ICAS-90-2.3.2

OPTIMIZATION OF AIRCRAFT CONFIGURATIONS IN A MULTIDISCIPLINARY ENVIRONMENT

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ABSTRACT

A decomposition and multidisciplinary optimization methodology for aircraft design is presented, based on multilevel optimization and use of global sensitivity equations to account for interdisciplinary effects. A brief study of a hypersonic cruise vehicle is developed to illustrate methodology. The vehicle is sized for minimum take-off gross weight considering aerodynamics, structures, and mission performance.

INTRODUCTION

Hypersonic vehicle design requires consideration of an extensive parameter array for successful configuration development. Weight sensitivity, as measured by the growth factor, is in the range of ten-to-one for single-stage-to-orbit vehicles, and demands highly sophisticated and optimized airframe structure. Furthermore, material selection, which strongly influences structural concepts and manufacturing techniques, is driven by service temperatures, which are determined in turn by flight path parameters, particularly speed and altitude. Optimum structural design, therefore, requires concurrent consideration of the structure, its materials, and the mission itself.

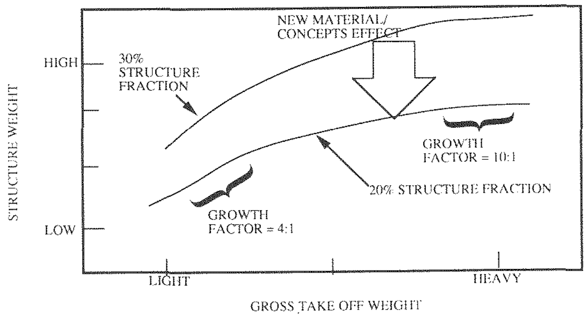

Figure 1 - Effect of Structural Weight on Gross Take-Off Weight

Weight trends illustrated in Figure 1 indicate the importance of low structural weight to vehicle size, performance, and, ultimately, cost of hypervelocity vehicles. These trends dominate air-breathing single-stage-to-orbit vehicles. The need for very low structural fractions, of the order of 20 percent of TOGW (take-off gross weight), has led to new but high cost material applications, particularly titanium aluminides, ceramics, and carbon-carbon. In addition to these materials, advanced fabrication techniques, typically requiring high temperature complex processes are required. This scenario leads to high-cost structure and requires a balance of vehicle performance and material/structural concepts that is significantly more demanding than required by present high-performance aircraft. In this context, typical trades between structural concept, material properties, fabrication requirements, and cost require concurrent consideration of vehicle shape and mission performance.

In this environment, multidisciplinary optimization methods provide a powerful design technique and are expected to provide vehicle designs having the best balance of structure, vehicle concept, mission capability, and cost. These compromises are not new issues, but new tools are becoming available which can make the trades easier and more accurate, and which can yield a design that is truly the best for all issues considered. The tools are formal optimization capabilities which handle complex problems based on a variety of mathematical approaches, large-scale computing capabilities, and interdisciplinary interaction based on simulation and system sensitivities. Implementation of these tools for complex vehicle system design is made

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*** Project Manager, Advanced Technology, Member AIAA possible by advanced computing capabilities which allow economical simulation of complex aerodynamic, structural and material performance and mission analysis. These computational tools form an accurate model simulating the vehicle being designed, and avoid the compromises previously required when using mathematical equations describing the desired behavior.

Aircraft optimization based on sensitivity analysis allows mapping the interactions which actually occur among the components and engineering disciplines in the real vehicle onto the data flow among the computational modules in the system mathematical model. This mapping, in turn, yields the equations quantifying design variable effects on vehicle performance. These data support both engineering judgement and formal optimization to control and amplify interdisciplinary design trade-offs. This paper addresses a multidisciplinary approach to its design based on sensitivity derivatives and global sensitivity equations which account for interdisciplinary effects.

MULTIDISCIPLINARY OPTIMIZATION

During the past several years, optimization tools and structured approaches to multidisciplinary design have been developed and are suitable to address the problem outlined. Sobieski (1) presented a systematic methodology for decomposing large, complex systems into a series of smaller subsystems, using sensitivity derivatives of the data exchanged among these subsystems as the basis for total system optimization. That approach has been subsequently expanded, for example, Sobieski (2,3) and Abdi (4), and is the basis for the approach taken in this paper.

