Strategy for Multilevel Optimization of Aircraft

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A specific decomposition methodology of a complex system of aircraft design variables to discrete levels where the variables have relatively equal impact is proposed. Multidisciplinary optimization techniques utilizing sensitivity derivatives and a global sensitivity matrix to combine the levels are used to develop a total optimum design. An advanced fighter wing example is used to illustrate the potential of improved design optimization in this multidisciplinary environment as compared to conventional sequential design development.

Introduction

EMERGING military aircraft design concepts require integration of an increasing number of conflicting design features. For example, high angle-of-attack and high-acceleration maneuver wing flexibility and planform solutions conflict with efficient high-speed cruise solutions. Furthermore, these maneuvers place higher than normal demands on control authority and low airframe weight, so that application of multidiscipline design optimization techniques could be expected to provide significant payoff compared to conventional sequential design approaches. Payoff can be decreased design cycle time or an improved design while providing a natural base for concurrent engineering approaches for the total design process.

The dominant payoff is an improved design, even at the expense of increased engineering costs as these costs are typically minor in the context of total development costs of a new vehicle. A primary motivation for exploring these issues is that desired very high weight savings must go beyond development of advanced structural and material applications only, and exploit active controls and new aircraft configurations. Furthermore, application of multidisciplinary design optimization techniques can provide new designs that would not necessarily be developed using conventional approaches.

For example, in a conceptual design study for fighter aircraft, Vanderplaats[1] developed a result for a wing planform that was different when optimized for the entire mission than would have been expected based on past experience. What we are finding is that the optimization process and tools that are now in place allow a larger number of variables to be considered than can be accounted for in the traditional trade-study environment, providing more degrees of freedom and more opportunities to save weight or otherwise improve a design. As another example, Abdi et al.[2] and Ide et al.[3] performed a preliminary study of a hypersonic vehicle forebody combining aerodynamics and structural effects to optimize inlet mass flow and developed a significantly different shape than the baseline.

Aircraft structure-aerodynamic-control optimization, where aerodynamic compromises are allowed in order to develop a lighter-weight vehicle for a total optimum design for constant performance will be pursued in this paper.

During the past several years, mathematical optimization tools and structured approaches to multidisciplinary design have been developed to address complex aircraft design problems. Sobieszczanski-Sobieski[4] presented a systematic methodology for decomposing large complex systems into a series of smaller subsystems, using sensitivity derivatives between these subsystems as the basis of generating a global sensitivity equation for total system optimization. This approach has been subsequently expanded and demonstrated by applications, e.g., Refs. 5–7. Other authors have considered the interaction of aerodynamics structures and controls on aircraft design. For example, Grossman et al.[8] focused on computational aspects of the aerodynamics-structures problem for a transport wing, and showed that a modular (black box) method for computing sensitivity derivatives was significantly superior to finite-difference methods. Simos and Jenkinson[9] presented conceptual design results for a short-haul aircraft, obtained by optimizing operational and mission-performance factors. Wrenn and Augustine[10] developed a multilevel decomposition of a transport using, which was optimized for mission performance, structural weight, and detailed structure efficiency. In that study, design data and related sensitivity derivatives were passed between levels for sequential optimization at the mission level.

The approach taken in this paper is a multilevel breakdown of the total aircraft system, with levels linked by key parameter sensitivity derivatives, using a global sensitivity approach for optimization at the flight-mission level.

An issue is which variables are to be considered in the design process. The view held in this paper is that design variables considered at each level of detail during the design process should have similar relative effect on the results being sought. The purposes of this paper are to present a strategy for multilevel, multidisciplinary design of an aircraft that allows focusing of effort on various levels of design complexity as the design progresses, and to demonstrate the advantage of total system optimization as compared to conventional sequential design.

Overall Strategy

Shown in Fig. 1 is a typical advanced fighter, which requires successful integration of a wide range of performance, operational, and development requirements. Sobieszczanski-Sobieski et al.[6] present a summary of approaches to system decomposition, which includes formal and intuitive methods. The former could be based on a mathematical structure from which the necessary relationships may be derived, whereas the latter is based on detailed physical understanding of the problem. Although an adequate formal structure could be developed using a technique such as a detailed work-breakdown structure, from implementation and flexibility points of view, a heuristic approach will be used for the problem at hand.

