APPLICATION OF ADVANCED MULTIDISCIPLINARY ANALYSIS AND OPTIMIZATION METHODS TO VEHICLE DESIGN SYNTHESIS

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Abstract

Advanced multidisciplinary analysis and optimization methods, namely system sensitivity analysis and non-hierarchical system decomposition, are applied to reduce the cost and improve the visibility of an automated vehicle design synthesis process. This process is inherently complex due to the large number of functional disciplines and associated interdisciplinary couplings. Recent developments in system sensitivity analysis as applied to complex non-hierarchic multidisciplinary design optimization problems enable the decomposition of these complex interactions into sub-processes that can be evaluated in parallel. The application of these techniques results in significant cost, accuracy, and visibility benefits for the entire design synthesis process.

Introduction

As in any engineering design, the vehicle design process has a qualitative side that depends on human intuition, creativity, and judgement, and a quantitative side that must be supported by analysis being performed by computers. The entire vehicle design process is a very large undertaking, involving many engineers who tend to group according to their specialties. This grouping provides a natural basis for developing a broad framework to bring as much concurrent manpower as possible to bear on the project for compression of the calendar time. On the quantitative side of the process, that mode of operation calls for decomposition of the entire problem into smaller subproblems that can be identified with the specialty groups. Numerous decomposition schemes have been proposed in the field of Operations Research, as surveyed in Ref. [1], and in the field of engineering applications, e.g. Ref. [2]. In the latter reference, a distinction is drawn between a hierarchic decomposition in which there are several levels of subproblems, each depending on the input from a level above, and a non-hierarchic decomposition in which the subproblems are all interconnected at the same level.

In the hierarchic decomposition, each subproblem contains its own optimization. An example of an application to a large problem is detailed in Ref. [3]. In the non-hierarchic decomposition, the optimization is performed at the system level for the entire vehicle. However, the sensitivity analysis that generates the derivatives needed for that optimization is based on many sensitivity analyses, each executed concurrently within specialty groups. Since in large system application, the sensitivity analysis may account for more than 90% of the time needed for the overall optimization, the concurrency of the discipline sensitivity analysis has a potential for compression of the overall time schedule. An even more important benefit of this approach is that it channels the quantitative information exchange among the specialists into the format of the derivatives, providing visibility of the mutual influences among the engineering groups. Experience with this approach has been accumulating recently as evidenced in Refs. [4] and [5].

The purpose of this paper is to show that system sensitivity analysis and non-hierarchical system decomposition can be an effective tool for configuration optimization when applied to an automated vehicle design synthesis process. To this end, the paper defines the need for a multidisciplinary approach to vehicle design synthesis, describes such an approach that has been adopted at the Fort Worth Division of General Dynamics (GD/FW), examines the role of sensitivity information in the design process, outlines an algorithm for system sensitivity analysis, and describes how a particular vehicle configuration optimization problem may be formulated on the basis of the system sensitivity data. The report concludes with a discussion of the numerical results of an example application.

Need for a Multidisciplinary Approach

Recent developments in the quantitative aspects of design, namely advancements in both computer technology and the availability of sophisticated analysis and optimization methodologies, have resulted in quantum improvements in the computational environment that supports the design process. These developments have also served to improve the accuracy of the results obtained from this process by increasing both the number of participating functional disciplines and their contributing levels of detail. However, the increased number of functional disciplines involved in today's vehicle design trade studies has placed an even greater burden on the design process simply because of the increased number of interdisciplinary couplings that must be resolved.

A recent example of this complexity can be found in today's hypersonic vehicle design trade studies. In the case of hypersonic vehicle design and analysis, attempts to reduce the aerodynamic drag on the vehicle by elongating the forebody to a more slender shape also impacts the position of the nose shock relative to the inlet. Although this lengthening of the forebody is favorable in terms of reducing the aerodynamic drag on the vehicle, it may also reduce the vehicle's propulsive efficiency. The net result may be an increase in the mission-sized takeoff gross weight of the vehicle, which is the opposite result intended. Such aerodynamic-propulsion interaction is but one example of numerous complex functional discipline interactions commonly found in today's design trade studies. This is depicted by the arrows connecting the functional disciplines in Figure 1.

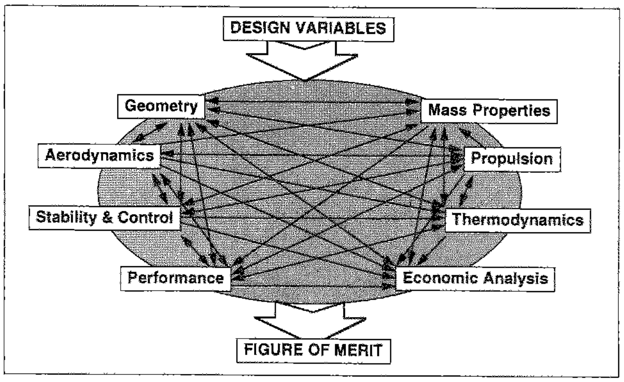

FIGURE 1 - FUNCTIONAL DISCIPLINE INTERACTIONS IN DESIGN TRADE STUDIES

Conventional approaches to resolving these interdisciplinary interactions usually involve performing parametric or one-factor-at-a-time analysis of the design variables of interest. Unfortunately, this approach may be prohibitively expensive and time consuming when applied to complex and computationally-intensive design trade studies as detailed in Ref. (6). Often the result is to reduce the number of design variables of interest and to simplify or omit many of these interactions.

A discussion on the need for a multidisciplinary approach to design synthesis would not be complete without referencing recent industry initiatives in Concurrent Engineering (CE) and Total Quality Management (TQM). These initiatives have served to reemphasize the need to develop aerospace systems in a true multidisciplinary environment. Too often in the past, aerospace systems were developed only after each functional discipline had optimized their own contribution independently. Little consideration was given to the integrated effect on total system performance. This is especially important in today's cost conscious environment in which vehicles may be optimized on the basis of cost, reliability, maintainability, and supportability in addition to the traditional design-to-performance criteria. The initiatives are intended to encourage industry to consider all elements of the product's life cycle from conceptual design through product disposal, including quality, cost, schedule, and use requirements. (7)

These developments and initiatives have resulted in a more realistic set of requirements for today's automated design synthesis program. It needs to be flexible so that any number of functional disciplines can be incorporated. It must be capable of varying the level of detail of each functional discipline's module and taking advantage of recent advancements in the areas of computational speed, parallel processing, and computer networking. It should also be supportive of the qualitative side of the design process by providing timely and accurate information (i.e. sensitivity analysis) to reinforce human design decisions.