To describe this approach, it is convenient to consider a system limited to only three contributing analysis, or "black boxes" which is a number small enough to simplify the discussion and yet large enough to develop a pattern that readily generalizes to a system composed of n black boxes. To give the three black boxes a physical meaning, they are named A, S, and M and represent the aerodynamics, structures and mission, respectively. It is understood that each black box contains an appropriate mathematical model, e.g., a finite element program with the pertinent pre- and post-processors in S. However, the very purpose of the black box concept is to hide the internal detail and to consider the black box as an input-to-output transformer that is, simply, a set of simultaneous equations whose solution vector is the output. The equations may be written in a compact form as a vector functions set to zero and operating on a set of arguments. The list is ordered so that the last on the list is the output vector while the input vectors are grouped in the inner parentheses. The input group begins with the vector of design variables (independent variables of the problem) X followed by the Y-vectors output from the other black boxes in the system:

$$\begin{aligned} &A((X, Y_s, Y_m), Y_a) = 0 \\ &S((X, Y_m, Y_a), Y_s) = 0 \qquad (1) \\ &M((X, Y_a, Y_s), Y_m) = 0 \end{aligned}$$

In the above, Y_a contains the aerodynamic pressure coefficients, Y_s includes the elastic deformations, and Y_m comprises the mission performance definition. The design variables in X may represent major configuration parameters such as wing aspect ratio and sweep angle, cross-sectional dimensions, and specific impulse.

Of course, not every element of each of the Y and X input vectors is actually used in each of the black boxes. The usage is selective, for instance, S uses the aerodynamic pressure data in Y_a but may ignore the local Mach number values. Similarly, S will use the wing geometry and cross-sectional dimensions data in X, while only the former will be used in A.

The system analysis produces an output vector $Y' = [Y_a : Y_s : Y_m]$ as an implicit function of X. Owing to the output-to-input transmissions of the Y vectors, the system equations have to be treated as simultaneous even though they are partitioned into the A, S, and M sets. If any of the constituent black boxes contains nonlinear analysis, the system becomes iterative.

When the system analysis is completed, the design process requires answers to the "what if" questions regarding the influence of perturbations in X. These questions may be posed directly by engineers in an interactive mode or they may be generated by a formal optimization procedure. Derivatives of Y with respect to X quantify answers to these questions and may be approximated by a finite difference technique that requires repetition of the system analysis for an increment of one X_k at a time. This finite difference technique, or a parametric study approach similar to it, have well-known disadvantages of the high cost and often-inadequate accuracy, however, an alternative free of these disadvantages was proposed in reference 3 in the form of of an algorithm for a system sensitivity analysis that yields the derivatives of Y with respect to X directly.

That algorithm requires the system analysis to be completed as a prerequisite, that is a solution Y for a given X must be available. Then, for the given X and the corresponding, known Y, the algorithm begins with generation of the derivatives of the output with respect to the input for each black box. These derivatives are by definition the partial derivatives so that they can be computed for each black box taken in isolation, and treating all the X and Y inputs as independent variables. Computation of the partial derivatives amounts to a disciplinary sensitivity analysis and may be executed using any technique available for a particular black box at hand. Preferably, a quasi-analytical method should be used (a survey of such methods for various disciplines is provided in reference 5) but a finite difference method may have to be used wherever a quasi-analytical method has not yet been implemented. For the three-part system, the partial derivatives are collected in the Jacobian matrices J_{as}, J_{am}, J_{sa}, J_{sm}, J_{ma}, J_{ms}, and in the vectors R - one R for each design variable. Each matrix J corresponds to the output-to-input transmission that links the black box identified by the second subscript to the one identified by the first subscript. For example, the i-th column of J_{as} contains the partial derivatives of the elements of Y_a with respect to the i-th element of Y_s received in A. A k-th R vector contains the partial derivatives of Y with respect to the k-th design variable, X_k.

As shown in reference 3 on the basis of the implicit function theorem, the above partial derivatives may be used to assemble a set of simultaneous, linear, algebraic equations that yield a vector of derivatives of Y with respect to X_k:

$$\begin{vmatrix} J & -Jas & -Jam \\ -Jsa & I & -Jsm \\ -Jma & -Jms & I \end{vmatrix} \{dY/dXk\} = \{R\}k \qquad (2)$$

The derivatives in $\{dY/dX_k\}$ have the meaning of total derivatives and reflect the interactions among the black boxes, unlike the partial derivatives that appear as coefficients in the above equations and represent only the sensitivity of the isolated black boxes. For example, if X_k is the wing sweep angle, then the partition $\{dY_a/dX_k\}$ in $\{dY/dX_k\}$ will indicate the rate of change of the body aerodynamic pressure accounting for vehicle angle of attack influence on the aerodynamics directly and, indirectly, through elastic deformation changes..

The derivatives $\{dY/dX_k\}$ may be used to guide a formal optimization algorithm and for extrapolation purposes to evaluate the effects of small but finite increments of the design variables. In strongly nonlinear problems, it may be cost-effective to enhance the extrapolation by the second order terms and the above system sensitivity analysis may be formally extended to calculate the second derivatives as shown in reference 6. The improvement of the extrapolation accuracy gained by using at least the diagonal terms in the matrix of the second derivatives was demonstrated in reference 4.

