JOURNAL OF AIRCRAFT
Vol. 32, No. 2, March–April 1995

Multidisciplinary Optimization in Aircraft Design Using Analytic Technology Models

Brett Malone* and W. H. Mason†
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

An approach to multidisciplinary optimization is presented that combines the global sensitivity equation method, parametric optimization, and analytic technology models. The result is a powerful yet simple procedure for identifying key design issues. It can be used both to investigate technology integration issues very early in the design cycle, and to establish the information flow framework between disciplines for use in multidisciplinary optimization projects using much more computationally intense representations of each technology. To illustrate the approach, an examination of the optimization of a short-takeoff, heavy transport aircraft is presented for numerous combinations of performance and technology constraints. The results show explicitly the takeoff weight penalty for transonic cruise Mach number and the wing sweep variation with cruise Mach number. Conceptual designs can be optimized rapidly with this approach.

Nomenclature

AR = aspect ratio
$C_{D\text{cruise}}$ = cruise drag coefficient
$C_{D\text{wave}}$ = transonic wave drag
C_{D0} = zero lift drag
C_{fix} = fixed weight fraction multiplier
$C_{L\text{cruise}}$ = cruise lift coefficient
C_l = section lift coefficient
E = Oswald efficiency factor
$\boldsymbol{F}$ = vector function of governing equations for design system
f = vector function of governing equations for subsystem
G = global sensitivity coupling matrix
h = cruise altitude, ft
K_A = technology factor used in M_{DD} computation
K_s = wing weight equation technology factor
L/D = lift-to-drag ratio
M = Mach number
M_{crit} = critical Mach number
M_{DD} = drag divergence Mach number
n = ultimate load factor
R = range, nm
S_{csw} = wing-mounted control surface area, ft^2
S_{ldg} = landing distance, ft
S_{to} = takeoff distance, ft
S_w = wing area, ft^2
sfc = specific fuel consumption, lb/h/lb
T_{req} = required thrust, lb
T/W = thrust-to-weight ratio
t/c = wing thickness ratio
V = cruise speed, kt
V_{rot} = takeoff rotation velocity, ft/s
W_{cargo} = cargo weight, lb
W_{eng} = engine weight, lb
$W_{f\text{clm}}$ = fuel weight used in climb segment, lb
W_{fix} = fixed weight, lb
W_{fuel} = fuel weight, lb
W_{initial} = aircraft weight at beginning of cruise phase, lb
W_{to} = takeoff gross weight, lb
W_{wing} = wing weight, lb
X = independent design variable set
$\boldsymbol{Y}$ = vector set of dependent design variables
$\Lambda_{0.25}$ = wing quarter-chord sweep, deg
λ = taper ratio

I. Introduction

AIRCRAFT conceptual design is becoming an increasingly complicated process. To achieve advances in performance, each technology, or discipline, must be much more highly integrated than in the past. In addition, designs of interest often depart radically from past experience. The designer is forced to confront many issues immediately, and the initial decisions made will essentially dictate the cost and schedule of the project. Under these conditions, the designer needs tools that provide good insight into the key technology integration issues at the earliest possible time. Rapid system evaluation with good insight into the important design parameters is the key to a successful initial design.

Aircraft designers are acutely aware of the importance of initial sizing and optimization. One well-known current method for aircraft sizing is ACSYNT (Air Craft SYNThesis), which was originally described by Vanderplaats,[1] and is undergoing continual development.[2] Although extremely valuable, it would be useful to provide the designer with a simpler, PC level, very rapid means of focusing directly on the issues arising from the integration of different disciplines in the complete system.

The problem of understanding how to combine different disciplines to achieve optimum designs has been addressed by Sobieski and co-workers for several years. This work has as its long-term goal the establishment of a rational means of coupling the most powerful computational methodology available for each discipline. An overview of the work has been given recently by Sobieski,[3] and the key idea of a global sensitivity equation (GSE) method to define interactions between disciplines has been described in detail in Ref. 4. This technique can provide an important alternative to more traditional sizing programs, even though it is intended to address more detailed design problems. Applications of this methodology have been described in Refs. 5–7. NASA experience is described in Ref. 8.

Presented as Paper 91-3187 at the AIAA/AHS/ASEE Aircraft Design Systems and Operations Meeting, Baltimore, MD, Sept. 23–25, 1991; received March 16, 1992; revision received June 22, 1994; accepted for publication July 7, 1994.

*Research Associate, ACSYNT Institute, Blacksburg, VA. Student Member AIAA.

†Associate Professor, Department of Aerospace and Ocean Engineering. Associate Fellow AIAA.

