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Airbreathing Hypersonic Vehicle Design and Analysis Methods

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ABSTRACT

The design, analysis, and optimization of airbreathing hypersonic vehicles requires analyses involving many highly coupled disciplines at levels of accuracy exceeding those traditionally considered in a conceptual or preliminary-level design. Discipline analysis methods including propulsion, structures, thermal management, geometry, aerodynamics, performance, synthesis, sizing, closure, and cost are discussed. Also, the on-going integration of these methods into a working environment, known as HOLIST, is described.

INTRODUCTION

The Systems Analysis Office (SAO/Hypersonic Vehicle Office) at NASA Langley Research Center provides evaluation, analysis and design of hypersonic airbreathing vehicles for both industry and government. A wide range of vehicles and missions are investigated, including single-, two-, and three-stage-to-orbit vehicles, as well as endoatmospheric cruise and accelerator vehicles. Due to the highly integrated engine/airframe and the extensive flight envelop inherent in airbreathing hypersonic vehicle design, analyses involve many interdependent disciplines with high sensitivities among the design variables and a highly nonlinear design space¹. It is therefore necessary to resolve airbreathing hypersonic vehicles to a preliminary design level, even for what would traditionally be considered as conceptual design. With this amount of detail required as well as the requirement for a short response time, analysis methods have been developed and improved to provide both rapid and accurate results. This paper describes the advancement in SAO design and analysis methods during the past six years.

Figure 1 illustrates the set-up of the Systems Analysis Office, with technical experts and analysis

methods in each of the disciplines. In the center of the figure, HOLIST is being developed as a working environment for design, analysis, and optimization of airbreathing hypersonic vehicles. The basic synthesis system in HOLIST is currently operational. As it is further developed, HOLIST will include elements from all of the disciplines, with upgrades continually being made as discipline methods advance. Following is a brief introduction to the airbreathing hypersonic vehicle design process, discussion of selected discipline methods and the current and planned capabilities of HOLIST.

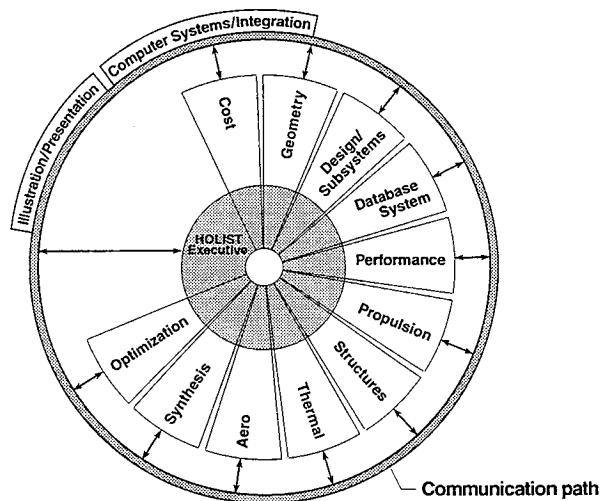


Figure 1. SAO Hypersonic Airbreathing Vehicle Analysis, Design and Optimization.

HYPERSONIC VEHICLE DESIGN/ ANALYSIS METHODS

A schematic of the design/analysis process is shown in Figure 2. The process begins with a vehicle geometry definition, as shown in the left of the figure. Propulsion, aerothermal and trajecto-

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ry analyses are completed to yield the propellant fraction required (PFR). The propellant fraction available (PFA) is determined from packaging, structural and thermal management analysis, as well as weights prediction. In the upper right of the figure, the plot of PFR and PFA versus TOGW illustrates the process of closing a vehicle. For example, if upon first analyzing a vehicle, the PFA is less than the PFR, the vehicle must be sized up to a higher TOGW until the curves intersect, thus closing the vehicle. Note, however, that to achieve the accuracy required for airbreathing hypersonic vehicle design, the vehicle is closed on volume and area, in addition to weight.

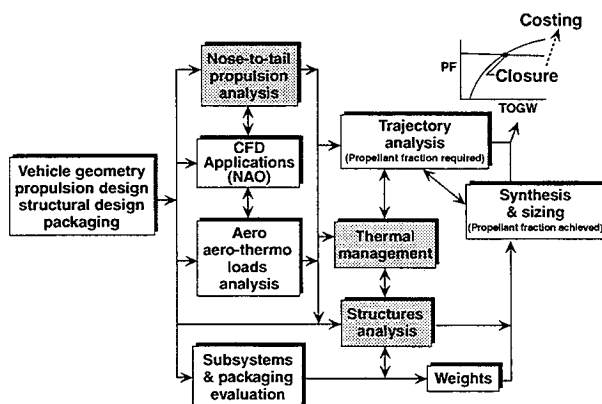


Figure 2. Vehicle Design/Analysis Process in SAO.