Such a program has been under development at GD/FW for several years. The program, the Adaptable Design Synthesis Tool (ADST), is described in the next section. (8) This description will provide the foundation for discussions relating to the incorporation of sensitivity analysis and optimization methodology into the program.

Adaptable Design Synthesis Tool Description

The rapidly-expanding aircraft operational environment has served to emphasize the complex and difficult issues that must be dealt with in designing aerospace vehicles. Issues ranging from a vehicle's life cycle cost to its operational effectiveness in a hostile environment have contributed significantly to an increased demand, particularly at the conceptual design level, for an automated design synthesis tool capable of conducting design trade studies in a fast, consistent, and cost effective manner. In addition, today's design synthesis tools must be able to perform design trade studies for hypersonic and trans-atmospheric vehicles as well as for conventional vehicle concepts.

To meet these demands, an automated computational design synthesis program, ADST, is currently under development at GD/FW. The primary difference between ADST and other synthesis programs is one of development and application philosophy. Most aircraft design synthesis programs are intended to emulate, and eventually replace, the traditional aircraft preliminary design process. As such, they are invariably developed by coupling existing preliminary-design computer programs that predict aerodynamics, propulsion, mass properties, and mission performance into one complex and time-consuming sequential process.

ADST is intended to instead complement the traditional design process by evaluating conceptual designs rapidly with preliminary-design levels of detail and confidence. In addition, the adaptability and versatility of the ADST program will enable the evaluation of a wide range of vehicle concepts from conventional to hypersonic. This versatility enables user selection of the particular functional modules to be included in a particular study and permits control over the design level of detail. Some of ADST's rather unique features include the ability to optimize or survey any combination of 21 design variables and five technology factors; the user-selection of one of three sizing modes; the availability of three optimization strategies; and the ability to size a vehicle to virtually any type of mission profile.

Currently, the ADST program consists of functional modules for Geometry, Aerodynamics, Propulsion, Mass Properties, Economic Analysis, and Performance. Each module is developed and maintained by its respective functional discipline and is updated accordingly as new methodology becomes available. Modules for Thermodynamics and Stability & Control are presently in development and modules for RM&S, Structures, and Avionics are planned for development. Most of the functional modules in ADST (Aerodynamics, Propulsion, Mass Properties, and Economic Analysis) are based upon simplified analytical equations, which are related to more detailed methodology through the use of calibration factors. This calibration process is performed once for the baseline and enables the prediction of the functional discipline characteristics within 20-30% of the baseline design variables. Results for the baseline vehicle obtained with the simplified modules and the calibration factors are typically within 5% of the results obtained with more detailed methodology. This calibration process provides a favorable alternative to other approaches involving the use of either extremely simplified models or time consuming detailed methods.

ADST is a self-contained program that completely automates the design synthesis process and provides the capability to rapidly perform vehicle design trade studies. The organization of the functional discipline modules and overall description of the design synthesis process is illustrated in Figure 2. The design synthesis process begins with the definition of the baseline vehicle concept and the baseline mission profile. The baseline vehicle concept includes all of the information necessary to completely define the baseline vehicle, including the calibration factors for each discipline. The baseline mission profile provides the information needed by the performance module to compute the fuel required for the mission. Once the baseline information has been loaded into the synthesis program, each functional discipline module is called. This process begins with the Geometry module, which computes the geometric characteristics of the vehicle in addition to the fuel available for the mission. The Mass Properties module is then called to compute the scaled component weights for the vehicle. Next, the Aerodynamic and Propulsion modules are called to compute tabular data for use in the mission calculations. Finally, detailed mission performance data is computed which results in the fuel required. A cost statement for this current configuration can be computed and output at this point if desired.

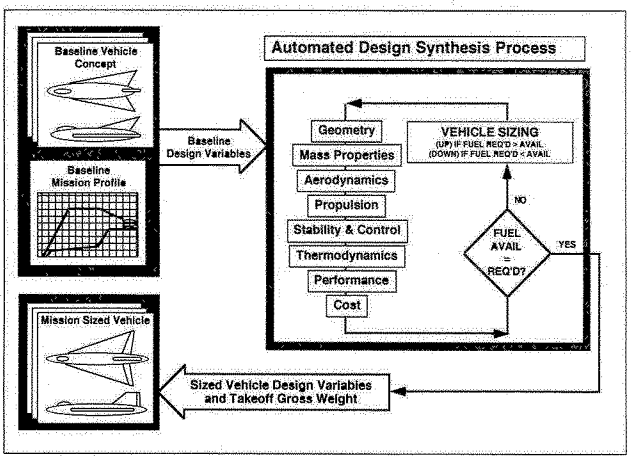

FIGURE 2 - ADST FUNCTIONAL MODULE ORGANIZATION AND PROCESS DESCRIPTION

Next, a comparison is made of the fuel available and the fuel required. If there is an excess amount of fuel available, the vehicle is sized down (according to one of three scaling algorithms, specified by the user). If there is a fuel deficit, the vehicle is sized up to accommodate the required amount of fuel. This iterative process, which typically converges in 3 to 4 iterations, results in a mission-sized takeoff gross weight for the input set of design variables. There is an additional loop not shown in Figure 2 that is available when performing design variable surveys or optimization. When performing a survey, a unique mission-sized vehicle results for each combination of the design variables. In the case of design variable optimization, the fuel balance needed to size the vehicle is formulated as a design constraint and added to any user-specified performance requirements. The optimization algorithm then predicts new values for the design variables which improve the objective function and promote constraint satisfaction.

The optimization process requires information from the design synthesis process in order to minimize the user-specified objective function, which is mission-sized takeoff gross weight or total life cycle cost. Typically, this information is provided in the form of total derivatives for the objective function with respect to each of the specified design variables. The next section of this paper describes how system sensitivity analysis can be used to provide the necessary information to the optimizer.

