligned} Y_a^t &= \{Y_{ap}^t(X_a, X_p, Y_{sa}, Y_{pa}), Y_{as}^t(X_a, X_p, Y_{sa}, Y_{pa})\} \\ Y_p^t &= \{Y_{pa}^t(X_a, X_p), Y_{pp}^t(X_a, X_p, Y_{ap}, Y_{sp}), Y_{ps}^t(X_a, X_p)\} \\ Y_s^t &= \{Y_{sa}^t(X_a, X_p, X_s, Y_{as}, Y_{ps}), Y_{sp}^t(X_a, X_s), \\ &\quad Y_{ss}^t(X_a, X_p, X_s, Y_{as}, Y_{ps})\} \end{aligned} \tag{1}$$

The equation for Y_p, for example, expresses the fact that the dependent design variables calculated by the performance discipline include i) the gross weight and fuel weights which depend on gross weight and wing shape and ii) the aircraft range and block fuel which depend on wing shape, gross weight, flexible polar curves and wing structural weight.

Sensitivity of the dependent design variables with respect to the independent ones yields a linear system of equations in the form of Sobieski's [3] *generalized sensitivity equations.* If

$$Y^t = \{Y_a^t, Y_p^t, Y_s^t\} \text{ and } X^t = \{X_a^t, X_p^t, X_s^t\} \tag{2}$$

then:

$$S\left[\frac{dY}{dX}\right] = \left[\frac{\partial Y}{\partial X}\right] \tag{3}$$

where

$$S = \begin{bmatrix} I & 0 & -\frac{\partial Y_{ap}}{\partial Y_{pa}} & 0 & 0 & -\frac{\partial Y_{ap}}{\partial Y_{sa}} & 0 & 0 \\ 0 & I & -\frac{\partial Y_{as}}{\partial Y_{pa}} & 0 & 0 & -\frac{\partial Y_{as}}{\partial Y_{sa}} & 0 & 0 \\ 0 & 0 & I & 0 & 0 & 0 & 0 & 0 \\ -\frac{\partial Y_{pp}}{\partial Y_{ap}} & 0 & 0 & I & 0 & 0 & -\frac{\partial Y_{pp}}{\partial Y_{sp}} & 0 \\ 0 & 0 & 0 & 0 & I & 0 & 0 & 0 \\ 0 & -\frac{\partial Y_{sa}}{\partial Y_{as}} & 0 & 0 & -\frac{\partial Y_{sa}}{\partial Y_{ps}} & I & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & I & 0 \\ 0 & -\frac{\partial Y_{ss}}{\partial Y_{as}} & 0 & 0 & -\frac{\partial Y_{ss}}{\partial Y_{ps}} & 0 & 0 & I \end{bmatrix} \tag{4}$$

Equation (4) gives the sensitivity derivatives of the coupled disciplines ($d(.)/d(.)$) as a function of the sensitivity derivatives of the uncoupled disciplines ($\partial(.)/\partial(.)$).

It is critical to maintain the size of the individual Y_{ij} vectors small. Indeed, they not only affect the size of the S matrix but, more importantly, drive the number of derivatives required from each discipline. Since those derivatives are found by finite difference, they make up a substantial part of the total optimization cost. Wrenn and Coen [2] discuss that point in detail and show that size control is achieved by the use of a reduced basis approach to model elastic displacements and pressure distributions and a polynomial approach to model the elastic polar curves.

OPTIMIZATION SYSTEM DESCRIPTION

Figure 2 presents a graphic description of the generic optimization capability developed for this study. It is a VAXstation II-based system currently implemented to handle 5 disciplines with up to 100 independent variables and 500 dependent variables. The system is designed to provide for user intervention at any point in the design process. It proceeds in *design cycles*, each requiring full analysis and sensitivity analysis of the problem. Within each cycle, different *design alternatives* can be produced by changing such things as the type of problem approximation, the type of algorithm used, the combination of dependent and independent variables optimized, the move limits for approximations.