Analytic technology models have been demonstrated to provide an excellent means of understanding technology integration issues.[9] Using very simple algebraic models, the key interactions between structures, propulsion, and aerodynamics were demonstrated. Considering the value of both simple and sophisticated analysis in design, it appears reasonable to combine both levels of simulation in a single design methodology. This has been done using a concept called "variable-complexity design" by Unger et al.[10] This concept can be applied in numerous ways to the specific design problems. Another example is the "combined global-local approximation" approach proposed by Haftka.[11]

This article describes an approach that combines aspects of the methods described above for use by designers during early stages of configuration feasibility studies. The purpose is to provide insight into the key design issues with minimum effort. Analytic technology models are defined, and the approach is structured so that they can be replaced by improved models as desired. Sobieski's GSE method is then used to determine the interactions between disciplines. With the gradients of the design available from the GSE analysis, a numerical optimization solution can be obtained.

After a review of the mathematical basis of the GSE method, the technology models are defined. Using a short takeoff heavy transport as an example, the results from both the GSE analysis and the optimization are presented. Due to the simplicity of the approach, results of nearly 100 optimizations are used to illustrate the effects of various design variables, design Mach number, takeoff distance, and wing section lift constraint.

II. Review of a Global Sensitivity Approximation

We describe the individual technologies, or disciplines, as the subsystems to the entire aircraft being designed. These subsystems include, e.g., aerodynamics, structures, and propulsion. Within each subsystem are the individual parameters that are key to the design process. These include such items as takeoff field length or wing weight.

In the traditional design approach, these subsystems would be treated individually, allowing little or no communication with the other subsystems in the process of gradient computations in the optimization process. These disciplines are highly coupled and this coupling must be captured to calculate accurate and meaningful derivatives.

By coupling, it is meant that the influence of one discipline's output, or key parameter, on another discipline's output is measured and used to augment that parameter's gradient with respect to a certain design variable. For instance, a gradient of takeoff gross weight with respect to a specific design variable would normally involve a finite difference calling only the weights subsystem. When this approach is taken, however, the important influences of the aerodynamics subsystem are not considered. The solution to the takeoff gross weight is an iterative procedure that depends heavily on the relationship between these two disciplines. As a result, the coupling effects between the two disciplines are quantified in the solution to the GSEs. A system of only three subsystems is introduced for simplicity, however, the approach may be generalized to n subsystems.

The given problem of sizing an aircraft using W_{to} as an objective function subject to several design constraints can be described as the solution to the set of equations given by the technologies. With each technology represented as an individual subsystem, the governing equations of the entire system can be written as a vector function:

$$F(Y1, Y2, Y3, X) = 0 \tag{1}$$

If we have entirely independent subsystems, we can use the implicit function theorem[12] to rewrite each subsystem in the following manner:

$$Y1 = f1(Y2, Y3, X) \tag{2a}$$

$$Y2 = f2(Y1, Y3, X) \tag{2b}$$

$$Y3 = f3(Y1, Y2, X) \tag{2c}$$

It is important to note here that each subsystem function must be independent. By this, it is meant that a certain output of a subsystem cannot depend on another output from the same subsystem.

We can now linearize the system of equations shown in Eq. (2) in the neighborhood of the solution using a Taylor series expansion:

$$Y1 = Y1_0 + \frac{\partial f1}{\partial X}\Delta X + \frac{\partial f1}{\partial Y2}\Delta Y2 + \frac{\partial f1}{\partial Y3}\Delta Y3 \tag{3}$$

If we then rearrange the set of linearized equations to reflect the form of Eq. (1), we can write

$$F1 = Y1 - Y1_0 - \frac{\partial f1}{\partial X}\Delta X - \frac{\partial f1}{\partial Y2}\Delta Y2 - \frac{\partial f1}{\partial Y3}\Delta Y3 = 0 \tag{4}$$

and, thus

$$F = (F1, F2, F3)^T = 0 \tag{5}$$

We can write the Jacobian, or the global sensitivity coupling matrix, from the system, Eq. (4) in the following form:

$$\begin{bmatrix} I & -\dfrac{\partial Y1}{\partial Y2} & -\dfrac{\partial Y1}{\partial Y3} \\ -\dfrac{\partial Y2}{\partial Y1} & I & -\dfrac{\partial Y2}{\partial Y3} \\ -\dfrac{\partial Y3}{\partial Y1} & -\dfrac{\partial Y3}{\partial Y2} & I \end{bmatrix} \tag{6}$$

noting that each component of the matrix, Eq. (6) is a matrix within itself.