System Sensitivity Analysis - An Outline

The numerical side of design process depends on the analysis of a mathematical model of the design artifact, in this case an aircraft or vehicle. Analysis of the mathematical model accepts an input that describes the environment the vehicle operates within and the stimuli it responds to. This yields an output vector of the data on the ensuing behavior (response) of the vehicle. These data are valid for a particular set of values of the design variables. It is essential for the designer to know how that behavior will change if any of the design variables are altered. Under the prevailing practice, answering such "what if" questions requires the perturbation of one variable at a time and the repetition of the analysis in order to generate information for a finite differencing or for a parametric study. *In other words, one needs to test the effect of a particular change under consideration in order to determine whether that change is going to have the desired effect.*

This "trial-and-error" approach is a consequence of working with zero order information, i.e. the function values for the given arguments. If we also had the first order information and the values of the derivatives of those values with respect to design variables, the effect of any contemplated change of the variables could be evaluated before committing to further implementation and re-analysis. The purpose of the system sensitivity analysis is to produce such first order information more efficiently and accurately than can be obtained by finite differencing. Mathematical means of producing first order information are tantamount to giving the designers a mathematical model of the design for quick answers to "what if" questions as is often the case in conceptual design.

For large and complex systems, the perturb-and-reanalyze approach to generating data for finite differences that approximate the derivatives may be impractical as well as too costly and inaccurate. However, an algorithm for the system sensitivity analysis was introduced in Ref. (9) as an alternative to finite differencing in the generation of first order derivatives. This algorithm was extended to include higher order derivatives in Ref. (10). An example of the algorithm's application, including the use of the first and second order derivatives in optimization, is given in Ref. (11). Although the references provide a comprehensive description of the algorithm, its outline is given herein to make this paper self-contained.

System Sensitivity Approach

The system sensitivity algorithm, developed in Ref. (9), treats the system as an assemblage of black boxes, with each black box containing a mathematical model to represent a particular aspect of the system behavior or a physical subsystem. For introductory purposes it is convenient to limit the number of black boxes to three and to develop a pattern that readily extrapolates to "N" black boxes. (A more detailed approach, relevant to the aforementioned ADST program, will be formulated in a later section of this paper.) The general approach begins with a typical system model involving three functional disciplines denoted by the black boxes shown in Figure 3.

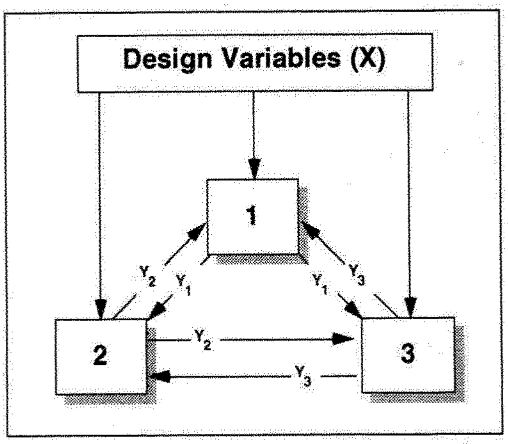

FIGURE 3 - EXAMPLE SYSTEM MODEL

It is not important to describe the contents of each black box as long as the inputs and outputs for each block can be recognized. Each of the black boxes are coupled, since output from one black box may be transmitted as input to another. An i-th black box is viewed as a converter that transforms the design variables, denoted by input vector $\{X\}$, and the outputs from the other boxes, denoted by input vectors $\{Y_j\}$, to an output vector $\{Y_i\}$, assuming that $j \neq i$. Of course, it is recognized that not every element of X and Y_j is actually used. The usage is selective since not all output variables from each black box are inputs into the other black boxes. One can now formulate the system governing equations by collecting the functions $Y_i = f(X,Y_j)$ into a set of equations. For i=1, 2, and 3, we have:

$$Y_1 = f(X, Y_j),\ j = 2, 3; \quad (1)$$

$$Y_2 = f(X, Y_j),\ j = 1, 3; \quad (2)$$

$$Y_3 = f(X, Y_j),\ j = 1, 2; \quad (3)$$

These equations are coupled by Y_j and constitute a mathematical model of the entire system. According to the implicit function theorem detailed in Ref. (12), a differentiation of Eqs. (1), (2), and (3) performed while observing the rules of chain differentiation and recognizing Y as an implicit function of X yields the following set of equations:

$$\frac{dY_1}{dX} = \frac{\partial Y_1}{\partial X} + \frac{\partial Y_1}{\partial Y_2}\frac{dY_2}{dX} + \frac{\partial Y_1}{\partial Y_3}\frac{dY_3}{dX} \quad (4)$$

$$\frac{dY_2}{dX} = \frac{\partial Y_2}{\partial X} + \frac{\partial Y_2}{\partial Y_1}\frac{dY_1}{dX} + \frac{\partial Y_2}{\partial Y_3}\frac{dY_3}{dX} \quad (5)$$

$$\frac{dY_3}{dX} = \frac{\partial Y_3}{\partial X} + \frac{\partial Y_3}{\partial Y_1}\frac{dY_1}{dX} + \frac{\partial Y_3}{\partial Y_2}\frac{dY_2}{dX} \quad (6)$$

Eqs. (4), (5), and (6) can be rearranged such that the total derivatives are placed on the left-hand side of the equation:

$$\frac{dY_1}{dX} - \frac{\partial Y_1}{\partial Y_2}\frac{dY_2}{dX} - \frac{\partial Y_1}{\partial Y_3}\frac{dY_3}{dX} = \frac{\partial Y_1}{\partial X} \quad (7)$$

$$\frac{dY_2}{dX} - \frac{\partial Y_2}{\partial Y_1}\frac{dY_1}{dX} - \frac{\partial Y_2}{\partial Y_3}\frac{dY_3}{dX} = \frac{\partial Y_2}{\partial X} \quad (8)$$

$$\frac{dY_3}{dX} - \frac{\partial Y_3}{\partial Y_1}\frac{dY_1}{dX} - \frac{\partial Y_3}{\partial Y_2}\frac{dY_2}{dX} = \frac{\partial Y_3}{\partial X} \quad (9)$$

These equations, termed the Global Sensitivity Equations (GSE) in Ref. (9), are simultaneous, linear, and algebraic regardless of the nature of the functions $Y_i = f(X, Y_j)$, provided that the first-order derivatives for these functions are obtainable. For system sensitivity purposes, we wish to obtain the total derivatives, $\frac{dY_i}{dX_k}$, which quantify the rate of change of Y_i due to a change in the k-th independent variable, X_k, and that represent a combination of the direct and indirect influences of X_k with all the interactions accounted for. The total derivatives can also be used to provide gradient information to an optimizer for the purpose of optimizing the design variables of interest.