The heart of the system is the commercial package OPTDES [8] which offers several optimization algorithms. Those used in this study are linear programming, sequential linear programming, method of centers, generalized reduced gradients and sequential quadratic programming. Since analyses and sensitivity analyses are quite expensive, OPTDES optimizes a sequence of approximations to the actual design problem. These approximations are all based on zeroth and first order information on the dependent variables and include linear, reciprocal and the two-points approximation of Fadel *et al.* [9].

To provide an audit trail for the design process and allow for restart from any design cycle, critical optimization information is stored primarily in RIM [10], a commercial relational database management system. Cycle information retained includes initial values and upper and lower bounds on the independent and dependent variables. Because of its potential size, cycle gradient information is kept in conventional

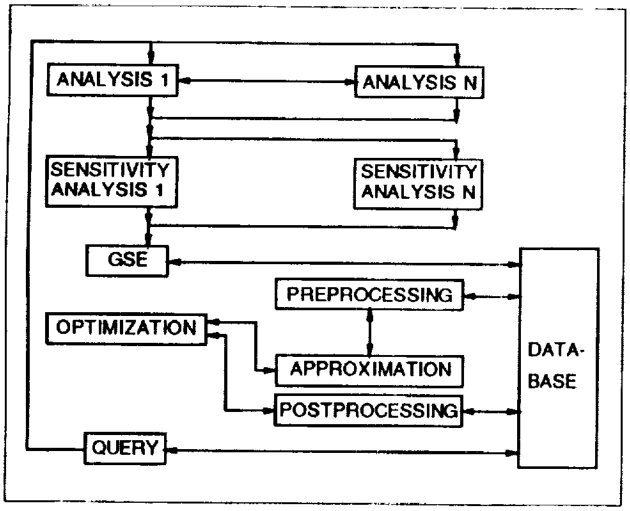

Figure 2 Integrated design system

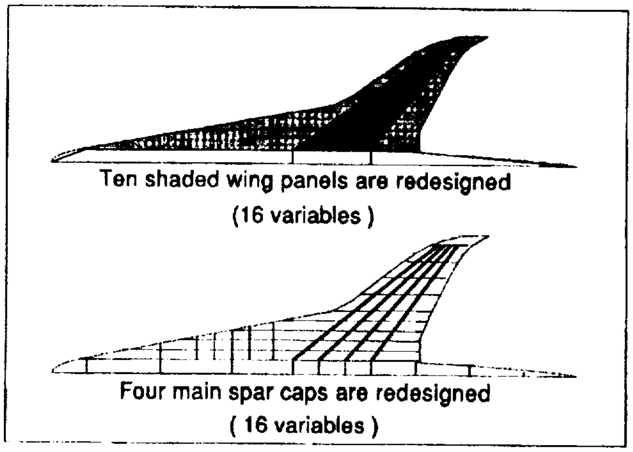

Figure 3 Layout of plates and caps

file format. Design alternative information retained includes final independent and dependent variables for each alternative design within each cycle.

Each design cycle begins with system analysis and sensitivity analysis. This step can be conducted with any existing analysis package and on any computer or distributed system of computers. Each discipline produces one file containing its own analysis and sensitivity analysis information. This information is then input to program GSE which sets-up and solves Eq. 3 and stores the relevant data in the RIM database and the gradient files. Once optimization is completed, the user may interactively query the database and track graphically or in tabular output any combination of independent or dependent variables. The user may also gauge the accuracy of the approximations selected by comparing analysis results predicted with those obtained after reanalysis. The user may then decide to produce more design alternatives within the current cycle or to initiate a new cycle using as starting design any of the design alternatives generated previously.

MODEL DESCRIPTION

For the sake of completeness, this section gives a very brief description of the aircraft design model; Wrenn and Coen give an extensive description in [2]. The initial configuration for the aircraft was proposed by Robins *et al.* [11].