If, e.g., we have a number of subsystem parameters within a certain discipline, then that one component within the GSE matrix would look like the following:

$$\frac{\partial Y1}{\partial Y2} = \begin{bmatrix} \dfrac{\partial Y1(1)}{\partial Y2(1)} & \cdots & \dfrac{\partial Y1(1)}{\partial Y2(ny2)} \\ \vdots & \ddots & \vdots \\ \dfrac{\partial Y1(ny1)}{\partial Y2(1)} & \cdots & \dfrac{\partial Y1(ny1)}{\partial Y2(ny2)} \end{bmatrix} \tag{7}$$

where each component of the $Y1$ and $Y2$ vectors is a subsystem parameter, such as cruise C_L, or wing weight.

The matrix, Eq. (6), denoted as G here, is then used to solve for the global sensitivities by using the local sensitivities with respect to X as the right side(s):

$$[G]\cdot\begin{bmatrix} \dfrac{DY1}{DX} \\ \dfrac{DY2}{DX} \\ \dfrac{DY3}{DX} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial Y1}{\partial X} \\ \dfrac{\partial Y2}{\partial X} \\ \dfrac{\partial Y3}{\partial X} \end{bmatrix} \tag{8}$$

There is a full set of these derivatives for every design variable, therefore, Eq. (8) must be solved repeatedly for each different right side. Since these are linear equations, this can be done efficiently by factoring the G matrix only once, and back-substituting each right-hand side over it. Once the global derivatives, or sensitivities, are found, this information can then be supplied to the optimization routine for search direction calculation.

III. Technology Models

In this analysis the aircraft W_{to} will be the key figure of merit. W_{to} is defined to consist of

$$W_{to} = W_{wing} + W_{fuel} + W_{eng} + W_{fix} + W_{fclm} + W_{cargo} \quad (9)$$

The main purpose of this optimization procedure is to find the wing design and engine size required to minimize the total aircraft weight for the specified mission and field performance. Components other than the wing and fuel weight were taken to be either fractions of the takeoff weight, or prescribed constants. For initial development, ACSYNT was used to obtain accurate weight fractions.

A. Weights

1. *Structures*

The wing structural weight can be estimated using wing weight equations. Several levels of approximation are available. The equation from Raymer[13] is one example:

$$W_{wing} = 0.0051 K_s S_w^{0.649} S_{csw}^{0.1} \frac{AR^{0.5}}{(t/c)_{root}^{0.4}} \cdot \frac{(nW_{to})^{0.557}(1 + \lambda)^{0.1}}{\cos \Lambda_{0.25}} \quad (10)$$

The weight prediction from this equation was checked against data in Torenbeek[14] for typical transports and found to be accurate to within 2–3%.

2. *Fuel Weight*

The fuel weight for cruise is found using the Brequet range equation:

$$W_{fuel} = W_{initial}\left\{1 - e\left[\frac{R \cdot sfc}{V(L/D)}\right]\right\} \quad (11)$$

3. *Engine Weight*

The engine weight is found based on a required thrust and assuming a known thrust-to-weight ratio for the class of propulsion system selected. Thus, the engine weight is found from

$$W_{eng} = T_{req}/(T/W)_{eng} \quad (12)$$

Specific fuel consumption can be constant, or vary if information is available.

4. *Systems/Miscellaneous*

The remaining weights can be defined as aircraft structure and systems weight excluding the wing structural weight. This weight can be expressed as a fraction of the takeoff gross weight:

$$W_{fix} = C_{fix} W_{to} \quad (13)$$

B. Aerodynamics

The aerodynamics technology level for an aircraft is given by the drag polar:

$$C_{D_{cruise}} = C_{D_0} + C_{D_{wave}} + (C^2_{L_{cruise}}/\pi ARE) \quad (14)$$

The subsonic zero lift drag coefficient was estimated from a turbulent skin friction form drag analysis taking into account the entire aircraft wetted area. Effects of Mach number and Reynolds number are easily incorporated.

The transonic wave drag model is based on Lock's empirically based approximation[15]

$$C_{D\text{wave}} = 20(M - M_{crit})^4 \quad (15)$$

which was recently derived theoretically by Inger.[16] When M is less than M_{crit}, the wave drag is zero. Using the definition of the drag divergence Mach number

$$\frac{dC_{D\text{wave}}}{dM} = 0.1 \quad (16)$$

M_{crit} can be found using Eq. (15) as

$$M_{crit} = M_{DD} - \left[\frac{0.1}{80}\right]^{(1/3)} \quad (17)$$

The drag divergence Mach number was found using the Korn equation as extended to include sweep by Mason[9]:

$$M_{DD} = \frac{k_A}{\cos \Lambda} - \frac{(t/c)}{\cos^2 \Lambda} - \frac{C_L}{10 \cos^3 \Lambda} \quad (18)$$

Here, k_A is a technology factor (range 0.87–0.95). This expression provides the relation between the thickness and sweep for transonic drag rise. This expression also contains the effects of increasing takeoff weight and wing area through the cruise lift coefficient.