In reference 7, a strategy based on a multilevel decomposition of an airplane system into levels of equivalent design influence was developed. The motivation for this approach is to allow evaluation of design parameters in a context where their effect can be readily measured. A further motivation is that consideration of all variables as once will lead to a poor computational situation, in which a clear optimum would be difficult to determine because of convergence issues and masking of important detail parameters by more dominant ones. A further issue is interdisciplinary linking of design variables which has to be considered, particularly at the preliminary design level. This equivalent design parameter influence approach does not consider weak variable linking, allowing design process simplification and focus on design drivers. As will be seen in the subsequent example, computer simulation, CFD for example, is used to focus on variables of interest for sensitivity analysis, while implicitly including all necessary parameters for correct problem description. This later issue is discussed further in reference 4, where functional descriptions are constructed by computational simulations, with examples shown in references 7 and 8.

DESIGN STUDY

A case study of a hypersonic vehicle, Figure 2, will be used to illustrate how the method can be applied, and demonstrate computation formulation. This vehicle configuration has a long forebody and a small wing, sized by takeoff and landing requirements, and is typical of a class of manned air breathing vehicles having orbital capability and conventional takeoff and landing performance. Figure 3 illustrates a cruise flight profile. Emphasis is on the cruise portion of the flight, with the focus on structural optimization considering material effects traded against variations in flight profiles to adjust structural temperatures as required by a particular material. Engine efficiency was held constant.

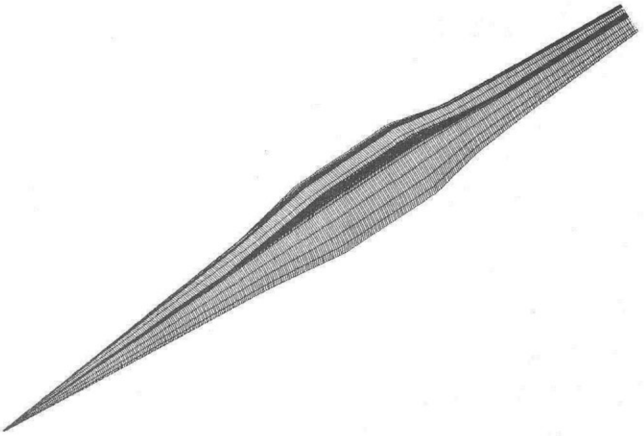

Figure 2 - Baseline Vehicle

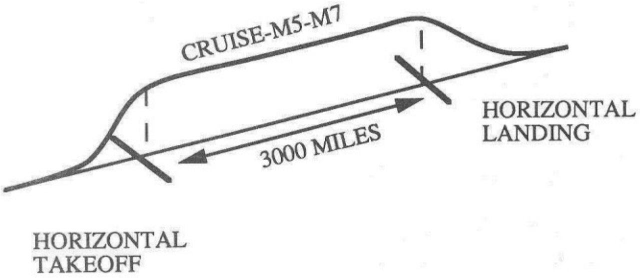

Figure 3 - Study Cruise Mission

A typical flight could also consist of a conventional horizontal takeoff and hypersonic cruise and return, or acceleration to orbit insertion, orbit, and return to earth, with a conventional landing. For the orbital case, cross-range requirements and orbit entry parameters have critical effects on material selection, primarily because of temperature considerations, and consequent airframe weight and cost. For a cruise flight, cruise altitude and speed effect vehicle temperature, engine efficiency, and therefore airframe weight.

Figure 4 illustrates the overall strategy used in the design study. Primary emphasis in the study example is on structural behavior and material application, as shown in Figure 5. Aerodynamic performance and mission capability are included a part of the trade-off to optimize vehicle weight and overall performance. A through review of conceptual hypersonic vehicle design is given by Hunt and Martin (9), which includes all design aspects at the conceptual/ preliminary level. The design study considered here, while only a subset of the total problem, illustrates an approach to global optimization for the overall design process.