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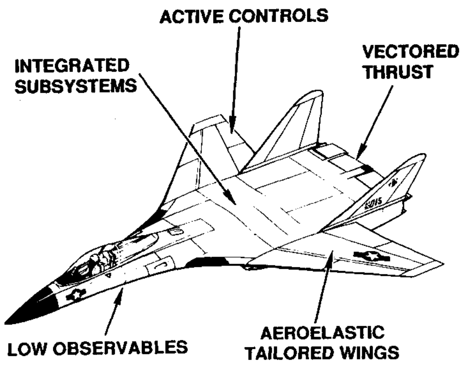

Fig. 1 Contemporary vehicle design requirements.

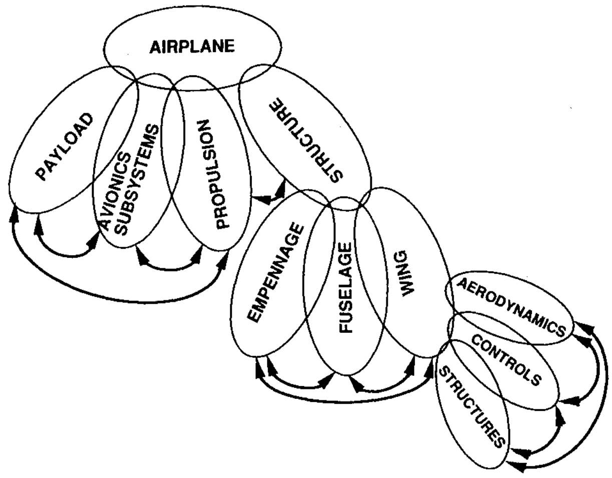

Fig. 2 System analysis structure.

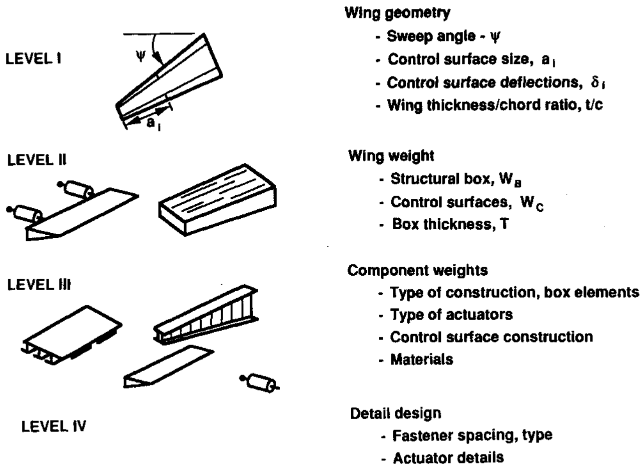

Fig. 3 Wing multilevel definition.

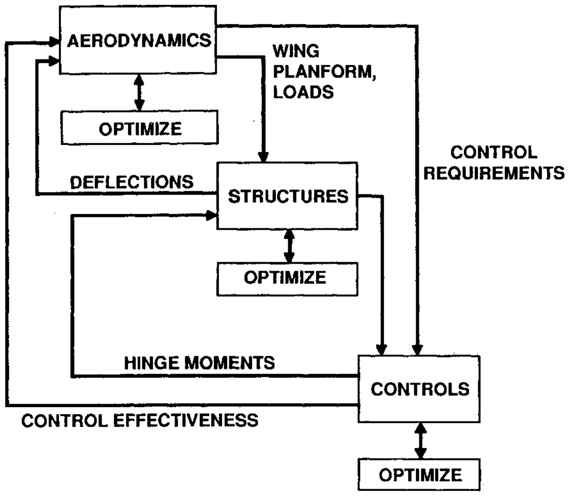

Fig. 4 Typical conventional design-optimization process.