This model was employed because of its ability to smoothly reflect the changing drag divergence Mach number during the design iterations. A comparison of the prediction from this method with ACSYNT showed good agreement.

The aerodynamic model also includes a constraint on C_L based on C_l. For a maximum value of the section lift coefficient and assuming a nearly elliptic spanload distribution, the total aircraft lift coefficient limit is given by

$$C_L \le \frac{\pi}{2} \frac{\sqrt{\lambda(2 - \lambda)}}{(1 + \lambda)} C_l \quad (19)$$

This connects the section lift coefficient limit defined by the level of aerodynamic technology to the total aircraft lift limit.

C. Performance

1. *Takeoff*

The takeoff distance is found from the rotation velocity based on the takeoff weight and the field performance configuration aerodynamics using estimates for rotation, transition, and climbout distances. This model is based on the analysis by Krenkel and Salzman.[17]

2. *Landing*

The model for analyzing the landing performance was developed using the methods in Ref. 18. The ground roll uses a constant deceleration, taking into account antiskid braking, thrust reversing, ground spoilers, and speed brakes. The thrust reversing model used assumes 40% of the maximum thrust available for reversing.

IV. Subsystem Vectors and GSE Matrix

Each of the above technologies is considered an analysis that contributes to the overall system. These technologies are simply analytic expressions for the purpose of illustration. However, they could be large, complicated, and somewhat independent analysis routines that represent the most sophisticated computational methods for each technology or discipline. The key is the relationship between the input and the output information required for these technologies, and what each technology requires in terms of system information (i.e., design variables).

To properly capture the relationships between disciplines, the GSEs must be written in the format described in Eq. (6). Thus, the technologies were placed in three separate subsystems for use in the calculation of the global sensitivities. The contents of each subsystem vector are

$$Y1 = (C_L, V_{rot}, C_D, S_{to}, S_{ldg})^T$$
$$Y2 = (W_{fuel}, W_{wing}, W_{eng}, W_{fix}, W_{fclm}, W_{cargo})^T$$
$$Y3 = (W_{to})^T \tag{20}$$

We found that W_{to} was required to be grouped separately from the other weights. In finding the derivatives, care must be taken to ensure that the proper dependent and independent variables are maintained. Even though the takeoff weight is simply the sum of the component weights, it is a separate subsystem because it must contain the coupling effects of its components.

The design variables were chosen to include the key parameters for optimization in conceptual aircraft design. Seven design variables were chosen as the representative set for optimization:

$$X = (AR, S_w, h, M, \Lambda, t/c, \lambda)^T \tag{21}$$

The takeoff gross weight was selected as the objective function for the optimization problem, although any of the components (or a combination) of the Y can be selected as the figure of merit. In addition to the objective function, the constraints chosen were the takeoff distance and the attainable section lift coefficient in the cruise phase, as discussed above.

The computer code was designed in an organized fashion that followed the "contributing analysis" thinking. An automated "black box" procedure was established that made computing the local derivatives and the global sensitivity matrix straightforward. By setting up the problem in a black box fashion, every discipline was an independent routine that modeled what might on a larger scale be an entirely separate analysis program. The flow of data between these routines was controlled such that the inputs of any one discipline were strictly a function of the outputs of the other disciplines. Communication between each discipline was done entirely through these Y vectors.

V. Example Problem

A. Problem Statement

An example was selected to illustrate the method. In this case, a short-takeoff, medium-range heavy, transport was used. The appropriate optimization problem statement is given by

$$\min f(x)$$

s.t. takeoff distance ≤ max allowable takeoff distance

wing section lift coefficient

≤ max allowable section lift coefficient

$$l \leq x \leq u \tag{22}$$

Where $f(x)$ is the objective function, taken here to be the takeoff gross weight. According to appropriate technology limitations in the field of structures and aerodynamics, suitable lower l and upper u bounds were placed on the design variables.

B. Baseline Configuration

Table 1 shows the specified mission along with a suitable candidate for the propulsion system. ACSYNT was used to establish a baseline model from the data. Because ACSYNT is a fully developed and well-tested aircraft sizing software package, it was used not only for the baseline estimates, but also as a comparison code throughout the development of the multidisciplinary process. Using published data for similar aircraft,[19] a geometry module was created. A mission profile was specified for the candidate aircraft based on a 3000-n.mi. cruise range. This cruise range accounted for the base mission range plus an extra distance to account for reserve fuel requirements. The given initial estimates for the takeoff gross weight and fuel weight came from this analysis. ACSYNT also gave estimates of C_{D0} that were used to verify the analytic aerodynamic models.