The system partial derivatives, $\frac{\partial Y_i}{\partial Y_j}$, may be collected for the i-th black box into a Jacobian matrix $[J_{ij}]$ of the dimension $N_i \times N_j$. The partial derivatives for the design variables, denoted by $\frac{\partial Y_i}{\partial X_k}$, may be placed into a vector $\{RHS\}_i$ of the length N_i. For the partials where i=j, we have $J_{ii} = I$ -- an identity matrix. Using this notation, the Eqs. given in (7), (8), and (9) can be organized into the following form:

$$[SSM]\{\frac{dY}{dX_k}\} = \{RHS\}_k \quad (10)$$

Where [SSM], the System Sensitivity Matrix, has the following composition:

$$[SSM] = \begin{bmatrix} I & -J_{12} & -J_{13} \\ -J_{21} & I & -J_{23} \\ -J_{31} & -J_{32} & I \end{bmatrix} \quad (11)$$

And, {RHS} is expressed as:

$$\{RHS\}_K = \begin{bmatrix} \{RHS\}_1 \\ \{RHS\}_2 \\ \{RHS\}_3 \end{bmatrix}_K \quad (12)$$

The above pattern developed for i=1,2,3 clearly extends to a general case of i=1, 2,...N. There are as many $\{RHS\}_k$ as elements in {X}. However, [SSM] is generated only once for a given {X}; therefore, the system of Eq. (10) may be efficiently obtained by solving the GSE simultaneously for the total derivatives.

The [SSM] matrix and the {RHS} vector from Eqs. (11) and (12) can be explicitly stated in terms of the partial and total derivatives for the black boxes of interest:

$$\begin{bmatrix} I & -\frac{\partial Y_1}{\partial Y_2} & -\frac{\partial Y_1}{\partial Y_3} \\ -\frac{\partial Y_2}{\partial Y_1} & I & -\frac{\partial Y_2}{\partial Y_3} \\ -\frac{\partial Y_3}{\partial Y_1} & -\frac{\partial Y_3}{\partial Y_2} & I \end{bmatrix} \times \begin{Bmatrix} \frac{dY_1}{dX} \\ \frac{dY_2}{dX} \\ \frac{dY_3}{dX} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial Y_1}{\partial X} \\ \frac{\partial Y_2}{\partial X} \\ \frac{\partial Y_3}{\partial X} \end{Bmatrix} \quad (13)$$

If the input-to-output conversion for each black box produces $Y_i = f(X, Y_j)$ as a continuous function of the arguments X and Y_j, the partial derivatives $\frac{\partial Y_i}{\partial X}$ and $\frac{\partial Y_i}{\partial Y_j}$ exist. They represent the direct influence of these arguments on the output as opposed to an indirect influence. For example, the sweep angle affects the pressure distribution on the wing directly through aerodynamic predictions and indirectly through its influence on the structural analysis output of displacements. The partial derivatives may be computed by finite differencing or by a quasi-analytical technique. The former is the simplest to implement without accessing the inner workings of a black box; the latter is inherently more efficient and more accurate but requires modifications to the black box analysis. Quasi-analytical methods for sensitivity analysis have been well-established in some disciplines, notably in structures (a survey was given in Ref. (13)). Initiation of similar developments in CFD is discussed in Ref. (14) and in its corresponding references.

Regardless of the method used, a black box sensitivity analysis is a local operation applied to a black box isolated from all others. Therefore, all such analyses may be executed concurrently -- an attractive feature considering the availability of distributed computing. Other important features not to be overlooked are the visibility into the functional discipline interactions that are provided by the partial derivatives and the design sensitivity information provided by the total derivatives. This information, which is not traditionally available using a one-factor-a-time approach to vehicle design synthesis, can be useful in determining what impact a proposed design change will have on the output from each black box as well as for the overall system objective.

The system sensitivity approach appears to be ideally suited for implementation into an automated vehicle design synthesis program, such as ADST, since the functional modules required to compute the partial derivatives are readily available. The benefits of this approach are a reduction in the time and cost associated with performing design trade studies and the improved visibility provided by the derivatives. This is particularly true when utilizing a design synthesis program in an optimization mode, since the total derivatives obtained by solving the GSE can also be used to drive the optimization.

Summary of Steps Required to Formulate and Solve the GSE

Figure 4 contains a flowchart (Chapin-format) that summarizes the sequence of steps that should be taken in formulating and solving the GSE. (4)

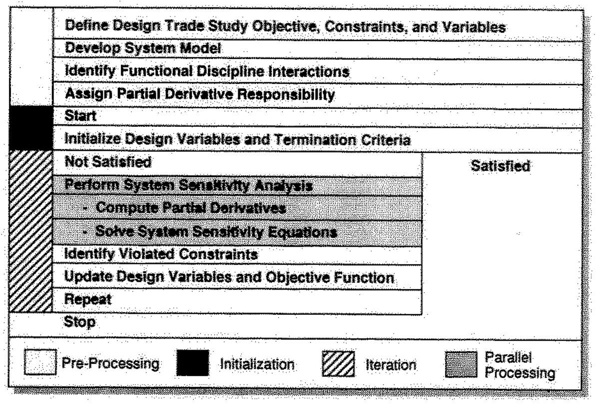

FIGURE 4 - CHAPIN-FORMAT OF OPTIMIZATION PROCEDURE USING GSE

Step 1: Define the trade study objective(s), associated constraints, and the controllable design variables that will be used to define the optimum.

Step 2: Develop a system model that identifies all of the functional discipline participants in the trade study using the black box notation.

Step 3: Identify all the functional discipline interactions in the system model. These interactions are simply information that is being passed from one discipline's black box to another.

Step 4: Assign partial derivative responsibility to each functional discipline. Although this may appear obvious, it is important that each functional discipline become actively involved in this process to ensure the accuracy of the partial derivatives and results. Once the interactions have been identified, the GSE can be formulated.

Step 5: Initialize the optimization process. This includes initializing the baseline design variables and associated termination criteria.

Step 6: Compute the partial derivatives and solve the GSE. This step is probably the most time consuming depending on the availability of distributed computing resources. The partial derivatives may be computed using finite differencing techniques or quasi-analytical methods. Once the partial derivatives have been computed, they can be arranged in the form of the GSE and solved simultaneously for the total derivatives.

Step 7: Compute the objective function and constraint values, which can then be passed to the optimization algorithm in conjunction with the total derivatives. The optimization algorithm will identify violated constraints and update values of design variable that improve the objective function.

Step 8: Repeat the process until an optimum for the objective function is obtained within the specified convergence criteria. Once this criteria is satisfied, the optimization process will stop and report the optimum design variables and associated objective function and constraint values.