System Structure

An entire airplane conveniently can be broken into subsets with reasonably well-defined interfaces. Thus, for example, the hardware interface between a wing box and the fuselage or a control surface are natural divisions. At the conceptual/ preliminary design level, these physical breakdowns still make sense, but rather than being strictly hierarchical, must instead be represented by a complex network with many-to-many relations among the elements since they are not yet well-defined. The cross linking would in some cases be quite strong, dominating the design at that level, whereas in other cases it would have little or no effect. Consideration of all variables at once would lead to a massive computational problem. The best approach to keep the number of variables within practical limits will be to reduce as many as possible of these new relationships to simple ones, preferably to eliminate as many as possible. This can be achieved by considering various levels of design-parameter influence, where parameters have similar influence at each level, and by not considering weak linking.

An illustration of proposed major levels is shown in Fig. 2 starting at the system level, where a measure of total system effectiveness could be, for example, life-cycle cost, or a selected mission parameter. At this level, takeoff gross weight is significant, as is airframe cost, but parameters such as fiber orientation or panel-stiffening concept have minor measurable effects. These latter factors are, however, of key importance to structural component weight and cost, and would therefore be evaluated at a lower level. Thus, system leveling or decomposition will use heuristic reasoning, experience, and sensitivity studies to display only those parameters that have significant effect on measures of merit at each level.

Figure 3 illustrates the proposed multilevel breakdown for a wing. Motivation for the proposed breakdown is ease and rapidity of design by focusing on the primary parameters that influence each level. At the first level, the total wing would be considered, with primary aerodynamic performance and control parameters as shown. At the second level, major wing subsystems would be evaluated, which for this example will be the wing box and the control surfaces, the latter considered as assemblies. The third level would evaluate detailed components such as wing skin panels and actuators. This is the level at which most conventional optimization is performed and there is a wide variety of computerized and manual tools available for analysis. The fourth level would address very detailed optimization consisting of issues such as fastener type and spacing, actuator details, and so forth. At the conceptual design level, primary concentration would be at the first and second levels. Support data from lower levels would typically be supplied by equations and data developed from past designs. Preliminary design would consider the first two levels, possibly the third level to some extent. Detailed design would focus primarily on the third and fourth levels, with only minor redevelopment of the second level. This paper will consider the primary performance (range and lift/drag) and structural-weight aspects of the design, compared to performance.

Optimization Strategy

A typical conventional design optimization sequence is illustrated in Fig. 4, where iteration between disciplines is handled in a sequential manner. In this methodology, there is little ability for optimum structural consideration, as an example, to significantly influence overall vehicle shape. A multidisciplinary design-optimization process becomes a more concurrent one, illustrated in Fig. 5, via use of a technique such as global sensitivity equations described by Sobieszczanski-Sobieski.[5] These sensitivity equations contain derivatives of the solution space with respect to the independent design parameters, expanded about a baseline solution using a linear Taylor series expansion. This approach, combined with finite differencing, provides a convenient but computationally intensive technique for calculation of sensitivity derivatives to support mathematical optimization, and will be used here, recognizing that sensitivities would have to be recomputed beyond some neighborhood of baseline design.

The objective function, or functions for the case of a multiobjective optimization, is the measure of merit used to guide the optimization process. In the case of the entire airplane, TOGW (takeoff gross weight), or any mission-performance parameter such as mission radius can be selected. For the case at hand, the single objective function of TOGW is used for the airplane as a whole (the parent system) with weight of each subsystem used as objective functions for suboptimization at each level.

Application

An example of a fighter wing will be used to further explore leveling concepts and to illustrate ideas that have been presented. The example will consider a simplified thread through the entire process that was illustrated in Fig. 2. The wing chosen, Fig. 6, has been used in previous studies, for example Ide et al.,[11] and part of that data base will be used here. First, formulation of the problem for the wing itself will be developed, followed by system level consideration of mission performance.

Formulation

The problem wil be formulated as a constrained optimization for which minimization of the function F

$$\min_{X} F(X) \tag{1a}$$

subject to the constraints

$$g(X) \leq 0 \tag{1b}$$

is to be obtained. The vector X contains the independent design variables of interest. Variables held constant during the optimization are not displayed, but are implicit. The example will minimize weight for a given mission, using aerodynamic performance criteria as constraints.