Each of the disciplines shown in Figure 2 are critical to the design of an airbreathing hypersonic vehicle. However some disciplines are more traditional in that they may be found in other speed regime analyses. The three shaded disciplines, propulsion, thermal management and structural analysis, are unique to airbreathing hypersonic vehicle design. As a result, SAO has developed unique tools and capabilities in these areas.

Propulsion

Airbreathing hypersonic vehicles are characterized by highly integrated engine/airframes as illustrated in Figure 3. Since the net propulsive thrust of an airbreathing hypersonic vehicle is a small difference between two large forces, namely the combustor/nozzle thrust and the forebody/inlet drag, it is necessary to resolve these forces accurately. The predic-

tion of the forebody flowfield properties and the mass capture are also critical to resolving the net thrust. Therefore, the ramjet/ scramjet cycle code, SRGULL², developed primarily in-house, uses a 2-D Euler calculation on the forebody and inlet, coupled with a boundary layer solution, to predict the forebody/inlet drag and the flow properties entering the engine. The ramjet/scramjet solution is then completed using a 1-D cycle analysis with equilibrium chemistry and multiple steps through the combustor. Finally, the nozzle forces are resolved using the 2-D Euler and boundary layer codes. A 3-D Euler capability is now being implemented into the code.

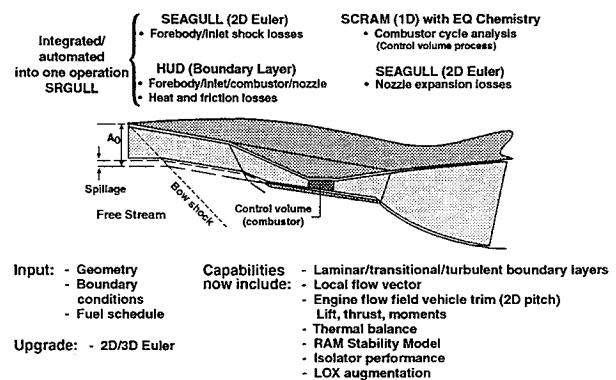


Figure 3. Tip-to-Tail Scramjet/Ramjet Cycle Analysis, SRGULL.

Capabilities in the SRGULL code include the analysis of laminar, transitional and turbulent boundary layers; engine flowpath forces such as lift, thrust and moments; and LOX augmentation. To first order, a thermal balance can also be accomplished. Given the wall temperature, heat flux to the walls (calculated by the code) and the fuel injection temperature, the amount of fuel required to actively cool the vehicle is determined. This fuel flow rate is then used to predict the net thrust for a thermally balanced system. Particularly at high hypersonic flight Mach numbers, the increased fuel flow rate, which is generally above an equivalence ratio of one, can significantly increase thrust. The prediction of coolant fuel flow rate is further refined in the thermal management analysis as described in the corresponding section below.

SRGULL³ also has the capability to predict engine unstart, which is another unique feature of this cycle code. Figure 4 shows the isolator/ram-

jet/scramjet keel-line at the top. The arrows mark points where fuel can be injected. The four plots show the pressure distribution through the engine as a function of distance along the engine for various freestream Mach numbers where transition between pure ramjet and pure scramjet occurs. Note that in the top plot, fuel is being injected from the middle injectors at an equivalence ratio of .3 and from the downstream injectors at an equivalence ratio of .7. Also note the rise in pressure that occurs upstream of the $\phi=.3$ fuel injector. If more fuel were to be added at this fuel injector the pressure rise would be pushed farther and farther upstream, until at some point an engine unstart occurs. Note that as the freestream Mach number increases, the fuel can be injected farther upstream without causing the disturbance to move upstream.

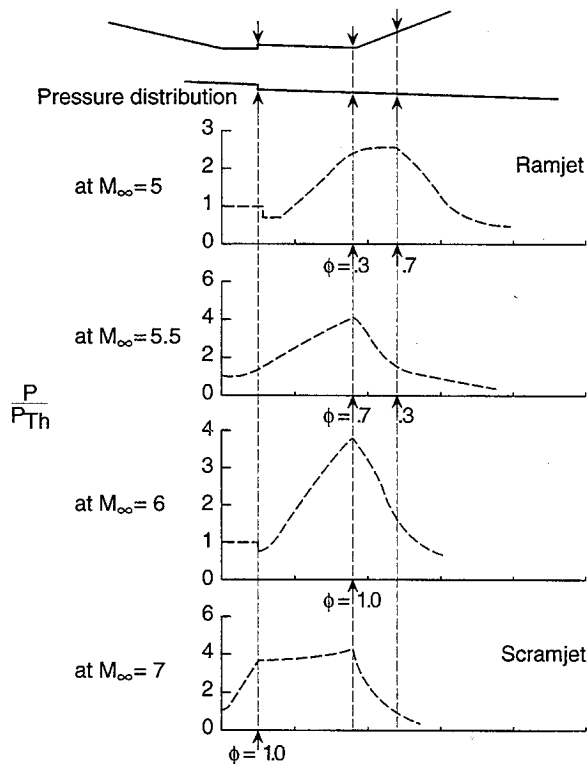


Figure 4. Ramjet to Scramjet Mode Transition with SRGULL³.