Table 1 Mission requirements

Cargo weight	150,000 lb
Range	3,000 n.mi.
Takeoff distance	5,000 ft
Landing distance	4,000 ft
Propulsion	4 CF6 class turbofans, $T/W_{eng} = 6$

Because the individual disciplines are actually sets of nonlinear, coupled equations,[4] a solution to these equations must be obtained initially before the global sensitivity equations can be calculated. The code incorporates a weight convergence algorithm that iterates between each subsystem until all the equations in each of the disciplines are satisfied. Fixed point iteration was used to converge W_{to} for a given cruise range and set of design variables.

C. Solving the Global Sensitivity Equations

Once the subsystems were defined in terms of the technology models, and all the discipline interactions calculated in the GSE matrix, the global derivatives were computed. The local gradient of W_{to} is zero for every design variable. This comes from the formulation of the takeoff gross weight as a separate subsystem. As specified, the $Y3$ subsystem does not have design variables explicitly in the formulation, rather, it is simply the sum of the elements in the $Y2$ discipline (the component weights). As a result, when a derivative of W_{to} with respect to any of the design variables is computed using finite differencing on that discipline alone, the gradient is zero. However, when the interactions of the aerodynamics and component weights subsystems are taken into account, the resulting global derivatives reflect the actual total function gradient.

D. Optimization

The optimization was performed using NLPQL,[20] a Fortran implementation of a sequential quadratic programming method for solving nonlinearly constrained optimization problems. At each iteration the search direction is a solution of a quadratic programming subproblem. NLPQL uses gradients of the objective function and the constraint functions obtained from the solution of the global sensitivities as described in Eq. (8).

E. Results

Using the analytic models for the technology, many (thousands) of optimization cases can be computed. For the general case, Table 2 shows the design variables, objective function, and constraints before and after the optimization. To achieve the minimum weight solution for this problem, the optimizer reduced the Mach number and unswept the wing. A large weight savings was obtained. However, the resulting aspect ratio is unreasonably high. For this result Raymer's wing weight equation was used. Other choices for this equation could be used, producing different results, and this is discussed later. Figure 1 shows the convergence history for the optimization using all seven design variables. Note that even though the weight is nearly converged at 17 iterations, the design variables are still changing until 24 iterations have been made.

Table 2 Initial point vs optimized solution

	Initial	Final
Aspect ratio	7.00	22.65
Wing area, ft^2	3,800	3,957
Cruise altitude, ft	39,600	35,936
Mach number	0.78	0.61
Midchord sweep, deg	21.0	1.0
Thickness ratio, t/c	0.10	0.18
Taper ratio	0.10	0.27
W_{t0}, lb	546,788	467,198
Takeoff distance, ft	6,301	5,000
Landing distance, ft	2,713	2,355
Cruise C_L	0.8431	0.9621
Cruise C_D	0.0714	0.0400

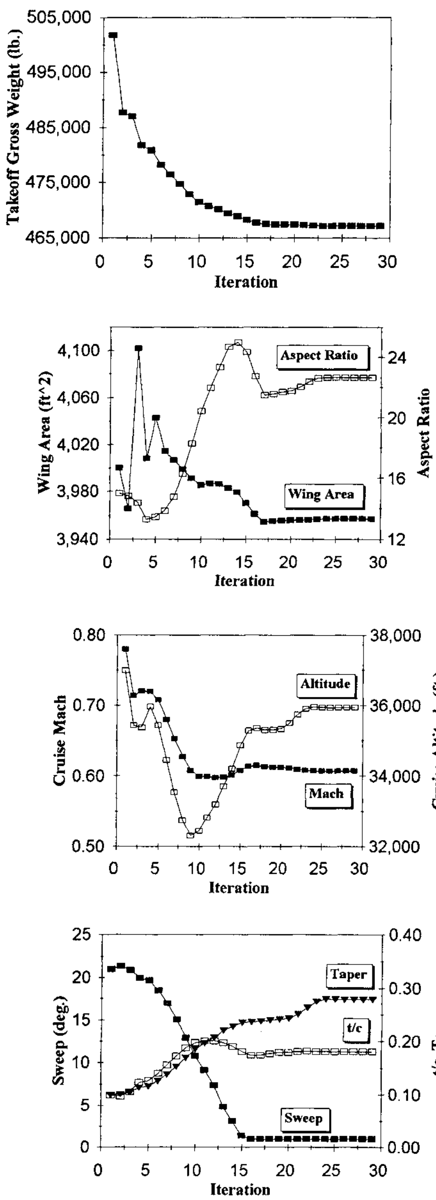

Fig. 1 Convergence history for full design set.