At the first level of the wing breakdown, weight is used as the objective function, related to aerodynamic performance at the next level. Wing weight W is expressed as

$$W = W(T) \tag{2}$$

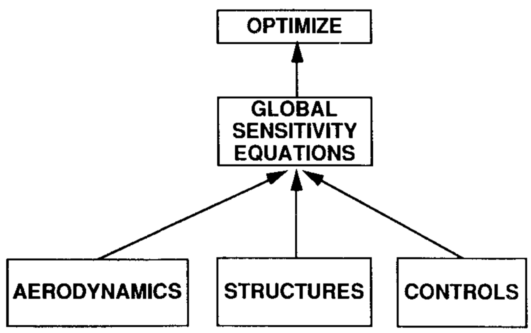

Fig. 5 Multidisciplinary design-optimization process.

where T is the wing root thickness. In this formulation, only the root thickness is displayed since it is the only variable that will be explicitly varied in this problem and will be used to tie the weight to aerodynamic performance at the next level. Wing structural weights will be developed from a suboptimization problem based on a finite element model of the wing, as discussed later. As with other parameters to be studied, the function is an implicit one. The actual relations and sensitivities are derived from a computer simulation that accounts for all other variables required to fully describe the contributing analysis.

The ratio of lift to drag L/D and the roll rate $\dot{\Theta}$ are used as simple measures of aircraft performance and are defined as follows:

$$L/D = L(\delta_i, T, \psi) \tag{3}$$

$$\dot{\Theta} = \dot{\Theta}(\delta_i) \tag{4}$$

where

δ_i = control-surface deflections, $i = 1-4$

T = wing root thickness

ψ = sweep angle

Side constraints on lift and roll rate are used to assure minimum performance.

$$L = W$$

$$\dot{\Theta} \geq \dot{\Theta}_{\text{baseline}}$$

Other variables, such as aspect ratio, are held constant for this study. Wing root thickness is used as the wing-thickness measure for aerodynamic performance as well as a primary parameter for structural-weight sensitivity as discussed above. At this level, overall wing geometry to be studied includes thickness and sweep-angle changes.

Sensitivity Derivatives

Sensitivities are developed as linear Taylor series expansions of these relations as follows:

$$W = W_0 + A \frac{\partial W}{\partial T} \Delta T \tag{5}$$

$$L = L_0 + B \sum_{i=1}^{4} \frac{\partial L}{\partial \delta_i} \Delta \delta_i + C \frac{\partial L}{\partial T} \Delta T + D \frac{\partial L}{\partial \psi} \Delta \psi \tag{6}$$

$$\dot{\Theta} = \dot{\Theta}_0 + E \sum_{i=1}^{4} \frac{\partial \dot{\Theta}}{\partial \delta_i} \Delta \delta_i \tag{7}$$

where the constants are coefficients of the expansion. Sensitiv-

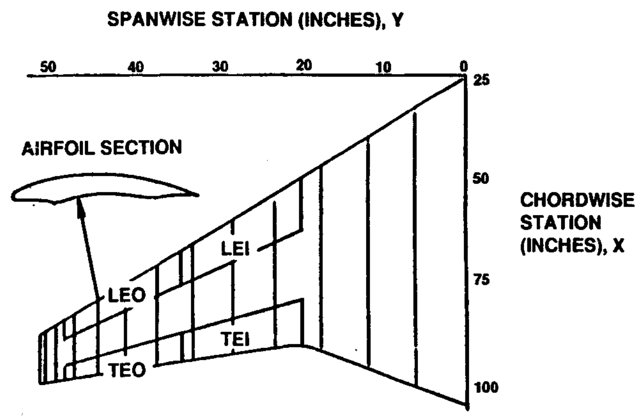

Fig. 6 Baseline wing.

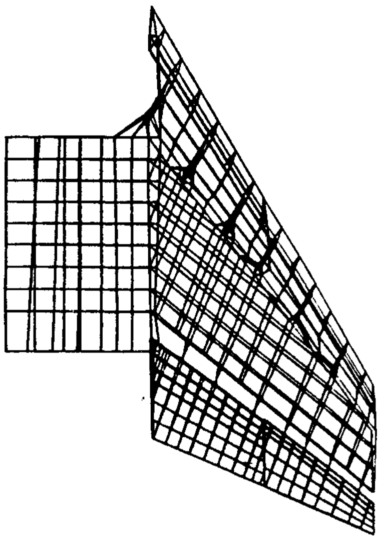

Fig. 7 Wing finite element model.