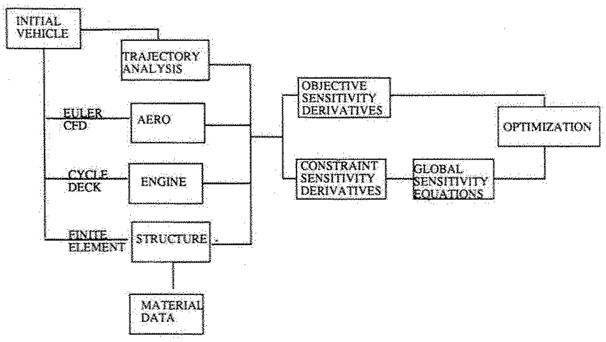

Figure 4 - Design Study Strategy

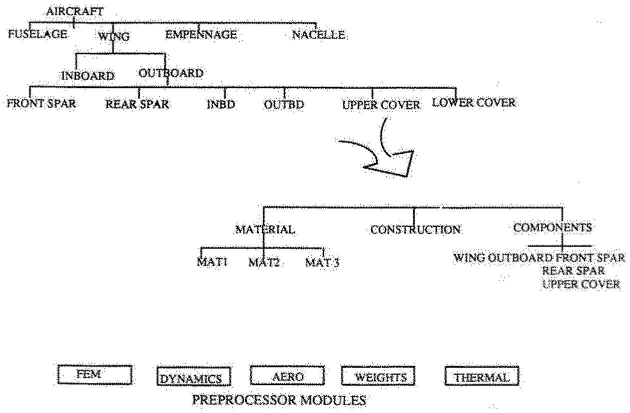

Figure 5 - Structural Material ApplicationStudy Plan

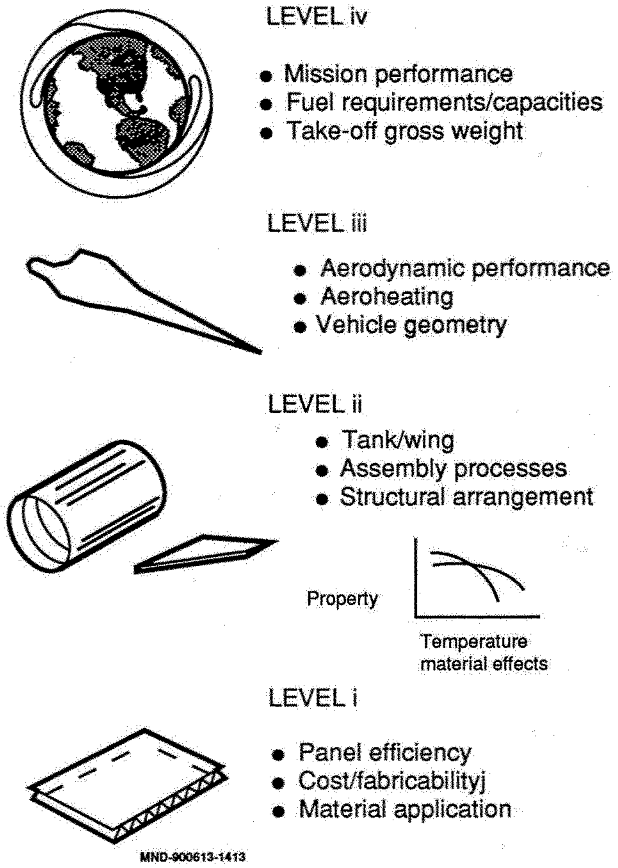

Figure 6 - Design Process Levels

OPTIMIZATION STRATEGY

Figure 6 illustrates the levels of equivalent design parameter influence used in this example. The design optimization process proceeds from level i to level iv with local optimization taking place at each level, related to the next level by sensitivity derivatives of parameters common to interfacing levels. The lowest level provides evaluation of structural details and material effects, leading to eventual mission analysis as the integrator of weight and performance trades. The overall approach uses Euler CFD to compute aerodynamic sensitivities, an FEM-based structure code for sub-optimization of the detail structure weight, and mission simulation to perform the multilevel design objective synthesis. The cruise segment of the flight is of particular interest because it is the primary structural temperature source, and is the only flight profile segment considered explicitly. Take-off and landing segments are allowed to vary to account for variations in vehicle weight. The cruise range is held constant, with the altitude and speed varied to explore effects on vehicle weight.

Structural optimization focuses on material selection and typical structure configuration, driven in turn by the temperature capability of the material and requirements of cruise parameters. For a typical cruise leg, a higher cruise altitude will tend to produce lower temperatures at the same speed, or speed can be increased to that allowed by the material, possible increasing engine efficiency for a lower total weight. The advantage in this example would be a flight profile tailored to a specific material set that is lower cost or more producible than another.

Figure 7 illustrates the overall effect of material selection on vehicle mission capability for a variety of advanced structural materials, based on material temperature capabilities. As flight speed is increased at a given altitude, the increasing temperature requires a more complex material. The principal structural trade is between structures using advanced high fabrication cost materials with high service temperature capabilities (intermetallic titaniums for example) and structures using near-term more easily fabricable materials (conventional titaniums) that may require more insulation (weight) or supplementary cooling.

OPTIMIZATION FORMULATION

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

$$\min_{X} F(X) \qquad (3)$$

subject to the constraints

$$g(X) = 0 \qquad (4)$$

is to be obtained. The vector X contains the independent design variables of interest. Variables held constant or not explicitly evaluated during the optimization are not displayed. The formulation for the following example minimized weight for the cruise segment using different materials with aerodynamic performance as the primary constraint.

Because it dominates total structural weight for the type of vehicles being considered, concentration is on the fuselage structure which is also the primary fuel tank. Basic structural configuration trades, illustrated as level i in Figure 6, may be accomplished using standard engineering calculations, test data, regression equations, or optimization codes. For new vehicle design, there is usually inadequate data to develop the necessary relations, and structural analysis and optimization are required to generate the required data.

