Automated Optimization Techniques for Aircraft Synthesis

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Abstract

Techniques for automating conceptual aircraft design are presented. Numerical optimization methods are employed to size the aircraft to fly a prescribed mission using a variety of design objectives, design variables, and constraints. Fully automated design is compared with traditional point design methods and time and resource requirements for automated design synthesis are given. Design examples using the NASA Ames aircraft synthesis program, ACSYNT, include optimization of a vehicle for minimum gross weight and sensitivity of the optimum vehicle to improvements in materials technology.

Introduction

Aircraft synthesis using automated design techniques provides an efficient means of obtaining preliminary estimates of vehicle weight, cost, and performance. Additionally, competing vehicle concepts can be evaluated on an equal basis, and the effects of technological advancements on overall vehicle cost and performance can be assessed.

The value and limitations of design automation have been widely recognized and numerous design studies have been reported in the literature. References 2-25 are indicative of the depth and scope of these works. While the automated design process is described in several of the references, relatively little work has been reported dealing with the basic question of how this automation is accomplished most effectively.

In considering design automation, two major concerns are often expressed. First is the accuracy of the information provided by the methods in each discipline (e.g., aerodynamics, propulsion, etc.). The second concern deals with the feasibility of automating the complex decisions involved in vehicle design. It is assumed here that the design process can be automated. This paper deals primarily with the question of how this automation might be efficiently achieved. While many of the principles presented here may be applied directly to the preliminary and detailed design phases, this discussion is limited to the conceptual design phase, that is, the design phase where the initial vehicle size and performance characteristics are defined. This is also the design phase in which numerous alternate vehicle concepts are defined and compared. Therefore, considerable time and cost benefits can result from effective automation of this process to provide a quantitative measure of the similarities and differences between vehicle concepts. It will be shown that effective automated design is not a matter of simply automating existing techniques, but requires a new and detailed consideration of the interaction of the various disciplines within the design process.

Most of the techniques presented here have been incorporated into the NASA Ames Research Center aircraft synthesis program (ACSYNT) and have been used continuously for more than two years. The ACSYNT program will be briefly described here, and those portions of the program dealing with design automation will be discussed, beginning with the basic requirement of estimating the weight of a vehicle to fly a specified mission. Numerical optimization techniques used in the program are described, and the procedures for automatically obtaining sensitivity of the design to various vehicle, mission, and technology parameters are presented. Examples are used to demonstrate the efficient application of these techniques.

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The Aircraft Synthesis Program - ACSYNT

Figure 1 is a block diagram of the ACSYNT computer program. This is representative of the synthesis programs used in government and industry. However, three features of ACSYNT are not commonly used in other programs. First is the integration into the program of the modules entitled convergence, optimization, and sensitivity. The convergence module calculates the gross weight of the vehicle to fly a prescribed mission. Optimization sizes the vehicle and propulsion system to achieve minimum gross weight (or to minimize or maximize some other parameter). The sensitivity module automatically varies a single design parameter such as wing area, range, or payload to determine the effect of this parameter on the vehicle design. During a sensitivity analysis, the vehicle may be reoptimized at each value of the sensitivity parameter. These three modules will be discussed in more detail in later sections.

The second unique feature of ACSYNT is that the vehicle is not sized within the discipline modules, but rather the sizing function is carried out by the optimization module. Six discipline modules currently exist in the ACSYNT program: geometry, trajectory, aerodynamics, propulsion, structures, and mass properties.

The vehicle geometric parameters are initialized the first time the geometry module is called. On subsequent calls to geometry, surface areas and volumes are calculated for use by the other modules and for use by the optimization code to make decisions on design changes. The trajectory module calculates the fuel weight necessary to fly the prescribed mission. This module calls the aerodynamic and propulsion modules to obtain the required lift, drag, thrust, and fuel flow information. This is the only situation in the program where one discipline module is allowed to call another module. The aerodynamics module calculates lift, drag, or angle of attack as required at a specified altitude and Mach number. The method ofAxelson[26] is programmed into this module to provide aerodynamic characteristics at high angles of attack. The propulsion module is a one-dimensional cycle analysis developed by Morris[27] which sizes the engine and afterburner (if used), and calculates engine performance and other characteristics at specified altitude and Mach number. Additionally, this module estimates the engine weight and physical dimensions and calculates nacelle dimensions for use by aerodynamics. Component weights are calculated in the mass properties module using empirical equations based on the weights of existing aircraft. This module also adds all component weights, fuel weight, and payload to provide a calculated vehicle weight based on the estimated gross weight. The structures module is not normally used in conceptual aircraft synthesis. However, this module is included in the ACSYNT program for simplified structural calculations of unique aircraft configurations such as the oblique-wing transport.[28] The economics module shown in Fig. 1 is not currently used in the ACSYNT program.

Each module is separated into three well-defined sections; input and data initialization, execution, and output of results. Each module is called for input only once, but may be called for execution many times during the design optimization process. Each module is called twice for output, first to print the results of the analysis of the initial aircraft and again to print the results for the optimized aircraft. The modules may be called for output more than twice at the user's option to print intermediate design information.

The control program defines the sequence of design operations and provides the third function unique to ACSYNT, that of data transfer. During program development, it was found that much less data needed to be transferred between modules than was originally anticipated. Recognizing that data handling and transfer was a major factor, a special effort was made to make this function simple and not overly large.