The wing structure is analyzed with Giles' [12] equivalent plate analysis capability. As shown on Fig. 3, the wing structure is modelled by 10 independent plates. The two plates making up the wing box have skin thickness distributions varying linearly both chordwise and spanwise. The remaining plates on the wing glove, leading and trailing edges and tip have constant thickness. In addition, wing spar and rib caps are modelled with the four main spars having linearly varying cap areas. The upper and lower wing surfaces are identical. The wing structure is of metal-matrix composite made of silicon-carbide fibers embedded in a titanium matrix. Its layout is quasi-isotropic. There are 16 design variables for the skins and 16 for the caps.

Aerodynamic loads are obtained with the linear code WINGDES developed by Carlson [13]. The static aeroelastic problem is solved by iterating between structural and aerodynamic disciplines until convergence of the wing deformations and the resulting loads. The aircraft is trimmed by adjusting the angle-of-attack and redistributing the fuel in the fuel tanks.

Five load cases are considered as shown in Table 1. The first three cases are chosen to calculate the aircraft's elastic polars, the last two are true structural loading cases and correspond approximately to the two corners of the upper horizontal limit on the V-n diagram.

For each load case, there are constraints limiting the strains and stresses (Tsai- Hill failure criterion) in the skins, panel buckling of the skins, and the normal strains and stresses in the caps. Each constraint is formulated as an envelope function (see Barthelemy and Riley [14]). In addition, there are minimum gauge constraints on wing skin thicknesses and cap areas.

Load case	Load factor (g)	Mach Number	Altitude (ft)
Mid-cruise	1.0	3.0	72700
Transonic climb	1.0	1.2	21300
Reserve cruise	1.0	0.9	43000
Max load, low speed	2.5	0.6	10000
Max load, high speed	2.5	3.0	59000

Table 1 Load cases description

All the partial derivatives of disciplinary response with respect to independent variables or to dependent variables from other disciplines are obtained by forward differences.

INITIAL NUMERICAL RESULTS

The results discussed in this paper were generated while integrating the disciplines of aerodynamics and structures (Fig. 1). The analysis is the traditional iterative static aeroelastic analysis while the coupling between the two disciplines is temporarily ignored for sensitivity analysis and the gradients generated for optimization assume no redistribution of loads. Later implementations of this problem will fully account for all the couplings.

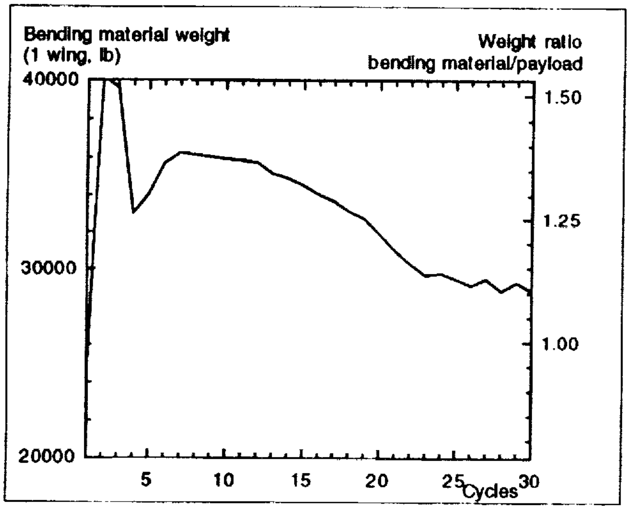

Figure 4 Wing weight convergence history

Figure 4 shows convergence of the wing structural weight from a constant skin thickness, constant spar cap area design scaled to match the weight estimates from Robins *et al.* [11]. These weight estimates were based on statistical expressions and, since there is very little data on supersonic transport design, they are likely to be used in an extrapolation mode, rather than in the more reliable interpolation mode. During the design process, the wing bending material weight increases by approximately 20%.

Each design cycle takes a full 4 hours on VAXstation II computers. About 3.5 hours are required for the analysis and sensitivity analysis processes. The remaining .5 hour is spent in optimizing the problem in an interactive mode. In view of this high computing time, the design follows a somewhat pragmatic approach so that if changes must be made in the design problem formulation or, even, if minor programming errors must be fixed, the process is restarted from the latest design generated. This particular design took 30 cycles. During the first few cycles, the optimizer worked at overcoming the initial constraint violation. In general, progress was somewhat limited at each iteration since tight move limits (mostly 10%, sometimes 5%) must be set to preserve approximation accuracy. After cycle 18, the structural weight dipped as the buckling constraints were reformulated to be more realistic.