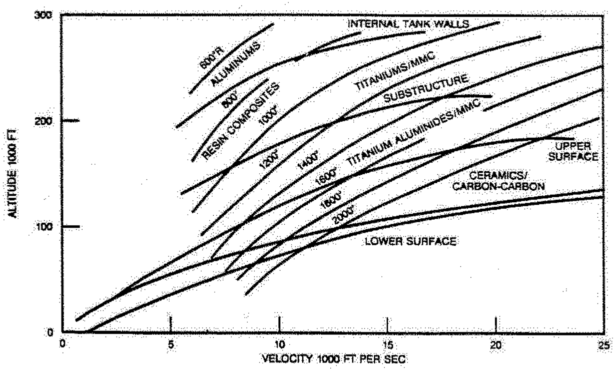

Figure 7 - Effect of Material on Overall Vehicle Performance

At level ii of the fuselage breakdown, structural weight is used as the objective function, related to aerodynamic performance at the next level through selected shape parameters. Representing the equation (1) structural component, fuselage weight is expressed as

$$W = f_1((r, l, T, Ym), Yw) \qquad (5)$$

where r is the fuselage radius, l the nominal fuselage length, and T a measure of structural temperature for critical areas. Here, T is the variable that will be used to relate structural weight to component design at the lower level and to aerodynamic heating at the next level and is the explicit part of the Y_a matrix in the structural component of equation 1. Note that there is an implicit relation between T and the weight through material properties as related to temperature. For this study, T is an array of temperatures related to specific structural areas of interest. The vector Ym contains mission effects on weight, and Yw is the vector of vehicle weights. For this example the notation will be limited to

$$W = f_1(r, l, T) \qquad (6)$$

In this formulation, only the fuselage diameter and length are displayed since these variables will be explicitly varied, and will be used to tie the weight to aerodynamic performance at the next level. Structural weights and required sensitivities will be developed from a finite element based structural optimization code. This code is used to optimize the fuselage structure for variations in length and diameter, using criteria for strength, stiffness, panel buckling, and local crippling. This process for weight sensitivities considered optimization of the structural shell at level ii, supported by trade studies and detailed component optimization at level i.

Table 1 summarizes a portion of these detailed studies, in this case performed using strength of materials calculations. These results are used to select basic shell optimization, at which time detailed optimization for the selected concept is performed. In this case, honeycomb develops the lowest unit weight, as may be anticipated, when the external surface required by the corrugated panel is accounted for.

Table 1. Wing Panel Concepts Evaluation

DESIGN CONCEPTS	CRITERIA	MAT'L	DESIGN TEMPT	$\bar{t}_{(in)}$	$\overline{\rho t}_{lbs/ft^2}$	REMARKS
SPF/DB BEADED STIFFENED PANEL	UNIAXIAL Nx= 750 #/IN	Ti_3Al RSR Ti SiC/Ti_3Al SiC/RSR Ti	1200° F 1800° F 1200° F 1800° F	.052 .060 .050 .060	1.23 1.21 1.10 1.17	•Low thermal stress
	BI-AXIAL Nx=750 #/in Ny=300	Ti_3Al RSR Ti SiC/Ti_3Al SiC/RSR Ti	1200° F 1800° F 1200° F 1800° F	.063 .070 .057 .072	1.48 1.40 1.88 1.39	
CORRUGATED PANEL	#/in UNIAXIAL Nx= 750 #/IN	Ti_3Al RSR Ti SiC/Ti_3Al SiC/RSR Ti	1200° F 1800° F 1200° F 1800° F	.035 .045 .034 .045	.85 .90 .78 .87	• Minimum thermal stress •Requires external surface
HONEYCOMB	UNIAXIAL Nx= 750 #/IN	Ti_3 Al RSR Ti RENE '41	1200° F 1800° F 1600° F	.030 .033 .030	.75 .67 1.31	• Closeout weight to be added

Using these results, overall structural optimization is performed as previously discussed. The basic model, used for both aerodynamic and structural analyses, consisted of ten stations as shown in Figure 8. At each station, the vehicle's cross section is defined by a number of curve segments which in turn are defined by a set of points. This baseline geometrical information is input to a program which performs a spline fit to the data points. The geometry is then discretized according to a user-specified number of segments in the traverse direction. Improved definition is developed in the longitudinal direction by using curve fitting techniques with specified longitudinal stations, resulting in the 57 station model shown in Figure 9.