This allowed for complete automation of the optimization and sensitivity functions which might not otherwise have been possible. Because less than 1000 words of data are transferred between the modules, the data are stored in a single, labeled, common block referred to as the global common block. During program development, it was found to be convenient to allow each module developer to create his own module as a stand-alone program. It was necessary to know only what information needed to be transferred to other modules and what information would be provided from other modules. This information is stored in a common block unique to each module. The module can then be run by itself simply by providing to this common block the input which would normally be provided by other modules. Upon program integration, a single data transfer routine was written for each module to transfer the data between the global and local common blocks before and after execution of the module. A catalog of information transferred to and from each module is maintained and stored on the computer. The subroutines used for data transfer are coded for each module based on information contained in this catalog. As the ACSYNT program is developed and expanded, new information is often added to the catalog, and new data transfer routines must be written. The updating of the catalog and the writing of the data transfer routines are fully automated so that an external program can be run interactively which updates the catalog and provides the data transfer routine as source codes to be integrated directly into the ACSYNT program.[29]

To execute the ACSYNT program, an initial estimate of the vehicle definition must be provided along with mission and payload requirements. The optimization module then resizes the vehicle to minimize the gross weight (or minimize or maximize some other parameter) subject to the design constraints such as sustained load factor, fuel volume, and field length requirements. The program contains approximately 15,000 source cards and operates in 6 overlays, the largest requiring 60,000 decimal words of storage on a CDC computer. Typical optimization times are 5 min on a CDC 7600 machine.

In the following sections, the techniques used to automate the design process are discussed.

Calculation of Vehicle Gross Weight - Convergence

In the typical design situation, the aircraft mission and payload are specified. The first step in the design process is to define a vehicle which will fly the mission. Based on prior experience, the designer is usually able to quickly define a vehicle which will approximately meet the mission requirements. Having defined the basic configuration, an estimate is made of the gross weight of the aircraft. Based on this estimate, the fuel and component weights are calculated. The fuel weight, component weights, and payload are then added, and the result is compared to the initial gross weight estimate. Assuming they do not agree within a specified tolerance, the estimated gross weight is updated, and the process is repeated until the solution has converged within an acceptable tolerance. For lack of a better name, this process will be referred to hereafter as the convergence process. Once convergence is achieved, volume and performance constraints are calculated. If necessary, the vehicle is resized, and the process is repeated until an acceptable design is obtained. The process is often accelerated somewhat by resizing the wing and engine at each step in the convergence process to satisfy the desired constraints.

The efficiency and reliability of the convergence process can often be enhanced by automation. The procedures for automating this process and the pitfalls which can arise in both the automated and nonautomated mode can be illustrated by considering the conceptual design of the oblique, all-wing, remotely piloted vehicle (RPV) of the 1500-lb weight class shown in Fig. 2.[25] The basic mathematical problem to be solved is to find the gross weight WG such that the estimated weight W_{Ge} and the calculated weight W_{Gc} are the same to within a specified tolerance. Figure 3 shows several possible situations. In this figure, the point where the curve W_{Gc} versus W_{Ge} crosses the 45° line identifies the converged vehicle. Curve 1 in the figure is representative of a case where the aircraft cannot fly the mission at any gross weight. In this case the aircraft configuration or engine size will have to be changed before convergence can be achieved. Note that the slope of curve 1 is everywhere greater than unity so that as the estimated weight is increased, the calculated weight will grow without bound. Curve 2 represents the conventional design process where for each W_{Ge} the wing and engine are resized to maintain a specified wing and thrust loading. Now assume that it is desired to achieve convergence within a tolerance of 1%. That is

$$\left|\frac{W_{Gc} - W_{Ge}}{W_{Ge}}\right| \le tol = 0.01 \tag{1}$$

Now if an estimate is made of $W_{Gc} = 0.9W_G$, the calculated weight is $W_{Gc} = 0.906W_G$. Therefore, even though a tolerance of less than 1% is achieved, the results are inaccurate by 10% (assuming the discipline modules are providing precise information). This results from the fact that as the wing and engine are increased in size, the aerodynamic drag and fuel flow are increased, leading to the necessity for further increasing the size. Consequently, the slope of the W_{Gc} versus W_{Ge} line is very near unity. This example typifies the difficulties which can arise in estimating the aircraft gross weight.

Because design decisions during optimization will be made based on the finite difference changes in the vehicle design variables (e.g., aspect ratio, wing area), the converged solution must be numerically much more precise than this. Therefore, a value of TOL = 0.0001 is used in the ACSYNT program, and this is usually achieved with less than five cycles through the discipline modules. This is not to suggest that the optimum aircraft weight is accurate within 0.01% (the accuracy of the overall design results are dependent on the quality of the discipline information). This tolerance is used simply to insure the stability of the numerical optimization process.

The reliability of the convergence process can be improved by elimination of the sizing function from the discipline modules. This has the apparent disadvantage that the converged aircraft may not have the prescribed performance measures that are clearly a function of these sizing parameters. However, recognizing that the vehicle will be resized as the design process continues, it is not necessary for each converged aircraft to precisely satisfy all design constraints. It is only necessary that the final optimized vehicle meet these constraints. Note that this is true even if the design process is not automated.

Curves 3 and 4 of Fig. 3 demonstrate the effect of removing the sizing functions from the discipline modules during convergence. For curve 3 the wing sizing function was removed from the geometry module, the effect being that the slope of the W_{Gc} versus W_{Ge} curve is reduced because the wing is not continually being resized. Curve 4 demonstrates the additional improvement in rate of convergence when the engine is not resized for each new estimate of W_{Ge}. That is, during convergence, the thrust-to- weight ratio of the aircraft changes, but the maximum sea level static thrust is constant. This is the natural situation if existing engines are to be used on a new aircraft.