As indicated in Figure 4, the steps required to formulate and solve the GSE can be separated into four categories. These categories are defined by the legend in the figure and include: pre-processing, initialization, iteration, and parallel processing. The first four steps are included in the pre-processing category since they involve the basic formulation of the problem. Step 5 is included as part of the initialization process. Steps 6 through 8 involve computation of the partial derivatives, the solution of the GSE, and the overall optimization of the problem, which is inherently an iterative process. The final category, parallel processing, is unique to step 6 and involves the concurrent computation of the partial derivatives, which reduces the overall computational time for this process considerably.

Thus far, this paper has defined the need for an multidisciplinary approach to vehicle design synthesis, described such a system (ADST) that has been developed by GD/FW, introduced the system sensitivity approach, and summarized the steps required to formulate and solve the GSE. The next section of the paper describes in detail, the application and implementation of the system sensitivity approach to the ADST program.

Application of GSE to ADST

Using the procedure outlined in Figure 4, a system model for ADST was developed. This system model, displayed in Figure 5, identifies the relevant functional disciplines and associated interactions included in this application.

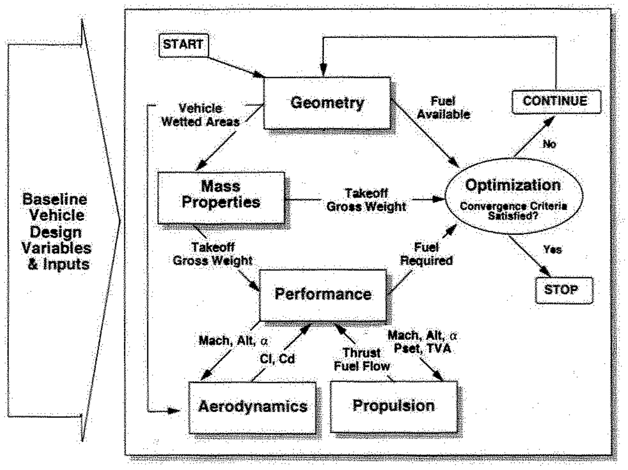

FIGURE 5 - ADST SYSTEM MODEL

The primary functional disciplines of interest for this study are Geometry, Mass Properties, Performance, Aerodynamics, and Propulsion. Each of the disciplines are represented in Figure 5 by black boxes. Experience and familiarity with the ADST program have shown that calculations for the Performance module are the most computationally intensive. The Aerodynamic module and Propulsion module calculations are less intensive primarily because of the calibration process employed in the program and because they are at a level of analysis characteristic of the conceptual design stage. The Geometry module and Mass Properties module calculations are the least intensive. The optimization module checks whether the convergence criteria, which includes the fuel balance and performance constraints, have been satisfied. If not, the module predicts new values for the design variables that improve the objective function and continues sequentially through the system again.

Table 1 contains a brief description of the inputs (including the design variables), outputs, and constants for each functional module in ADST.

TABLE 1 - FUNCTIONAL MODULE DESCRIPTION

Module	Inputs	Outputs	Design Variables	Constants
1 - Geometry	None	Fuel Available, Vehicle Wetted Areas	All	Baseline Geometry Information
2 - Mass Properties	Fuel Available, Vehicle Wetted Areas	Takeoff Gross Weight, Empty Weight	All	Mass Properties Calibration Factors
3 - Performance	Takeoff Gross Weight, Empty Weight	Fuel Required, Performance Constraints	All	Baseline Mission Rules
4 - Aerodynamics	Mach Number, Altitude, Angle of Attack	Lift Coefficient, Drag Coefficient	All Aerodynamic Related	Aerodynamic Calibration Factors
5 - Propulsion	Mach Number, Altitude, Angle of Attack, Power Setting, Thrust Vector Angle	Net Thrust, Fuel Flow	All Propulsion Related	Propulsion Calibration Factors

Using the numbering scheme provided in Table 1 and the system model displayed in Figure 5, the corresponding GSE for this system in Jacobian matrix form is:

$$\begin{bmatrix} I & 0 & 0 & 0 & 0 \\ -J_{21} & I & 0 & 0 & 0 \\ 0 & -J_{32} & I & -J_{34} & J_{35} \\ -J_{41} & 0 & -J_{43} & I & 0 \\ 0 & 0 & -J_{53} & 0 & I \end{bmatrix} \begin{Bmatrix} \frac{dY_1}{dX} \\ \frac{dY_2}{dX} \\ \frac{dY_3}{dX} \\ \frac{dY_4}{dX} \\ \frac{dY_5}{dX} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial Y_1}{\partial X} \\ \frac{\partial Y_2}{\partial X} \\ \frac{\partial Y_3}{\partial X} \\ \frac{\partial Y_4}{\partial X} \\ \frac{\partial Y_5}{\partial X} \end{Bmatrix} \tag{14}$$

The actual implementation of the GSE into ADST differed slightly from that of Figure 5 due primarily to the following considerations of computational efficiency. As explained in Ref. (9), the computational cost of the system sensitivity analysis critically depends on the number of elements in the vectors Y_j (called the interaction band width) transmitted from one black box to another. This is especially true when the partial derivatives are computed by finite differencing, as is the case in the problem at hand, because the number of executions of the analysis in the i-th black box depends on the number of partial derivatives that need to be calculated for that black box.

In the system depicted in Figure 5 and defined in Table 1, the interaction band width is particularly wide between the Performance, Aerodynamics, and Propulsion black boxes owing to the large Mach number and altitude coordinates that define a given mission profile. On the other hand, the band width between Performance, Geometry, and Mass Properties black boxes is very narrow. Taking advantage of that narrow band width, the number of executions of the Performance, Aerodynamics, and Propulsion modules were drastically reduced by merging Aerodynamics and Propulsion black boxes into the Performance black box as shown in Figure 6.