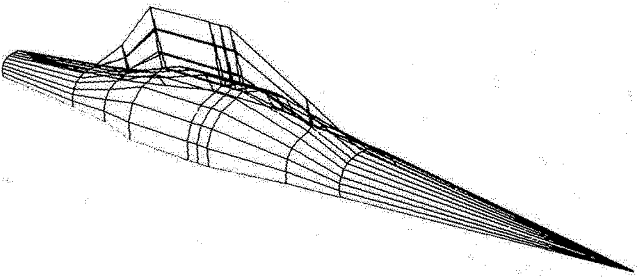

Figure 8 - Original, 10 Station Model

A finite element model was developed using membrane elements with sample substructures shown in Figure 10. The mesh generation technique includes different component construction and materials to facilitate trade studies. Three kinematic constraints were assigned to the two aft nodes to prevent rigid body motion, and rotational degrees of freedom were fixed at each node. Material properties were assigned to each

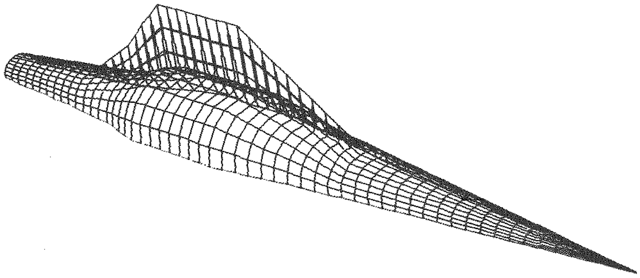

Figure 9 - Enhanced, 57 Station Model

element by using material type codes and internal data tables. A baseline sensitivity analysis for material application was run using a series of point loads and titanium aluminide at 70 and 1350 degrees Fahrenheit.

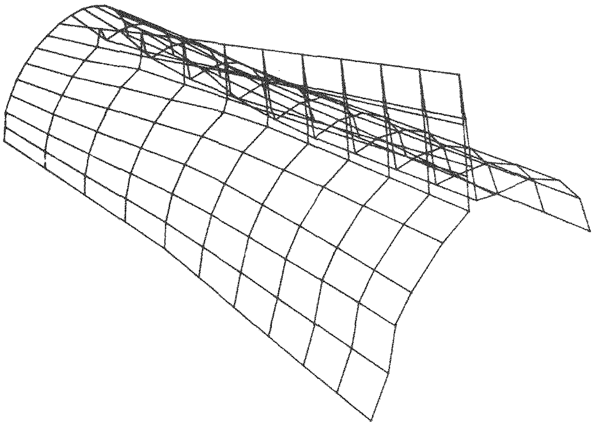

Figure 10 - Typical FEM Substructure

Maximum nose tip deflection were 9.58 inches and 11.64 inches for 70 degrees and 1350 degrees, respectively, and were proportional to moduli of elasticity at those temperatures. Since material properties are generally nonlinear with respect to temperature, a series of linear analyses can be used to represent nonlinear sensitivity of the vehicle temperature deformation through temperature dependent material properties. Figure 11 shows tip deflection sensitivity to temperature, and Figure 12 shows tip deflection as a function of applied loads.

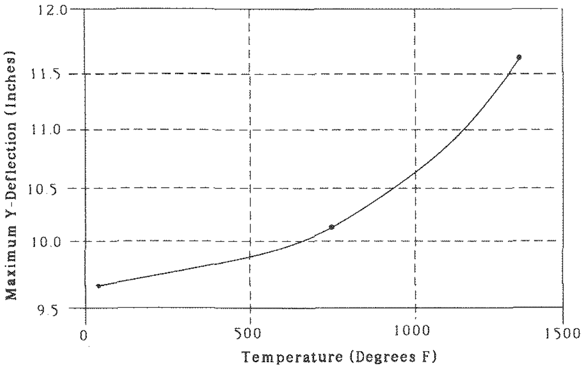

Figure 11 - Sensitivity Analysis-Deflection vs. Temperature

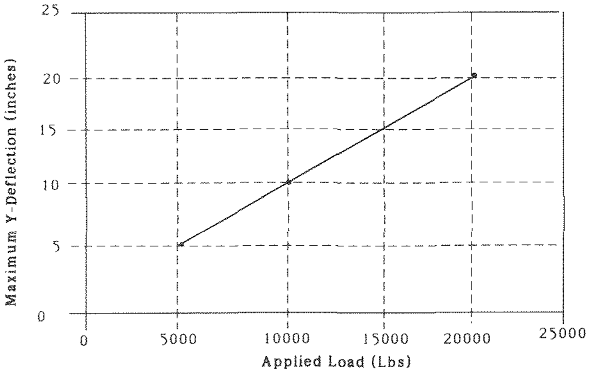

Figure 12 - Sensitivity Analysis-Deflection vs. Applied Loads

Aerodynamic computations at level 2 utilized a three dimensional unsteady Euler CFD code developed by Chakravarthy and Szema (10) with results for Mach 5.0 and α=0° shown in Figure 13. This code solves the steady/unsteady Euler equations based on time and space marching modes. The space marching mode is a Gauss-Seidel relaxation method which includes forward sweeps, backwards sweeps, or both. A finite volume (cell centered modes) implementation provides high accuracy-up to third order since total variation diminishing discretizaton is used , the method is more accurate and reliable in the high speed regime than other Euler methods which are based on central difference approximations.