Curve 5 represents additional improvements which can be achieved with a simple modification to the mass properties module. This module consists only of a set of empirically derived weights equations, so that its execution time is minimal as compared to the most time-consuming module, trajectory. The component weights are based on the estimated gross weight as well as the configuration and flight envelope information. Since this module sums all weights to provide W_{Gc} it is a simple matter to cycle through the module several times, and after the first cycle base the component weights on the previously calculated weight estimated weight, W_{Gc} instead of the estimated weight, W_{Ge}.

The horizontal line on Fig. 3 represents the most desirable situation for vehicle convergence. In this case, the converged W_G could be calculated with one cycle through the program regardless of the initial W_{Ge} estimate. Because the fuel and component weight estimates are dependent on W_{Ge} this cannot be achieved. However, as seen from the figure, by removing the sizing function from the modules and adding a simple iteration to the mass properties module, the accuracy of convergence to W_G is considerably improved. Note that each curve in Fig. 1 is normalized with respect to the converged W_G for that curve. The numerical value of W_G will be different in each case because the curves represent vehicles of differing geometry and engine size.

Experience has shown that the W_{Gc} versus W_{Ge} function is quite linear in the region within 10% of W_G. Computationally, an upper and a lower bound on W_G are first obtained and then linear interpolation is used to calculate the final W_G value. The difference between the bounds gives a first-order indication of the accuracy of the solution. More precisely, the accuracy of the solution is dependent on the slope of the curve dW_{Gc}/dW_{Ge}. It can be shown that the numerical solution is accurate within a tolerance of $TOL/(l + dW_{Gc}/dW_{Ge})$. Typically for the conventional aircraft, dW_{Gc}/dW_{Ge} equals approximately 0.7 so that a tolerance of TOL = 1% represents a true tolerance of only 3.3%.

Having the ability to estimate precisely the aircraft gross weight, the next step is to utilize this information in an automated design optimization environment to obtain an optimum configuration subject to the various mission and performance constraints.

Optimization Concepts

Consider a simple design example of the oblique-wing RPV of Fig. 2 and assume it is required to find the combination of thickness-to-chord ratio and wing area which will minimize the vehicle gross weight. Consider only a single constraint that the volume of fuel and equipment not exceed one-half of the total volume of the wing. The optimization problem can be stated as

$$\text{Minimize } W_G \tag{2}$$

Subject to;

$$V_R - 0.5V_w < 0 \tag{3}$$

where V_R is the volume of the mission fuel and equipment and V_W is the volume of the wing. In this example, the gross weight W_G is defined as the objective function. The volume requirement of Eq. (3) is referred to as a design constraint. The optimization problem now becomes one of determining the values of the design variables S and t/c which will minimize W_G. Note that the objective and the constraint are both implicit functions of the design variables and are computed using the ACSYNT program convergence routine. Because this is a two-variable design problem, it can be solved graphically as shown in Fig. 4 which is a plot of gross weight and volume requirements versus S and t/c. In this figure the optimum design is clearly defined as the minimum weight vehicle inside the hutched constraint boundary. Also, if more constraints are imposed such as sustained turn-rate requirements or field length limitations, these could also be drawn on the figure and again the solution obtained graphically. However, as additional design variables are considered such as maximum sea level static thrust and aspect ratio, it becomes more and more difficult to obtain the design solution graphically. Therefore, numerical optimization procedures are used to solve the n-dimensional, nonlinear, constrained optimization problem. In general, this numerical optimization problem is stated mathematically as

$$\text{Minimize } F(X) \tag{4}$$

Subject to;

$$g_j(X) \leq 0 \qquad j = 1, m \tag{5}$$

$$X_i^l \leq X_i \leq X_i^u \qquad i = 1, n \tag{6}$$

where F(X) is the objective function, for example gross weight or fuel weight. The vector X contains the n design variables such as thickness-to-chord ratio, aspect ratio, wing area, thrust, and body fineness ratio. In the case of the two -variable, oblique-wing design problem, the X vector would simply contain S and t/c which would be changed during the design process in such a way as to minimize the objective function W_G while satisfying the constraints. The term $g_j(X)$ defines the constraints which the designer wishes to impose on the optimization process, and m is the total number of constraints. In the case of the oblique-wing design problem, G would contain only one entry: the numerical value V_R - $0.5V_W$ The terms X_i^l and X_i^u are lower and upper bounds, respectively, on the design variable. For example, if a thickness-to-chord ratio of less than 0.05 is not considered meaningful, this would be imposed by specifying that $t/c \geq 0.05$. The terms F(X) and $g_j(X)$ may be either implicit or explicit functions of the design variables X, but must be continuous. If the inequality condition of Eq. (5) is violated, $g_j(X) > 0$ for any constraint, that constraint is said to be violated. This situation may arise many times during the optimization process, and the information will be used to guide the design to one which satisfies all of the constraints. If equality condition is met, $g_j(X) = 0$, the constraint is called active, and if the strict inequality is met, $g_j(X) < 0$, the constraint is inactive. Because precise zero is seldom meaningful on a digital computer, a constraint is called active if its value is within a specified tolerance of zero.

The n-dimensional space spanned by the design variables X is referred to as the design space. Any design which satisfies the inequalities of Eq. (5) is referred to as a feasible design. If a design violates one or more of these inequalities, it is said to be infeasible but still has usefulness in eventually reaching a feasible design. The feasible design which is minimum is said to be optimal. Note that if we wish to maximize some function such as sustained turn rate or range, it can be done by simply minimizing the negative of the turn rate or range, respectively. Thus, any design problem can be cast in the above form.