F. Optimized Solutions for a Range of Mach Numbers

The results shown in Fig. 1 give information for one design. Much more insight can be obtained by examining optimum results over the range of a specified parameter. Mach number is a good example. The effect of a mission-specified Mach number, as would be given in a typical design request for proposal, can be observed by fixing the Mach number and optimizing the aircraft with respect to the reduced design variable set. By implementing the optimization in this manner, we can easily identify the tradeoffs of performance, aerodynamics, and structures as the wing evolves from a low-speed design to a high-speed, transonic design.

Figure 2 shows a range of optimal solutions for specified Mach numbers from 0.5 to 0.9. Two cases are presented. The first case shows the effect of imposing only the takeoff constraint ($S_{t0} \leq 5000$ ft), whereas the second case includes the takeoff constraint and the section lift coefficient constraint ($C_l = 1.0$).

The optimal solution presented in Table 2 is shown as the minimum of the W_{t0} plot in Fig. 2. Increasing the Mach number above this value (0.61) results in an increased weight and wing area. The results show a decreasing aspect ratio as the wing area is sized for the takeoff constraint. At low Mach numbers, the wing is unswept, but as the cruise Mach number is increased the wing sweep suddenly starts increasing to alleviate the transonic drag effects. This effect can be compared to a sweep schedule that is used for a variable sweep wing aircraft such as the F-14 and F-111.[21] From a structural standpoint, the wing thickness is optimal at large values, however, aerodynamically, a thick wing creates increased form and wave drag.

The effect of adding the C_l constraint is most apparent in the taper ratio. For the first case, the taper ratio is reduced to the imposed lower bound (0.1) to reduce the wing weight. In the second case, however, the constraint limit imposed on the aircraft lift coefficient is a function of the taper ratio. Therefore, the addition of the C_l constraint illustrates how the optimizer uses taper ratio to meet the constraint limit value optimally.

G. Effect of Limited Design Variable Set

Insight can also be gained into the relative importance of design variables by examining the results of using limited sets of design variables.

1. *Case 1*

The design variables were limited to aspect ratio and wing area:

$$X = (AR, Sw)^T \tag{23}$$

All other design variables were held constant and the cruise Mach number was varied parametrically. The constraint limit placed on the takeoff distance was 5000 ft, and the section cruise C_l limit was 1.0. The numerical results in Fig. 3 show a decrease in the aspect ratio with increasing Mach. The wing area decreased to a point where the takeoff constraint became active, then remained at the required wing loading to minimize the design while remaining within the feasible design region. For this limited design variable case, the optimum solution is found at a Mach number of 0.73.

2. *Case 2*

The design variable set was expanded to include sweep

$$X = (AR, Sw, \Lambda)^T \tag{24}$$

The optimum aircraft occurs for $M = 0.7$, lower than case 1. The aspect ratio result shows the effect of the wing area being sized by the takeoff constraint. The wing area is nearly constant with Mach until the takeoff constraint becomes active at $M = 0.6$. Further decreases in Mach result in a rapid increase in the wing area.

As expected, to alleviate the transonic drag, the optimum wing sweep increases with increasing Mach number.

3. *Case 3*

Wing thickness is added to the design variable set:

$$X = (AR, Sw, \Lambda, t/c)^T \tag{25}$$

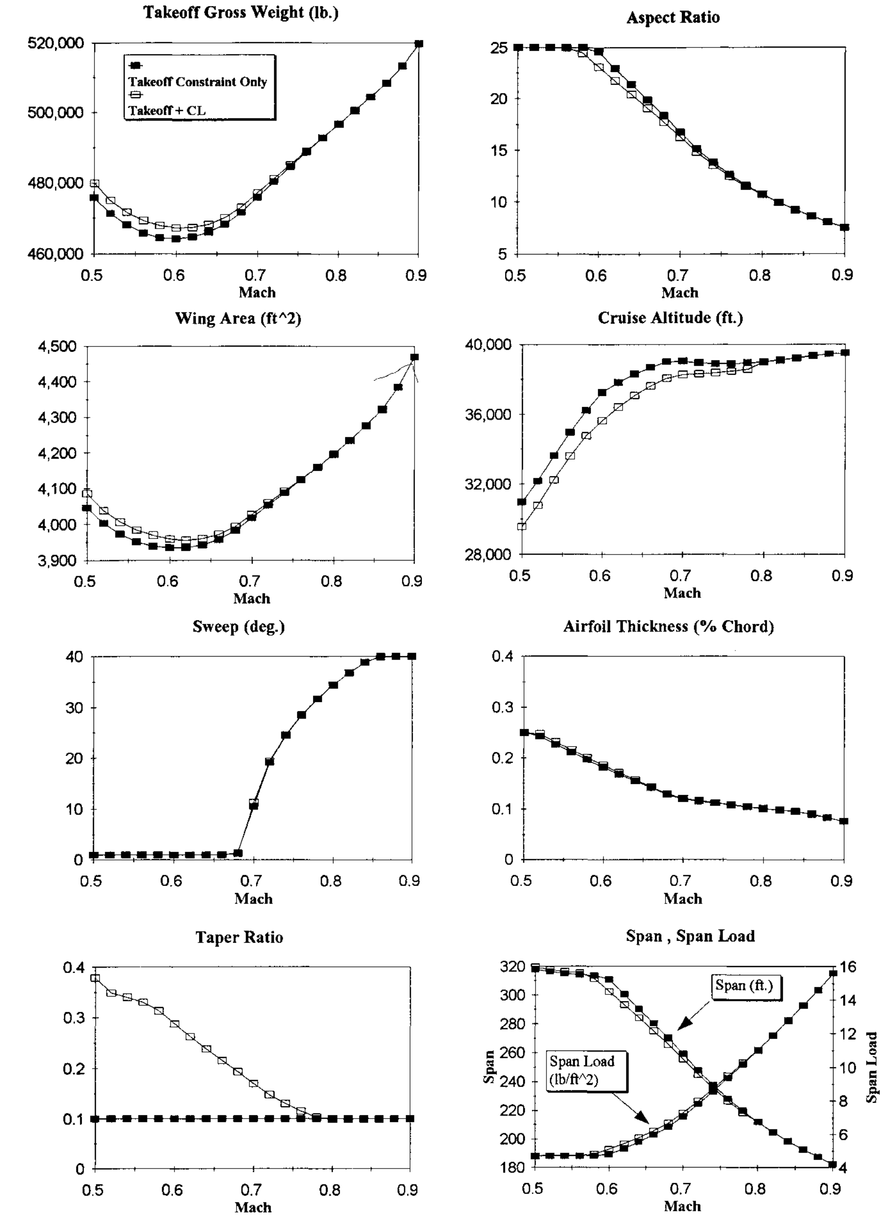

Fig. 2 Optimal solutions for a range of specified Mach numbers.

Several interesting results occur when the airfoil thickness ratio is added to the set of design variables. First, there is an obvious shift in technology focus from an aerodynamic design, as shown in cases 1 and 2, to a structural design. By using thickness as a design variable, the optimum solutions found at low Mach numbers reflect a very high aspect ratio. This is a direct result of the structural wing weight equation. As the thickness is allowed to increase above the baseline, the wing becomes lighter, thus allowing the higher aspect ratio designs to become more feasible. However, aerodynamically, the wing sweep plot shows that with a thicker wing, more sweep is needed at a given Mach number to account for the increased transonic drag.

4. Case 4

Corresponding to the results of the Mach parametric study, all the design variables except the Mach number were used. These results were previously discussed above:

$$X = (AR, Sw, h, \Lambda, t/c, \lambda)^T \tag{26}$$

H. Technology Complexity: Effect of Wing Weight Models

By implementing more sophisticated routines for calculating the wing weight, the results can be compared to the simpler analytic technology model. Three wing weight methods were used to compute minimum weight designs. The first case used Raymer's[13] wing weight equation, the second used McCullers',[22] and the third case used Nicolai's[23] equation. McCullers' formulation is the most sophisticated, integrating estimated span loads to arrive at bending moment distributions and material factors. This equation results in the lowest weight solution. The weight increases for wing area and aspect ratio were different than in Raymer's formulation. This led to higher aspect ratio designs with lower wing areas. However, the trends were the same. McCullers' formulation was the most flexible, allowing a more detailed representation of various wing components.

Nicolai's equation resulted in very high wing areas, which led to very short takeoff distances and lower aspect ratios. Nicolai's equation, although similar in form to Raymer's, places different exponential powers on the important design variables, resulting in a lower weight penalty due to wing area:

$$W_{\text{wing}} = 0.00428 K_s S_w^{0.48} \frac{ARM_0^{0.43}}{[100(t/c)_{\max}]^{0.76}} \frac{(NW_{\text{to}})^{0.84} \lambda^{0.14}}{\cos^{1.54} \Lambda_{1/2}} \tag{27}$$