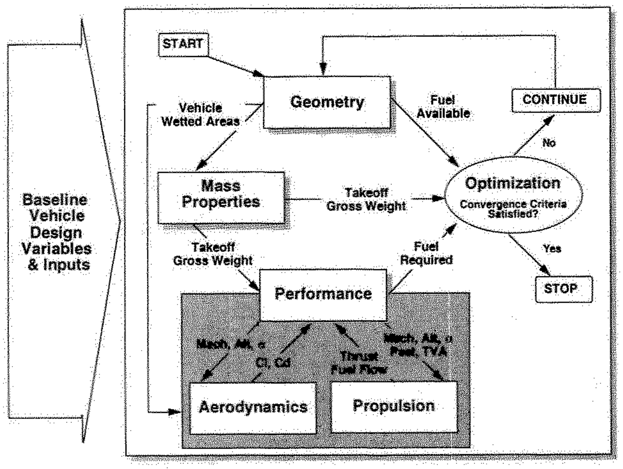

FIGURE 6 - REVISED ADST SYSTEM MODEL

Using the notation established in Table 1 and considering that the Performance black box actually represents the combined effect of Performance, Aerodynamics, and Propulsion, the resulting GSE for this system is:

$$\begin{bmatrix} I & 0 & 0 \\ -\frac{\partial Mass}{\partial Geom} & I & 0 \\ -\frac{\partial Perf}{\partial Geom} & -\frac{\partial Perf}{\partial Mass} & I \end{bmatrix} \begin{Bmatrix} \frac{dGeom}{dX} \\ \frac{dMass}{dX} \\ \frac{dPerf}{dX} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial Geom}{\partial X} \\ \frac{\partial Mass}{\partial X} \\ \frac{\partial Perf}{\partial X} \end{Bmatrix} \tag{15}$$

Note that the system is still non-hierarchical due to the lateral linking between the Mass Properties and Performance black boxes. The number of partial derivative calculations has been reduced from approximately several thousand to less than one hundred. The system model and associated functional module interactions, as displayed in Figure 5, were incorporated into the ADST program. The next section describes the results obtained for an example application using this system model and associated GSE.

Example Application

The synthesis of a hypersonic interceptor vehicle was accomplished using the system sensitivity information provided by the GSE formulated specifically for ADST. The example configuration is a Mach 5.5 vehicle capable of intercepting adversary aircraft at high speeds in minimum time. The baseline mission profile for this application is displayed in Figure 7.

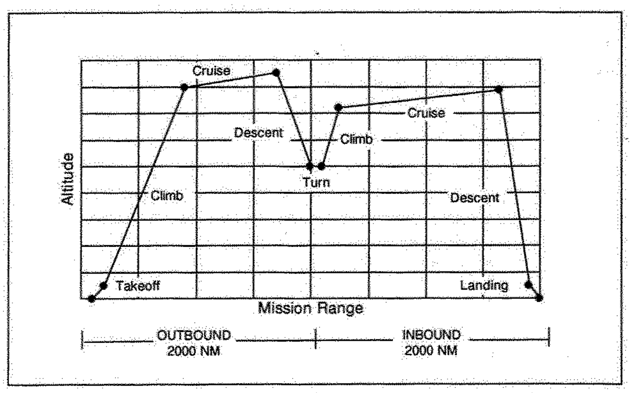

FIGURE 7 - BASELINE MISSION PROFILE

The explicit mission rules which define the policy, propulsion power-setting, and termination criteria for each mission segment are presented in Table 2. The mission rules are required inputs for the Performance module in ADST and are presented here to illustrate the complexity of this application's mission profile and to demonstrate the versatility of this module.

TABLE 2 - BASELINE MISSION RULES

Segment	Policy	Power Setting	Termination
Takeoff	Fixed Power	Max Power Turbojet	Alt=100, Mach=0.5
Climb	Min Time	Max Power: Turbojet to .8M Turboramjet to 3.25M Ramjet to 5.5M	Cruise Altitude
Cruise	Optimum Altitude, Constant Mach=5.5	Ramjet Power As Required	Search for Cruise Distance
Descent	L/D Max	Idle Power Ramjet	Alt=50000, Mach 3.25
Turn	Sustained Structural Load Factor = 2.5	Ramjet Power as Required	180 Degree Turn
Climb	Constant Mach=3.25	Max Power Ramjet	Cruise Altitude
Cruise	Optimum Altitude, Constant Mach=3.25	Ramjet Power As Required	Search for Cruise Distance
Descent	L/D Max	Idle Power Turboramjet	Mach=0.8
Landing	Fixed Power	Idle Power Turbojet	Alt=0.0, Mach=0.0

The mission rules do not fully define the mission profile since the resulting segment time, fuel-used, and range are a direct function of the vehicle's design variables and will change with each iteration of the optimizer. For instance, the minimum time trajectory for the climb segment is a function of the wing area and engine size of the vehicle. A change in either of these design variables directly influences the computed trajectory, affecting the final vehicle weight for the segment which in turn affects the optimum cruise altitude. However, the baseline mission profile stipulates that the outbound and inbound range for this mission profile must be 2000 nautical miles. This distance defines the adversary interception point for this application and also indirectly defines the termination range for each cruise segment.

The design variables were limited to wing area, turbojet size, and ramjet size. The engine-scale factors were of significant interest since the powerplant is a methylcyclohexane (MCH) fueled turbo-ramjet and the engine cycles operate independently or in unison depending on the particular Mach regime. When the turbojet operates independently, the ramjet airflow is ducted. Similarly, when the ramjet operates independently, the turbojet inlet is closed. Due to structural and thermodynamic considerations, it was assumed that the fuel required to perform the specified mission was stored in the fuselage. These considerations made it necessary to include another design variable, fuselage length, in the formulation of this problem. Variation of the fuselage length served to define the amount of fuel available to perform the specified mission.

Optimization Procedure

The objective of the example design synthesis trade study was to reduce the mission-sized takeoff gross weight by manipulating the design variables (wing area, turbojet size, ramjet size, and fuselage length), subject to the following constraints:

1. $|Fuel_{REQUIRED} - Fuel_{AVAILABLE}| \leq 0.1$ (16)
2. Time-to-Station ≤ 55 min (17)
3. Takeoff Velocity ≤ 195 knots (18)

It should be emphasized that by including the fuel available vs. fuel required as a constraint, the optimization procedure in Figure 3 is employed in a dual role. It synthesizes a flyable vehicle and simultaneously configures that vehicle toward an optimum. This eliminated the need to achieve a fuel balance prior to performing the optimization and reduced the computational time required locate the optimum design variables significantly. In conventional practice, these two functions would be performed separately and consecutively.

The usual practice of applying optimization methods to large scale problems involves coupling the optimizer with approximate analysis, e.g. a linear extrapolation based on the sensitivity derivatives instead of the full analysis (Ref. [15]). This approach has been widely accepted in industry primarily because of the computational time savings that result when compared to coupling the optimizer directly with the full analysis. In formulating a general scheme for the incorporation of optimization methods into the ADST program, it was determined that use of approximate analysis was not necessary. This determination was based on the relatively small number of design variables common in conceptual design trade studies and the fact that the time required for a function evaluation is not computationally prohibitive. For these reasons, the optimizer was coupled directly with the full analysis procedure as indicated in Figure 6.