The optimization program begins with an initial input X vector and mayor may not define a feasible design. In the case of vehicle synthesis, the initial X vector simply defines the designer's initial estimate of the aircraft configuration. The optimization process then proceeds iteratively by following the recursive relationship

$$X^{q+1} = X^q + \alpha^* S^q \tag{7}$$

where q is the iteration number, vector S is the direction of search in the n-dimensional design space, and α^* is a scalar which defines the distance of travel in direction S. The notation α^* for the move parameter is used here for consistency with mathematical programming nomenciature[30] and should not be confused with the angle of attack α. Also, S is used for consistency with mathematical programming nomenclature. The context in which the vector S is used will differentiate it from the optimum wing area S.

The optimization process proceeds in two steps. A direction S which will reduce the objective function without violating constraints is determined. Second, the scalar α * is determined so that either the objective function is minimized in this direction, a new constraint is encountered, or a currently active constraint is encountered again (because of the nonlinearity of the constraint).

Consider, for example, the oblique-wing RPV design problem. Assume an initial design at point A in Fig. 4 so that no constraints are active or violated. The program then begins by perturbing each of the X variables to determine its effect on the objective function W_G. That is, the gradient of W_G is calculated by finite difference using a single forward step, and the gradient vector is constructed as

$$\nabla F(X) = \nabla W_G = \begin{Bmatrix} \dfrac{\Delta W_G}{\Delta S} \\ \dfrac{\Delta W_G}{\Delta t / c} \end{Bmatrix} \tag{8}$$

Because no constraints are active or violated, it is obvious that the greatest improvement in the objective function is obtained by moving in the negative gradient or steepest descent direction so that $S = -\nabla W_G$. Having determined 5, the scalar α * in Eq. (7) must now be determined so that either the objective function is minimized in this direction or the constraint boundary is encountered. That is, a one-dimensional search is done in direction S to determine the appropriate value for α * so that an improved design is obtained at point B. No further improvement can be achieved in this direction without violating the constraint. It is now necessary to determine a new 5 vector which will improve the design but which will not lead into the infeasible region. The design variables are again perturbed to obtain the gradient of the objective function. At the same time, the gradient of the volume constraint V_R - 0.5V_W is obtained. Now a search direction must be found which will reduce the objective function without violating the constraint. Such a direction can be found by solving the following subproblem, which is a linear programming problem, with a single quadratic constraint.

Find S to maximize □

Subject to;

$$\nabla F(X) \bullet S + \beta \le 0 \tag{9}$$

$$\nabla g_j(X) \bullet S + \theta_j \beta \le 0 \qquad j = 1, NAC \tag{10}$$

$$S \bullet S \le 1 \tag{11}$$

where

$$\nabla F(X) \equiv \nabla W_G, \quad \nabla g_j(X) \equiv \nabla V_R - 0.5 \nabla V_W \quad \text{and} \quad g_j(X) = V_R - 0.5 V_W$$

The term NAC is the number of active constraints, one in this case. The details for solving this problem are given in Refs. 30 and 31. Note that if Eq. (10) is satisfied and 8 is positive, the resulting direction will reduce the objective function and is defined as a usable direction. Similarly, if Eq. (11) is satisfied and 8 is positive, S is called a feasible direction because for some small move in this direction no constraints will be violated. The prespecified parameter θ_j is referred to as a push-off factor and has the effect of pushing the design away from the active constraint. The value of θ_j must be zero or positive to maintain a feasible design. If θ_j were zero, the resulting direction would be precisely tangent to the active constraint. On the other hand, a very large θ_j would push the design away from the active constraint and nearly tangent to a line pf constant objective function. A value θ_j = 1 will yield a direction which approximately bisects the angle between the constant objective function and the constraint, as shown in Fig. 4. If the maximum value of β obtainable from Eqs. (7)-(12) is zero, then no direction exists which will both reduce the objective function and satisfy the constraint. The current design is optimal or is at least a local minimum.

In this example, a direction can be found, and a one-dimensional search leads to point C in Fig. 4 ending the second design iteration. The design variables are again perturbed to obtain the gradient of the objective and the active constraint. The subproblem of Eqs. (9)-(12) is again solved to obtain a new S vector, and the one-dimensional search now yields a solution at point D in Fig. 4 which is an optimum or at least near-optimum design. Once again, the design variables are perturbed to obtain the gradient of the objective and the constraint, and the subproblem of Eqs. (9)-(12) is again solved. This time the solution of the subproblem will be zero or near zero indicating that the optimal design has been achieved. Point D is clearly optimal since no direction exists at this point which will reduce the objective function any further without violating the constraint.

In the aircraft synthesis problem it is often difficult to insure that the initial design will satisfy all constraints. It is quite possible that the initial design will lie in the infeasible region, say point E in Fig. 4. Logic is included in the optimization program so that if this situation occurs, a direction vector 5 is obtained which will point toward the feasible region with minimal increase in the objective function.

Consider now the case where an initial design is described at point F in Fig. 4 and assume that it is desired to obtain the optimal solution simply by perturbing each variable in sequence to obtain the minimum gross weight which satisfies the constraint. Note that if either S or t/c is increased, the value of the objective function will increase. On the other hand, if S or t/c is decreased, the constraint on volume will be violated. Therefore, it is not possible to improve the objective function by minimizing with respect to one variable at a time. It is only by changing the variables in the proper combination that the optimal solution is obtained. This underscores the value of using optimization techniques to solve the design problem.