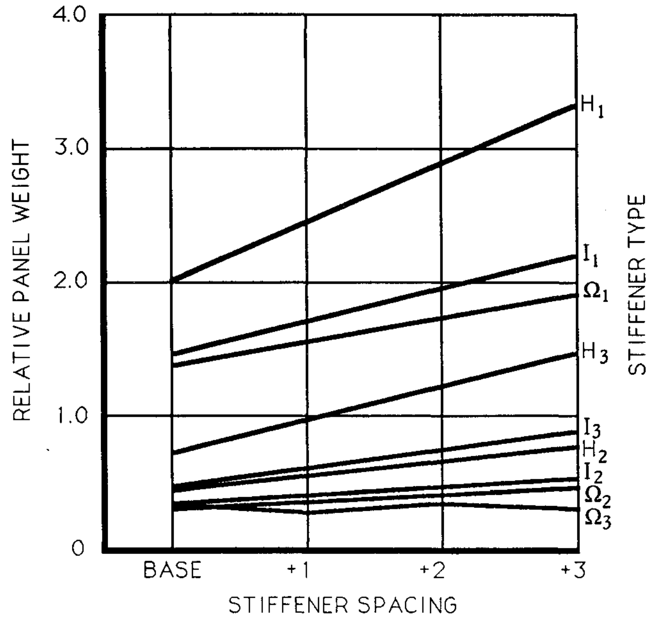

Fig. 8 Panel buckling efficiency.

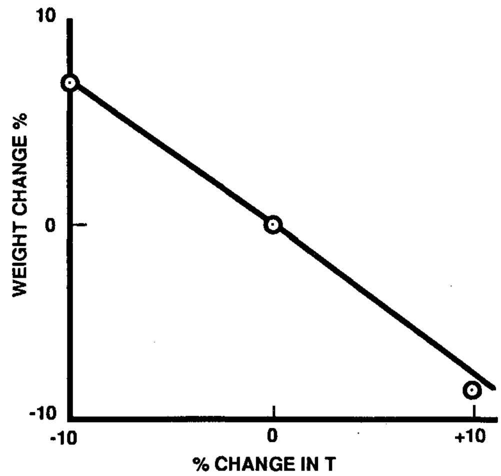

Fig. 9 Wing box structural weight sensitivity.

ities are obtained by simulation of structural and aerodynamics behavior.

Structural-weight sensitivities were obtained from a finite element based structural optimization code with the model illustrated in Fig. 7. This code was used to optimize the wing structure for the baseline sweep angle and root thickness using criteria for strength, stiffness, panel buckling, and local crippling and wrinkling as well as minimum gauges. This design-optimization step considered a variety of panel configurations, including stiffener type and spacing as a function of spar spacing. The wing is constructed of advanced composite skins and metallic substructure.

This inner optimization was performed because of the complexity of the structural optimization process and the definition detail desired. Weight sensitivities could also be derived from regression curves, should an adequate data base exist. The process for weight sensitivities thus considered optimization of the structural box at level two (Fig. 3) supported by a data base of detailed component optimization at level three.

Buckling-efficiency studies were based on the NASA OPCOM code and, since execution times were very rapid, were used to provide a data base for subsequent finite element definition. Additional details of the model are given in Ref. 7. Typical panel efficiency results are summarized in Fig. 8, and the corrugated stringer was used for further model development.

Wing box weight sensitivities to root thickness variations were computed by varying root thickness and recomputing box weight. To avoid complexities in calculating aerodynamic sensitivities for this illustration, a straight taper to a constant-tip thickness was used. Resulting sensitivities are shown in Fig. 9, where a 10% root thickness variation was used. Weight of fixed leading and trailing edges, tips, and other nonprimary structure weight, as well as weight of non-optimum material such as fasteners, and sealants were assumed constant.

Aerodynamic sensitivities were computed using a three-dimensional full-potential computational fluid dynamics (CFD) code described by Ide and Shankar.[12] Parameters varied were baseline sweep ± 10 deg; trimmed control-surface length a and deflections ± 5 deg and ± 10 deg; and baseline root thickness $\pm 10\%$. Sensitivities were calculated manually, and are presented in Table 1 for $M = 0.9$.