This optimization problem was solved using the ADST program and the associated system model. Two optimization programs were incorporated into ADST and applied to determine their effectiveness in solving these types of problems. The first optimization program used was ADS, described in detail in Ref. [16]. ADS is a general purpose numerical optimization program which contains a variety of different algorithms. The algorithm selected for this particular problem was sequential linear programming (SLP) using the modified method of feasible directions optimization strategy. The second optimization program applied to the problem was NPSOL, described in Ref. [17]. NPSOL was developed specifically for the nonlinear problem and employs a sequential quadratic programming (SQP) algorithm for which the search direction is the solution of a quadratic programming subproblem. Both ADS and NPSOL are well suited for solving problems formulated using the GSE approach since each program can readily accept user-supplied gradient information.

Application Results

Using the GSE developed for and installed into the ADST program in conjunction with each optimizer, the optimum design variables were obtained. This was accomplished by solving the GSE simultaneously for the total derivatives of the objective function and constraints with respect to each of the design variables for each optimization iteration. Table 3 displays the optimum values for the design variables (normalized with respect to baseline values), constraints, and objective function for this example application. In this table, results obtained parametrically using traditional methods are contrasted with results obtained from using the GSE approach with the ADS and NPSOL optimizers.

TABLE 3 - APPLICATION RESULTS

	Baseline Values	Traditional Method Results	GSE Method Results (ADS)	GSE Method Results (NPSOL)
Optimize Parameter				
Wing Area	1.0000	0.7905	0.7898	0.7849
Turbojet Size	1.0000	1.2342	1.2346	1.2346
Ramjet Size	1.0000	0.8001	0.8014	0.8025
Fuselage Length	1.0000	0.9587	0.9585	0.9582
Objective Function				
Takeoff Gross Weight	1.0000	0.8786	0.8734	0.8723
Constraint Functions				
|Fuel Balance| < 0.1	20045	0.0325	0.0058	0.0476
Intercept Time < 55 Min	62.34	52.69	52.35	52.19
Takeoff Vel < 195 Knots	216.74	191.32	191.06	190.98

The results obtained using either optimizer are in complete agreement with the traditional approach. In performing the optimization, the overall mission-sized takeoff gross weight of the vehicle was reduced approximately 13%, which included the satisfaction of the fuel balance and performance constraints. This was accomplished by reducing the wing area by 21%, reducing the ramjet size by 20%, increasing the turbojet size by 23%, and reducing the fuselage length by approximately 4%. Initially, the fuel balance and performance constraints, represented by Eq. (16), (17), and (18), were violated. However, for the optimized vehicle, all the specified constraints were satisfied.

It appears as though ADS and NPSOL worked equally as well on this particular problem since ADS converged in seven iterations and NPSOL converged in eight iterations. Figure 8 displays sizing history plots for the objective function and fuel balance constraint for both ADS and NPSOL. The figure contains a plot of the takeoff gross weight fraction (weight of the vehicle for each iteration divided by the weight of baseline vehicle) and a plot of the fuel balance (fuel available minus fuel required) for each iteration.

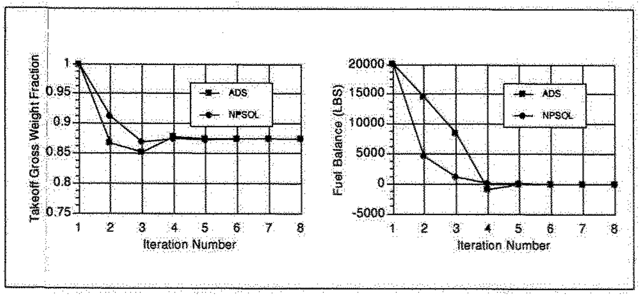

FIGURE 8 - APPLICATION SIZING HISTORY PLOTS

Selection of the SQP and SLP optimization strategies for ADS and NPSOL respectively, appeared to converge quickly. This is primarily because gradient information for all the design variables was supplied simultaneously once the GSE were solved for the total derivatives. Normally, optimization algorithms calculate gradients internally one design variable at a time which increases the number of iterations required to locate the optimum design considerably.

An obvious benefit of this approach is the visibility provided by the partial and total derivatives. Table 4 displays a sampling of some of the partial derivatives obtained from this application.

TABLE 4 - HYPERSONIC APPLICATION PARTIAL DERIVATIVES

	$\frac{\partial WFAVAL}{\partial X_k}$	$\frac{\partial WTEM}{\partial X_k}$	$\frac{\partial WTOGW}{\partial X_k}$	$\frac{\partial WFREQ}{\partial X_k}$
Baseline				
X1=Wing Area	0.0000	0.2040	0.0676	-0.0644
X2=Turbojet Size	0.0000	0.1044	0.0346	-0.0241
X3=Ramjet Size	0.0000	0.3215	0.1065	-0.0462
X4=Fuselage Length	3.0301	0.0012	0.0054	1.5604
Optimum				
X1=Wing Area	0.0000	0.1871	0.0606	-0.0534
X2=Turbojet Size	0.0000	0.1197	0.0387	-0.1317
X3=Ramjet Size	0.0000	0.3213	0.1040	-0.0313
X4=Fuselage Length	3.0301	0.0010	0.0049	0.9514

The partial derivatives shown in the table are normalized with respect to baseline values and are expressed as a percent-to-percent basis. Partials such as these indicate the relative influence of each input variable to the output variables of interest which can be of significant interest to the design team. If a partial derivative is negative, it means that a 1% increase in the input variable Y_j results in a corresponding decrease (measured in percent) in the output variable Y_i. Those partials which are specified as zero are simply not a function of the input variable Y_j. For this application the assumption was made that the the fuel required to perform the mission is stored in the fuselage. For this reason the partial derivative for fuel available as a function of wing area, denoted by $\frac{\partial WFAVAL}{\partial X_1}$, is zero as are similar partial derivatives for turbojet size and ramjet size.

It is also interesting to compare the partial derivatives computed for the baseline vehicle to those computed for the optimized configuration to measure the change in one of the parameters from the baseline to the sized vehicle. The relative magnitudes of each of the partial derivatives also provide information on how much influence each partial has on the overall objective function for each iteration. Based on the information provided in Table 4, fuselage length has the largest impact on fuel available, ramjet size has the largest impact on empty and takeoff gross weight, and fuselage length has the greatest impact on the fuel required on a percent-to-percent basis.

Similar information is available for the total derivatives for which a sampling is displayed in Table 5.