The methods used in this simple example are directly extendible to the n-dimensional problem where many design variables are considered.[30] Also, additional constraints can be imposed on the problem without increasing the complexity of the design process. The specific optimization technique used here is Zoutendijk's method of feasible directions[31]-[33] and has been coded as a general application numerical optimization program.[33]

Sensitivity Analysis

A major effort during the conceptual design process is the determination of the sensitivity of the aircraft weight, performance, and cost to changes in vehicle mission and technology parameters. With the convergence and optimization capability, this sensitivity function is easily automated as part of the control program operation. Two solutions of interest may be considered. As the parameter in question is varied, the vehicle may only be converged or it may be completely reoptimized to minimize the objective and satisfy all design constraints.

Consider as an example the sensitivity of the optimized oblique-wing RPV design of Figs. 2 and 4 to changes in the vehicle sizing parameter t/c. Figure 5 shows the vehicle gross weight as a function of tic for constant wing area. As t/c is reduced, gross weight changes only slightly. However, the volume requirement is not met so these designs would not be acceptable. On the other hand, as tic is increased, the volume requirement is met but at the expense of a rapid increase in We. As tic is increased, the gross weight increases rapidly, and beyond 17% the volume constraint is again violated, and the design becomes infeasible. This same information is available from Fig. 4 by considering various values of t/c for S/S = 1. Note that if t/c is reduced or if tic is increased more than 17%, the design becomes infeasible in Fig. 4. Between these values, the design is feasible but is not optimum with respect to the remaining design variable, (in this case wing area). Therefore, this information is of relatively little value in guiding design decisions.

A better approach is to reoptimize the design at several values of the parameter of interest; in this case, t/c is changed. The results of this approach are shown in Fig. 6. This figure shows how the wing area must be changed to maintain an optimum design. Now each design satisfies the volume constraint, and the gross weight increases for any change in t/c. The nominal value of t/c corresponds to the original optimized vehicle and therefore coincides with the minimum value of We. Note that We does not initially increase as rapidly as in Fig. 5 for increased tic because the aircraft is now reoptimized to maintain minimum gross weight.

In the general design situation where more than one constraint is active, the We sensitivity curve may not have a zero slope at the optimum, but will instead have a discontinuous slope. The gross weight will increase for even a small change in the sensitivity parameter and will increase at a different rate for positive and negative changes in this parameter.

Figure 6 also depicts the change in S with respect to t/c to maintain minimum gross weight subject to the constraint. This information is also available from Fig. 4, except now for each value of tic, S is changed to provide the design on the constraint boundary $V_R = 0.5V_W$.

Automatic sensitivity analysis, together with optimization, provides a very general conceptual design tool. In the following section examples are presented to show the generality and efficiency of these techniques as applied to the synthesis of an advanced tactical fighter.

Design Examples

A tactical fighter mission is shown schematically in Fig. 7. The mission and payload are representative of a long-range interdiction mission requiring significant supersonic cruise.[24]

The problem is to estimate the optimum gross weight of the vehicle to fly this mission and to define the sensitivity to various mission and technology parameters. It is predetermined that the vehicle will be of conventional wing-tail configuration and will use two afterburning turbofan engines. The fuselage size is specified based on estimated fuel and payload requirements so that, for the examples presented here, only five design variables are considered: area, sweep, thickness-to-chord ratio, and aspect ratio of the wing, and the engine thrust. Wing area is defined in terms of wing loading W/S, and thrust is defined in terms of thrust-to-weight ratio T/W for consistency with accepted nomenclature.

The design process proceeds in three steps. First, a vehicle is converged which will fly the specified mission. This aircraft is then optimized, and finally, the desired sensitivity information is obtained about this optimum.

In the following examples, an unrealistic vehicle is first defined which cannot be converged simply by changing the gross weight estimate. Optimization will be used to obtain an initial converged aircraft. Next, the aircraft will be optimized for minimum gross weight. Two methods are used: in the first, each proposed design is converged, and in the second, the vehicle is optimized without requiring that the intermediate results be converged aircraft. This second approach will be shown to be the most efficient. Finally, the sensitivity of gross weight to material technology and mission performance requirements is presented. All examples were run using the aircraft synthesis program (ACSYNT) on a CDC 7600 computer.

Case 1 - Convergence Using Optimization

Consider the initial aircraft definition shown in Fig. 8. For the specified geometry and thrust loading, this aircraft cannot fly the mission at any gross weight, so that the convergence characteristics are as depicted by curve 1 in Fig. 3. Now define an error function as

$$ERROR = \frac{W_{Gc} - W_{Ge}}{W_{Ge}} \tag{13}$$

If the absolute value of ERROR is less than the specified tolerance, Eq. (13) satisfies the convergence criterion of Eq. (1). If ERROR is negative, W_{Ge} is an upper bound on W_G, and convergence can be obtained. However, because the vehicle cannot be converged, ERROR may be a large positive number. Assuming a vehicle exists which will fly the prescribed mission, it can be obtained with optimization by minimizing ERROR. For this optimization problem, the estimated gross weight W_{Ge} is treated as a design variable in addition to the five sizing variables. The objective of the optimization is to minimize ERROR. At the end of optimization, if ERROR is greater than zero, the aircraft cannot be converged at any gross weight. If the optimum ERROR is less than zero, the aircraft can be converged using the sizing variables obtained from this optimization. In this case, a converged aircraft was possible, and the results are shown in Fig. 8. This optimization and the subsequent convergence process required 22 cycles through the discipline modules of ACSYNT and used 40 sec of CPU time.