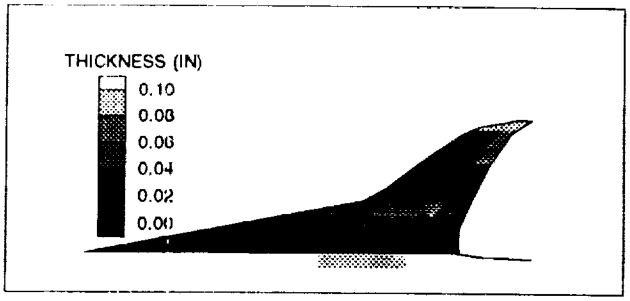

Figure 5 Wing skin thickness distribution

Figure 5 shows the wing skin thickness distribution. In general, the spanwise caps loaded up during the redesign while the skin thickness was reduced to minimum gauge or close to it. This is attributed to using the same material for the spar caps and the skins. In the caps, the material is unidirectional and laid-up spanwise, while in the skins, the material is quasi-isotropic, resulting in lower stiffness and lower allowables achievable in the skins and, therefore, lower loads and lower load levels. The active design constraints were either geometrical (minimum gauge on the skins) or corresponded to the two 2.5g load cases. The Tsai-Hill failure criterion, panel buckling constraint, skin shear strain constraint, and cap normal stress constraints were active for the low-speed pull-up. Both panel buckling and skin shear strains were active for the high-speed pull-up. Figure 6 shows the evolution of the Tsai-Hill constraint in the upper wing panel in the low-speed pull-up. The constraint is violated, if its value is positive. While it is initially violated in the center of the outboard panel and at the wing tip, optimization reduces violation so that the constraint becomes critical at the end of the design exercise.

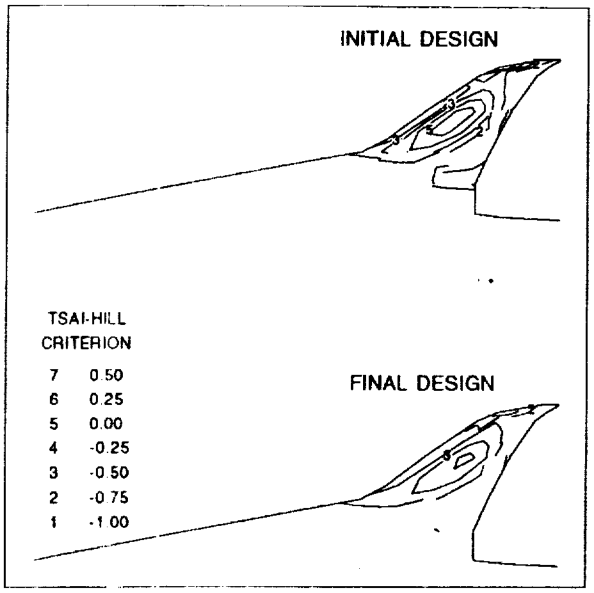

Figure 6 Tsai-Hill criterion, upper wing skin, M=0.6, n=2.5g

EXTENSIONS

This multidisciplinary design exercise serves as a pathfinder for method development in the activities described by Dollyhigh and Sobieski [1]. In its present formulation, it is to include three basic disciplines in the design process: linear aerodynamics, structural analysis and performance. When completed, it will permit optimum performance design of a wing configuration and internal structure under static aeroelastic constraints.

Eventually, the design exercise should be expanded to increase the realism of the model. Of particular interest would be the inclusion of dynamic (flutter) constraints. The level of details available within the individual disciplines should be increased as well. Finite element stress analyses and non-linear aerodynamics-based performance and load predictions must be included in a computationally efficient manner.

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