TABLE 5 - HYPERSONIC APPLICATION TOTAL DERIVATIVES

	$\frac{dWFAVAL}{dX_k}$	$\frac{dWTEM}{dX_k}$	$\frac{dWTOGW}{dX_k}$	$\frac{dWFREQ}{dX_k}$
Baseline				
X1=Wing Area	0.0000	0.2040	0.0676	0.9557
X2=Turbojet Size	0.0000	0.1044	0.0346	0.1618
X3=Ramjet Size	0.0000	0.3571	0.1183	1.7760
X4=Fuselage Length	3.0301	1.3411	2.4280	11.8630
Optimum				
X1=Wing Area	0.0000	0.1871	0.0606	-0.0432
X2=Turbojet Size	0.0000	0.1197	0.0387	-0.1482
X3=Ramjet Size	0.0000	0.3584	0.1160	-0.3147
X4=Fuselage Length	3.0301	1.2978	2.4206	-0.7166

The total derivatives are fundamentally different from the partial derivatives because they measure the influence of the design variables while fully accounting for the mutual couplings in the system. Similar to Table 4, the total derivatives in Table 5 show the influence that a 1% increase in each of the design variables has on the output variable in the numerator, also expressed in percent. For those cases in which the total derivatives and partial derivatives are equal (as is the case for the fuel available partials in Tables 4 and 5), the output variables from the particular black box are uncoupled with inputs from the other black boxes. Such is the case with the Geometry variables: vehicle wetted area and fuel available.

The total derivatives for the objective and constraint functions provided the information required by the optimization program (ADS or NPSOL) to determine the proper search direction. The total derivatives of mission-sized takeoff gross weight with respect to each design variable, denoted by $\frac{dTOGW}{dX_i}$, provided the gradient information for the objective function. There appears to be very little change in this total derivative for the optimized vehicle when compared to the baseline vehicle. This is probably due to the relatively strong impact of the fuel balance constraints on the mission-sized takeoff gross weight for this problem.

Application Cost & Benefits

Due to the development status of the ADST program, it was not possible to perform this particular application in a parallel processing environment. However, since the computational time required to execute each functional module is readily available, the resulting time savings for performing this design trade study in a parallel processing environment can be estimated using an approach discussed in Ref. (18). The time savings can be estimated by comparing the time required to perform the trade study using the GSE approach in both a sequential and parallel processing environment to that required by the approach.

However, this comparison would not be justifiable without considering the fact that the traditional method did not involve the application of optimization methods. Obviously, a percentage of the time savings that may be realized using the GSE approach is directly attributable to the application of an optimizer to the problem. For this reason, the computational time required to locate the optimum design variables for the example hypersonic application will be tabulated and contrasted for the following approaches: 1) traditional method consisting of a parametric survey of the design space followed by a one-factor-at-a-time variation of the design variables within the subspace of interest, without the use of formal optimization, 2) optimization method which involved computing the total derivatives by finite differencing on the full analysis (Figure 6), without the use of the GSE, 3a) using the GSE instead of the above finite differencing, executed on a single processor computer, and 3b) using the same approach described in 3a but employing a parallel processing computer.

FIGURE 9 - ELAPSED CPU TIME COMPARISION FOR METHODS 1, 2, 3a AND 3b

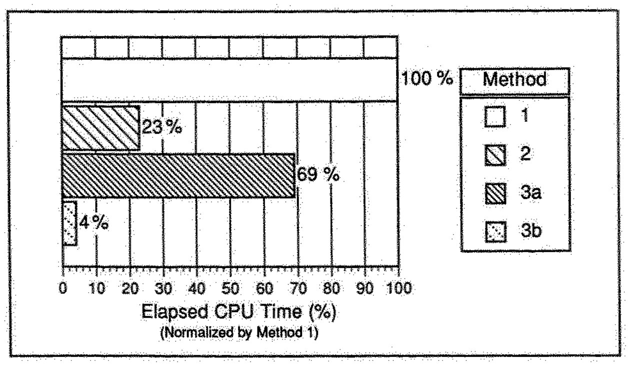

Figure 9 displays a comparison of the CPU elapsed time for methods 1, 2, 3a, and 3b, normalized by the time required by method 1. For a single processor computer, the CPU elapsed time is equal to the CPU time, but for a "N" processor computer, the CPU elapsed time is compressed by using all the processors simultaneously to the largest extent possible (in the case at hand, N=12). Application of method 2 reduces the time to 23%. Replacing method 2 with method 3a brings in the penalty for computing partial derivatives without, as yet, taking advantage of the parallelism intrinsic in the GSE method. Consequently, the time increases to 69%. However, employing method 3b that takes advantage of such parallelism, fully reduces the time to 4%, or nearly 1/6th of the time of method 2. The relative time reduction advantage of method 3b over method 2 depends on the size of the problem and the number of modules in the system whose partials may be computed concurrently. Therefore, that advantage is expected to increase with the size of the problem.

Nevertheless, the benefits of applying the GSE approach extend beyond the computational time savings which result in a parallel processing environment, since the GSE also provides the partial and total derivative visibility that methods 1 and 2 distinctly lack. Results from these comparisons reemphasize the need to consider the availability of parallel processing when applying the GSE approach to vehicle design synthesis trade studies. If concurrent computation of the partial derivatives is not feasible, due consideration should be given to the increased visibility of the design process provided by the GSE. Additional benefits accrue from the functional advantages associated with decomposing a complex system and assigning responsibility to the functional disciplines involved. In many cases, these benefits simply outweigh any computational disadvantages associated with the sequential processing of the partial derivatives. However, if parallel processing is available, then all the computational benefits of the GSE approach can be directly realized.

Conclusions

The application of system sensitivity analysis and non-hierarchical system decomposition methods to an automated vehicle design synthesis program appears to be ideal, particularly in an a parallel processing environment. These methods were successfully incorporated into the ADST program currently under development at GD/FW, and will be a key feature of the program in future vehicle design trade studies.

The example application served to quantify several important features resulting from the union of these techniques to an automated vehicle design synthesis program. These features include the ability to:

- respond directly to the ever increasing complexity of the vehicle design synthesis process by realizing the interdisciplinary synergism which exists
- encourage and support the use of concurrent engineering principals in today's aerospace system designs
- promote the quantitative aspects of design by taking advantage of technological advancements made in the areas of computational speed and parallel processing
- address the qualitative aspects of the design process by supporting human judgement decisions and providing for a means of communication between disciplines, and
- quantify directly the impact of a proposed design change for all disciplines involved in the design synthesis process.

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