Case 2 - Optimization to Obtain Minimum Gross Weight

Having obtained an initial converged vehicle, the next step is to optimize for minimum gross weight. This optimization was performed by converging the aircraft for each proposed design during the optimization process. The initial design violated the subsonic sustained load factor requirement shown in Fig. 7. The optimization process overcame this constraint violation and reduced the gross weight by 20%. The resulting design is shown in Fig. 8. This result is particularly interesting because it might have been expected that a Mach 2 cruise aircraft would have a much higher wing sweep than obtained here. The low-sweep, thin wing results from the performance requirements that approximately one-half of the mission be subsonic, and that the mission terminate with a 20-min loiter. This loiter requirement was found to be a major factor in the design because the loiter fuel weight strongly affected mission performance.

The design process required 7 design iterations (Eq. (7)), 56 converged vehicles, and 283 cycles through the discipline modules. Computer resources of 500 CPU sec were required for this optimization.

Case 3 - Gross Weight Minimization Without Convergence

In the previous example, each design proposed during the optimization process was converged, requiring an average of five cycles through the discipline modules per convergence. Computational efficiency can be improved by noting that it 'is not essential for the intermediate designs to satisfy the convergence requirements. It is only required that the final optimum design satisfy the convergence tolerance and fly the specified mission subject to the constraints. To achieve this, the gross weight was treated as a design variable to yield a total of six design variables. The calculated weight W_{Gc} was now the objective function to be minimized, and the error function, ERROR, in

Eq. (13) was constrained to be less than or equal to zero. This restatement of the optimization problem required no recoding of the ACSYNT program and necessitated only the modification of four input data cards. The optimum design was obtained with 102 cycles through the discipline modules. The optimum design was converged to a tolerance of 0.0005 as a natural consequence of the choice of design variables and constraints. Computer time of 180 CPU sec was required, representing nearly a factor of three improvement in computational efficiency to achieve the same result as in Case 2. This demonstrates that during optimization, not only may the constraints be violated, but the vehicle need not even be converged. It is only required that the final optimized vehicle satisfy the constraints and convergence tolerance. Therefore, this design procedure, using numerical optimization, represents a major departure from traditional conceptual design procedures.

Case 4 - Sensitivity to Technology and Mission Parameters

Figure 9 shows an example of the sensitivity analysis used to determine the effect of changing a single parameter on the vehicle gross weight and performance. The nominal vehicle, shown by the solid symbol, is the result of Cases 2 and 3. The nominal vehicle uses conventional technology. First, a sensitivity analysis was performed to study the effects of the subsonic sustained load factor requirement. In each case, the supersonic sustained load factor of four was maintained. The required subsonic load factor was changed, and for each value the vehicle was reoptimized to maintain a minimum gross weight. Note that the optimum vehicle gross weight is quite sensitive to sustained load factor, and for a subsonic load factor of five and by varying the five design parameters, no vehicle could be obtained which would fly the mission at any gross weight.

Next, a sensitivity analysis was performed with respect to materials technology whereby the component weights were multiplied by factors of 0.9 and 0.8, and for each case the vehicle was reoptimized subject to a subsonic sustained load factor requirement of 3. A 20% material weight reduction resulted in a 29% reduction in total vehicle weight.

Finally, the sensitivity to sustained load factor was again performed assuming this 20% material weight reduction. In this case, the sustained load factor was maximized for various upper bounds on gross weight. This was done only to show the generality of the method. The gross weight could just as well have been minimized for various constraints on load factor as before. Figure 9 graphically demonstrates the tradeoff between vehicle weight, performance, and advanced technology, and the results provide a quantitative measure of the benefits to be gained through technological improvements. Ten separate optimizations were performed in addition to the original optimization of the nominal vehicle. Computer resources of 2400 CPU sec and engineering time of 2 man-hr were required to obtain these results.

Accuracy Requirements

The question of reliability of the information provided by the discipline modules has not been addressed. However, it must be remembered that this aspect is fundamental to achieving a reliable design tool whether the process is automated or not. Moreover, it is especially essential that the discipline modules be valid in automated optimization because the process tends to capitalize on any weakness in the analytical model and produce unreasonable designs. In this respect, the combination of automated methods with existing design modules usually identifies a number of faults in the discipline modules that were thought to be fault free. For this reason, it is very important to make the discipline modules as accurate as possible.

In developing the ACSYNT program a concerted effort was made to correlate the results with existing aircraft. Figure 10 shows the correlation of gross weight (component weights, geometric, aerodynamic, and propulsion information were also correlated) for the F-5A aircraft. Optimization of an aircraft to fly the F-SA mission shows the ACSYNT program to be slightly conservative. If a 10% optimistic calculation of fuel weight is incorporated into the program, the converged aircraft is approximately 12% lighter than the actual F-SA. However, the optimization capitalizes on this error and resizes the vehicle to yield a net reduction in gross weight of 25%. For this reason, every effort should be made to ensure accuracy in the discipline modules or at least to ensure that the module information is slightly conservative.