Resolution between performance and weight can be made several ways. Multiobjective optimization can be developed by assigning ratios to separate objectives and performing the optimization cycle. Alternately, a variable linking process using historical data or some other relation can be used to associate weight and performance. Here, the approach will be to use a mission-effectiveness simulation to resolve weight and aerodynamics conflicts. For purposes of this illustration, range at constant speed will be used, in the form

$$R = R(L/D, W) \tag{8}$$

Following previous notation, the first-order Taylor expansion is obtained as

$$R = R_0 + F\frac{\partial R}{\partial L}\Delta L + G\frac{\partial R}{\partial W}\Delta W \tag{9}$$

where the notation L is used to represent L/D as before.

For steady cruise conditions, the Breguet equation, for example Ref. 13, can be used to compute appropriate derivatives. The problem has then been formulated to minimize aircraft weight for a constant range, with aerodynamic performance adequate to meet minimum requirements for lift and roll rate. For the fighter being studied, the sensitivities required in Eq. (9) are given in Table 2 for $M = 0.9$.

Results and Discussion

Using these sensitivity parameters, a constrained optimization for minimum weight was performed using the modified

Table 1 Primary parameter sensitivities

Sensitivity with respect to	L/D	$C_{M_{roll}}$	Useful range
$\frac{\partial}{\partial \psi}$	-0.06218 deg^{-1}	-0.005211 deg^{-1}	$\psi = 50$ deg → 60 deg
$\frac{\partial}{\partial a}$	$+0.06095$ in.^{-1}	$+0.01826$ in.^{-1}	$a = 7.3 \to 22.0$ in.
$\frac{\partial}{\partial \delta}$	$+0.02920$ deg^{-1}	$+0.1123$ deg^{-1}	$\delta = 0$ deg → 2 deg
$\frac{\partial}{\partial(\%T)}$	-0.09003 (% change)$^{-1}$	$+0.003556$ (% change)$^{-1}$	$\Delta T = -10\% \to +10\%$

Table 2 Range sensitivities

$\frac{dR}{dL/D}$, miles	$\frac{dR}{dW}$, miles/lb
127.6	-0.28

Table 3 Optimization results

Root thickness, T	+10%
Sweep angle, ψ	52.4 deg
Wing box weight	−8.3%
TOGW	−0.8%

method of feasible directions option of the Automated Design Synthesis program. Convergence was typically obtained in several cycles, with results summarized in Table 3. Baseline using sweep angle was 50 deg aft. As can be seen, the optimum design converged to the maximum allowed wing thickness to using structural weight while maintaining lift, but sacrificing drag. Wing sweep was increased slightly.

Constant engine efficiency was assumed, with fuel weight allowed to vary with L/D changes. Roll rate was held to be the same as the baseline design as a constraint, with resized control surfaces used for trimming.

The significant wing structural weight reduction of 8.3% is due to sacrificing overall aerodynamic efficiency for this single condition. Although the tradeoff is a valid one, more complete mission simulation would be expected to alter specific results. For example, sensitivities of the objective functions to variations in key mission segments was shown by Simos and Jenkinson[9] to have potentially significant effects. Furthermore, studies by Johnson[14] showed a wide variation in optimum commercial aircraft wing planform as a result of changing objective functions. These results indicate the potential for significant vehicle-design improvement when the entire system is considered, with sufficient detail at the various levels to adequately model each discipline. Significant extension is now needed to fully develop an adequate computer system and data base to take full advantage of these developments.

Conclusions

A systematic method for decomposing complex aircraft design process into a series of levels for suboptimization has been presented. This multilevel definition is developed so that design variables have relatively equal impact at each level. When coupled with currently available computational capabilities in aerodynamics and structures, this approach provides a systematic technique for optimization at the various levels and combining these suboptimizations into a total system with accurate representation of the complex design drivers. A relatively simple example was used to show the potential of this process to develop an improved design compared to one developed by conventional sequential approaches and, hopefully, the value of a system view of the design process. Although still requiring extensive further work to expand capabilities and understand cross-discipline design variable effects, these integrated approaches, as being investigated and developed by a number of authors, promise to develop breakthrough vehicle designs that successfully integrate complex and conflicting design requirements.

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