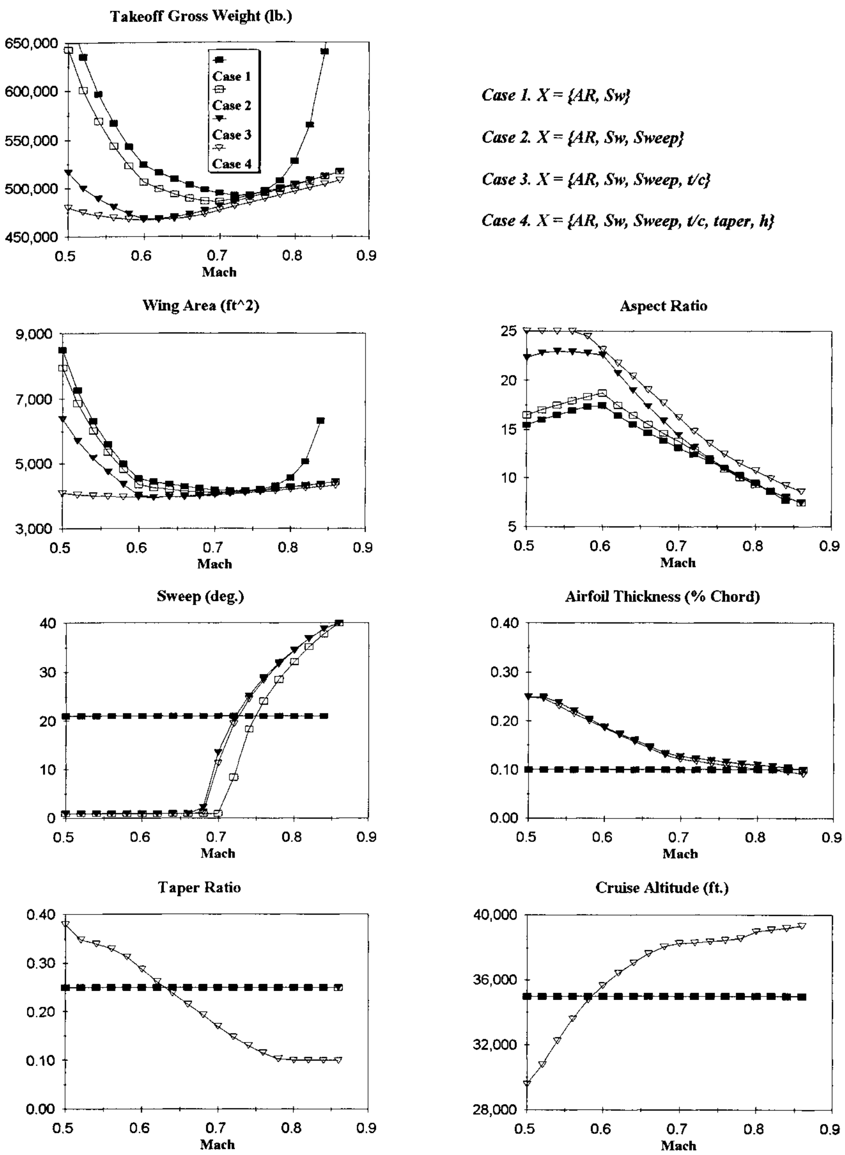

Fig. 3 Effect of design variable set on optimum solution.

As a result of the different penalty factor, optimum designs achieved using Nicolai's equation have higher wing areas. The complete set of results is contained in Ref. 24.

VI. Remarks and Conclusions

The approach to multidisciplinary optimization proposed here for use at the conceptual/preliminary design level provides the designer with a wealth of information with a minimal investment in time. To use the approach effectively we summarize the lessons learned and resulting recommendations for use of this approach.

A. Optimization

Smooth analytic models work best with optimization. Precise gradient information in the form of numerically accurate tolerances are required. Considering technology model accuracy, optimization exploits the peculiarities of any technology model.

B. Problem Formulation

Independent variables are sometimes hard to identify. Analytic models provide a fast way to examine the formulation and results from the problem formulation. We decided to make W_{to} a separate independent variable as a result of our problem analysis at this stage.

C. Value of Parametric Optimized Solutions

This approach provides insight and context to the results. We found that without parametric studies, erroneous optimization solutions (local minima, uncertainty due to inaccurate gradients) were very hard to identify. It is much easier to identify explicitly the role of individual design variables and constraints following this approach.

D. GSEs

Gradient information is controlled by the user and provided to the optimizer. Explicit sensitivities are available for examination at each step.

We recommend that this approach always be used with analytic models before using more exact numerical analysis. Not only does it define the information flow exactly, but valuable insights into both the problem formulation and the behavior of the solution are available in days rather than weeks using this approach. Also, this approach can provide a starting point for optimization using more detailed calculation procedures.

The approach described here provides a means of bridging the gap between formalized optimization methodology and aircraft sizing programs that are currently in use, providing a simple way of gaining greater insight into the problem of aircraft design and initial sizing.

Acknowledgments

Support for portions of this work was provided by NASA Langley Research Center, Hampton, Virginia, under Grant NAG-1-224, and by the National Science Foundation, Washington, DC, under Grant DDM-9008451, and is gratefully acknowledged.

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