In addition to correlations with existing aircraft, it is important that the sensitivity of the discipline information with respect to changes in vehicle design parameters is reasonable. For example, it is not sufficient that the wing weight estimating relationship correlates with existing aircraft. In designing a new vehicle, this relationship must also properly predict the effect on wing weight of changing the design variable such as aspect ratio, sweep, and thickness-to-chord ratio. In developing the ACSYNT program, numerous weight estimating relationships were obtained from government and industry. Each of these was correlated against existing aircraft, and the results were consistently accurate within 10%. However, because the program was to be used to define new vehicles, the effect of changing the design parameters on the weight estimates was also studied. Figure 11 is an example of this work where the effect of aspect ratio on predicted wing weight was determined using a conventional fighter aircraft as a nominal design. Note that the sensitivity of the wing weight (and therefore gross weight) estimate to changes in the single variable is quite different for the various equations supplied by government and industry. Indeed, the equation used in generating curve 1 predicts that as the aspect ratio is increased (all other design parameters held fixed), the wing weight decreases, a situation which clearly would not be supported by detailed structural design. Therefore, in developing an automated aircraft synthesis capability, it is essential that a major portion of the effort be devoted to ensuring the accuracy and reliability of the discipline information. Additionally, the design results must be constantly checked by qualified personnel to further ensure the validity of the results.

Summary

Application of numerical optimization techniques to automated aircraft synthesis has been presented. These methods are shown to be a general and efficient way to obtain quantitative information to evaluate proposed new vehicles. In a typical conceptual design study, far more information is obtained than was presented in the examples here. Typically, sensitivity of the design to 5-10 mission parameters and 3-5 technology parameters is studied for each of several basic vehicle concepts. Computer resources of 20 to 30 hr on a CDC 7600 computer are common.

The design process, whether automated or not, provides results which are only as accurate as the analysis on which the design is based. A carefully developed and applied automated design capability can enhance the design process by providing valuable information on which to base research and development decisions.

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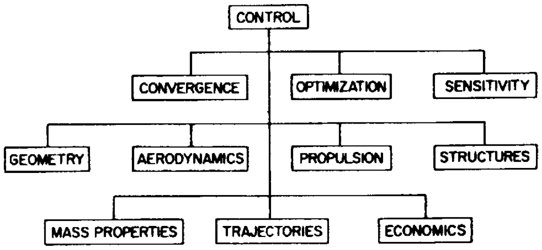

Fig. 1 The aircraft synthesis program, ACSYNT.

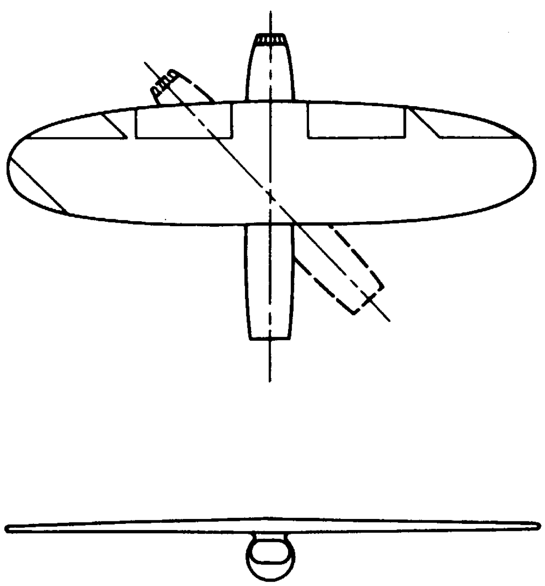

Fig. 2 Oblique-wing, remotely piloted vehicle.

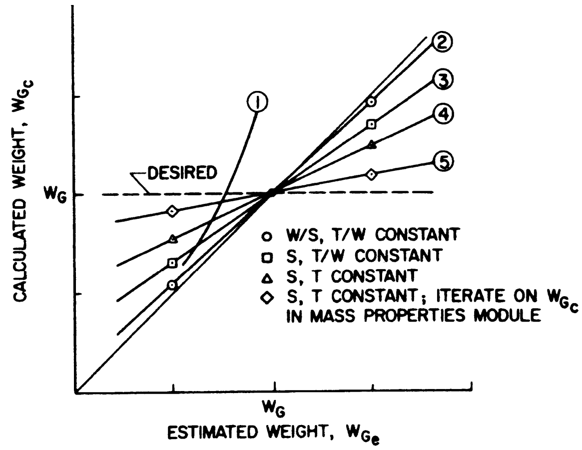

Fig. 3 Vehicle convergence.

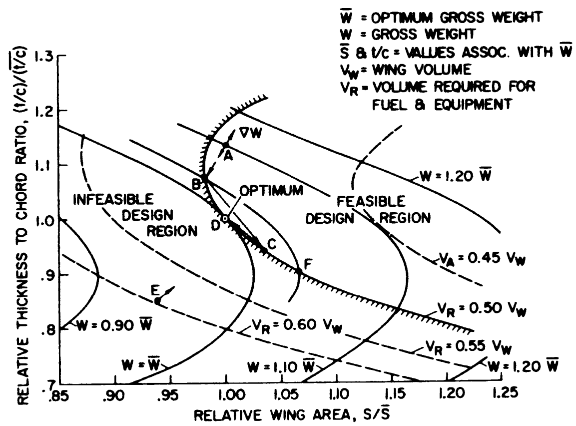

Fig. 4 Oblique-wing, RPV design space.

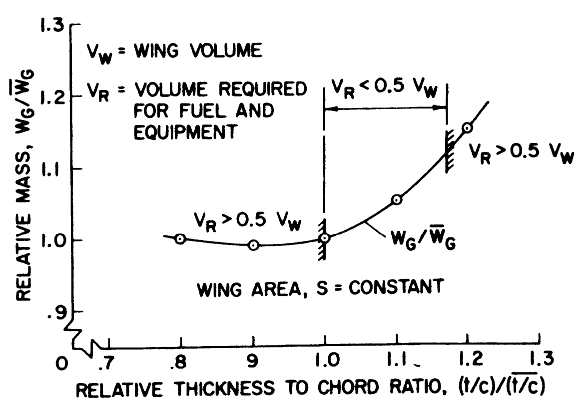

Fig. 5 Sensitivity of oblique-wing RPV to thickness-to-chord ratio.