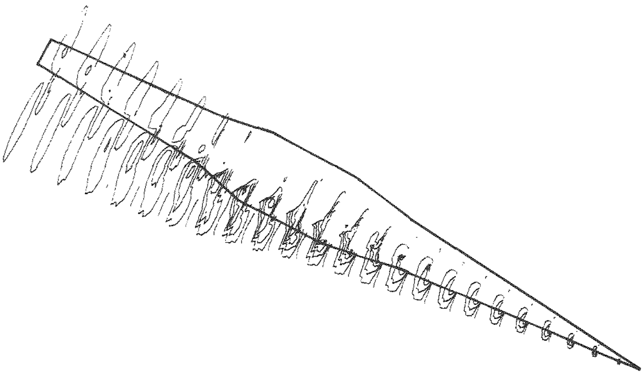

Figure 13 - Aerodynamic PressureDistribution for M=5.O, α=0°

This code utilized an internal grid generator which created a two dimensional grid in the Y-Z plane at five consecutive planes along the X direction. The code makes use on an H-O type grid topology.

Following notation of equations 5 and 6, the aerodynamic segment of equation 1 is expressed as :

$$A= f_2(l,d,t_i,T) \qquad (7)$$

where t_i are trajectory parameters. Aeroheating, represented by the vector T, is a function of velocity, altitude, surface geometry, angle of attack, and material characteristics such as roughness, emmisivity, and catalytic activity.

Trajectory analysis and influence on vehicle weight is computed using a program such as POST

(Program to Optimize Simulated Trajectories), Brauer, et al (11,12) with the aircraft performance mission option. For purposes of this case study, mission analysis is represented by :

$$M = f_3 (D, h, v, W) \tag{8}$$

where D is vehicle drag, h the cruise altitude, v the cruise velocity. Fuselage shape is varied to optimize performance (weight for a specified mission leg) as speeds are varied. For this study, the propulsion is held constant with no explicit propulsion variables considered for optimization. The engine will tend to operate at the highest dynamic pressure that the material and vehicle configuration will sustain, temperature-wise.

The objective is to maximize specific impulse, I_{sp}, with minimum TOGW, based on varying material application and flight conditions, constrained by aerodynamic heating and performance. Then, the following matrix equation of sensitivity derivatives is to be obtained, and is the governing equation:

$$\begin{array}{c|ccc|} & \text{material} & \text{aero} & \text{mission} \\ \text{material} & I & 0 & -\frac{\partial f(m)}{\partial M} \\ \text{aero} & -\frac{\partial f(A)}{\partial m} & I & -\frac{\partial f(A)}{\partial M} \\ \text{mission} & -\frac{\partial f(M)}{\partial m} & -\frac{\partial f(M)}{\partial A} & I \end{array} \begin{Bmatrix} \frac{dm}{dx} \\ \frac{dA}{dx} \\ \frac{dM}{dx} \end{Bmatrix}$$

$$= \begin{Bmatrix} \frac{\partial f(m)}{\partial x} \\ \frac{\partial f(A)}{ox} \\ \frac{\partial f(M)}{\partial x} \end{Bmatrix} \tag{9}$$

where m has been introduced to represent material behavior a subset of structures in the case to be studied, engineering properties as a function of temperature. The functions f(m), f(A) and f(M) represent materials, aerodynamic behavior, and mission, respectively and are, in general, matrices. The sensitivity derivatives are as follows:

$\partial f(m)/\partial M$- material property change as affected by changes in mission parameters (speed).

$\partial f(A)/\partial m$- aerodynamic changes as affected by material properties (allowables).

$\partial f(A)/\partial M$- aerodynamic changes as affected by mission parameter changes.

$\partial f(M)/\partial m$- mission parameters changes as affected by material (density, strength).

$\partial f(M)/\partial A$- mission parameter changes as affected by aerodynamics (drag).

dm/dx, dA/dx, dM/dX- global sensitivity derivatives with respect to explicit design variables, x_i.

The right hand vector is the set of partial derivatives of in material properties, aerodynamic force and temperature, and mission parameters with respect to the explicit design variables, x_i.

APPLICATION STUDY

Solution of the matrix equation, (a), yields the global sensitivity equations needed to establish interdisciplinary effects. Sensitivities are represented as linear Taylor series of expansions about the baseline design, which using equation (6) as an example, becomes

$$W = W_0 + C_1 \frac{\partial f_1}{\partial r} \Delta r + C_2 \frac{\partial f_1}{\partial l} + C_3 \frac{\partial f_1}{\partial T} \Delta T \tag{10}$$

where the constants are coefficients of the expansion. Further mathematical details are given in reference 8.

Minimum take off gross weight was achieved by using the sensitivity analysis for trajectory optimization. In this example baseline vehicle parameters were perturbed, with an example illustrated in Figure 14 for Mach number effect on I_{sp}. For the vehicle studied, Figure 15 shows TOGW effect on fuel weight required, and includes effects of structural optimization and material application studies, and aerodynamic results discussed previously. Figure16 represents optimization parameters and partial derivatives of thrust, drag, and fuel flow with respect to weight of fuel required.

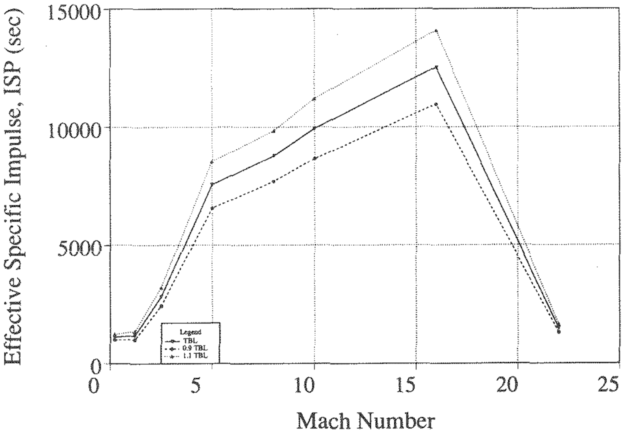

Figure 14 - Effect of Mach Number on I_{sp}

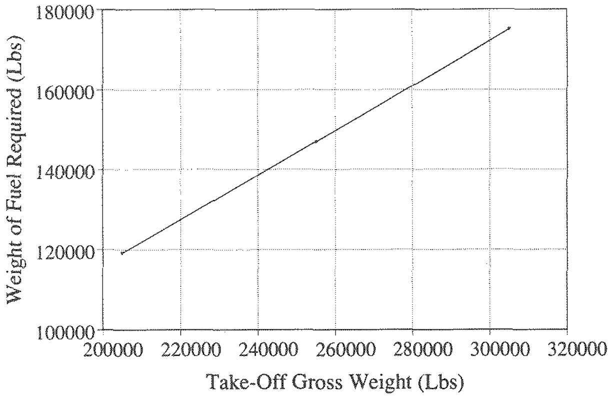

Figure 15 - Effect of TOGW on Fuel Weight

Constraints imposed on the trajectory included maximum dynamic pressure, angle of attack, and maximum heating rate to represent pressure/temperature boundaries. The resulting optimization converged to minimum fuel weight, therefore to minimum TOGW.

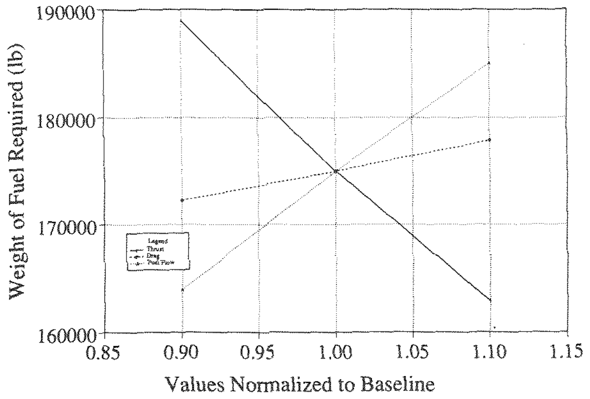

Figure 16 - Thrust, and Fuel Flow Sensitivities.

SUMMARY AND CONCLUSIONS

This paper has described a decomposition algorithm and multidisciplinary optimization that integrated a hypersonic vehicle cruise mission, aerodynamic performance, and structural design. The methodology is based on a multi-level decomposition which is arranged such that design variables have relatively similar impact at each level, facilitating suboptimization of primary design drivers at each level, and on simulation of principal vehicle behavior through use of computer codes representing aerodynamics, (CFD), structures (FEM), and mission performance. The example illustrated implementations of key features of the methodology and provided a minimum TOGW design based on minimum fuel for the selected mission.

For the complex integration required for hypersonic vehicles, the power of multidisciplinary optimization methods is readily apparent with continued use assured, although significant future development remains. In particular, as study fidelity is increased to account for representation of more design variables, overall process management and sensitivity derivative computation will become major tasks. To manage the even larger matrix of global sensitivity equations, formal suboptimization control methods and cascading of results via subsets of sensitivity equations which can be manipulated at the designer's direction will be needed. An initial approach for mechanization of such a process is presented by Levine, et al, (13). Automated sensitivity derivatives computation, including those of higher order, again under the designer's direction, will provide a major boost to acceptance and utilization of multidisciplinary methods as presented here and in other works.

ACKNOWLEDGMENT

The authors express their appreciation for the efforts of Mr. Greg Savoni, Rockwell International for supporting computations. Rockwell 'efforts were sponsored under Internal Research and Development.

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