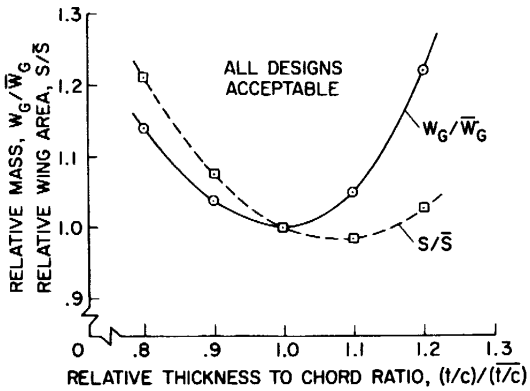

Fig. 6 Sensitivity of optimum oblique-wing RPV to thickness-to-chord ratio.

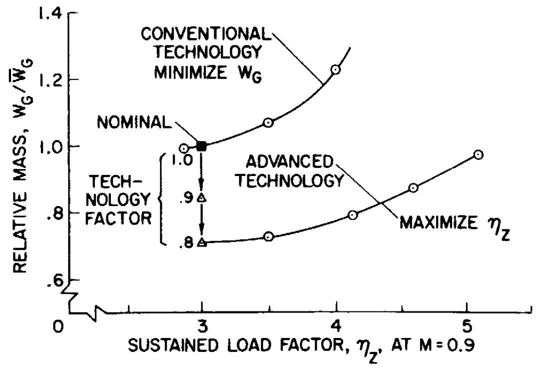

Fig. 9 Sensitivity of optimum tactical fighter to technology and performance parameters.

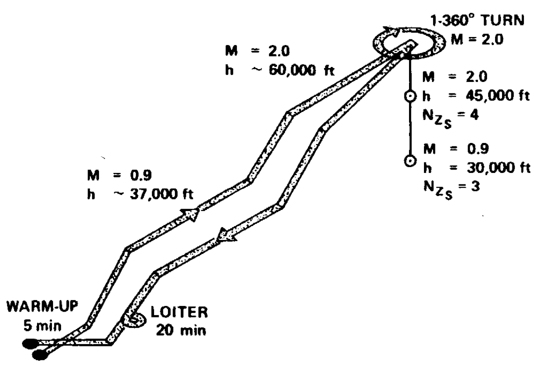

Fig. 7 Nominal mission trajectory.

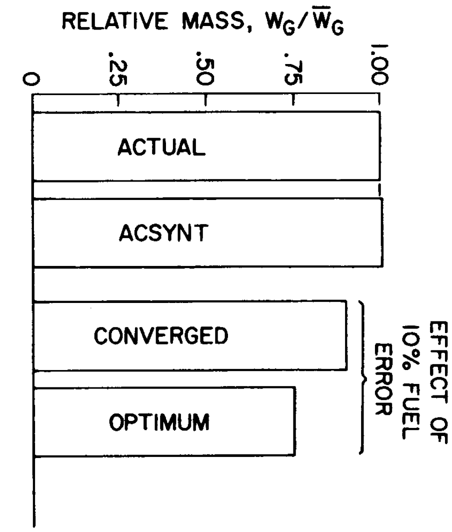

Fig. 10 ACSYNT correlation with F-5A aircraft.

PARAMETER	INITIAL	CONVERGED	OPTIMIZED
W	∞	28,500 kg (62,750 lb)	22,800 kg (50,300 lb)
W/S	∞	4,070 N/m² (85 psf)	4,120 N/m² (86 psf)
T/W	0.90	0.78	0.74
Æ	2.0	2.2	2.7
t/c	0.09	0.055	0.035
$\Lambda_{c/4}$	60°	47°	28°
η_z M = 0.9	—	2.88	3.00
η_z M = 2.0	—	4.08	4.00

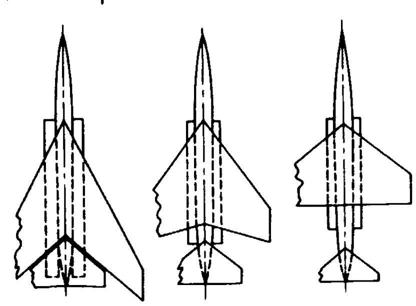

Fig. 8 Conceptual design of tactical fighter.

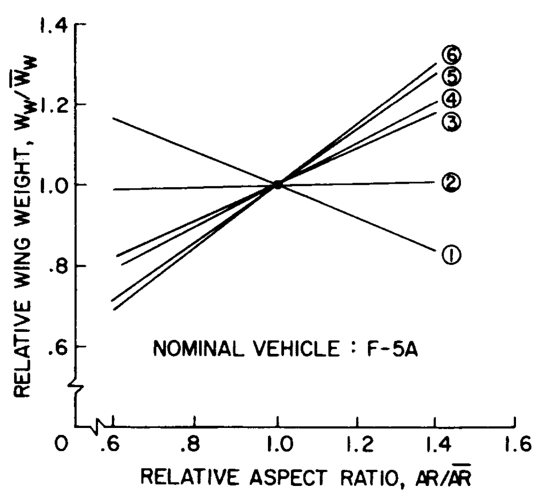

Fig. 11 Wing weight vs aspect ratio.