Figure 5 shows an experiment⁴ run in a Langley tunnel to study the effects of geometry changes on isolator flowfield characteristics. As shown, SRGULL accurately predicts the pressure disturbance in the isolator.

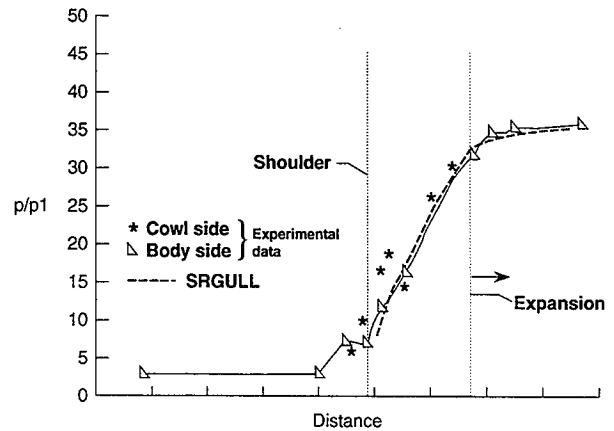


Figure 5. Isolator Model Comparison with Mach 4 Experimental Data⁴.

The Concept Demonstrator Engine (CDE) is currently being tested in the 8' diameter hypersonic tunnel at Langley. SRGULL has also accurately predicted the pressure distribution, including the pressure-rise magnitude and location, as compared to the experimental results.

Structures

Hypersonic vehicle structures are characterized by thermal loads that are as high as the mechanical loads. Again, due to the design sensitivities inherent in air-breathing hypersonic vehicles, it is necessary to accurately predict structural weight, as well as the aerothermoelastic flight response of the vehicle even at the conceptual/preliminary design level. Some of the codes used in the Systems Analysis Office include Pro/ENGINEER, for CAD (SAO is currently switching over to this code from another CAD package); MSC/NASTRAN, P3 PATRAN and RASNA for finite element analysis to predict element loads; and an in-house developed software package, ST-SIZE⁵, to perform panel failure mode analysis and panel sizing.

Figure 6 shows a schematic of how a structural panel is sized. Starting on the left-hand side of the figure, initial element stiffnesses, thermal coefficients, thermal and mechanical loads, and the finite element geometry are input into the finite element analysis code. Forces on each of the elements are then determined. Moving to the right of the figure, the element forces, material selections and panel and beam concepts are input to the ST-SIZE code. Here up to 30 failure mode analyses in

strength and 26 failure mode analyses in stability are performed, and the panel is sized to meet these failure modes. Given the new panel design, the element stiffnesses and thermal coefficients change and the FEA must recalculate the element forces. This iterative process continues until convergence is achieved. The net result is the minimum panel weight, which results from a maximally stressed panel that also meets each of the failure mode tests, all within the margin-of-safety.

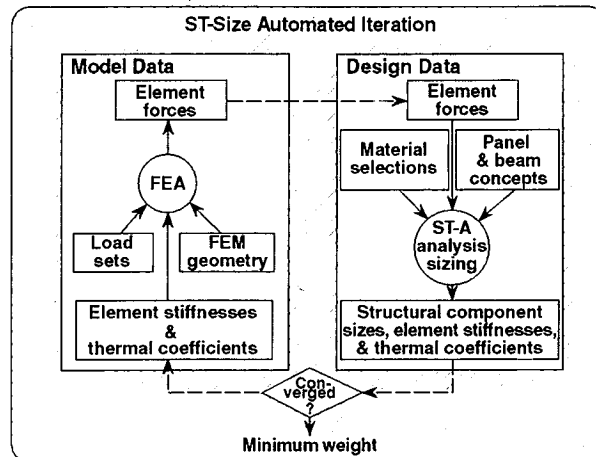


Figure 6. Structural Sizing Process.

In general, the structural panels of airbreathing hypersonic vehicles are unsymmetric—geometrically and/or thermally. As a result, traditional 2-D panel methods, which do not account for panel asymmetry, can predict inaccurate panel sizes. In contrast, an enhanced version of ST-SIZE, developed by SAO, models the panel asymmetry. This is accomplished by calculating the membrane bending coupling in the 2-D element. Thus a coarse global-sized mesh on a complete vehicle airframe and engine, modeled with 2-D elements as shown in Figure 7, will yield the same accuracy as a 3-D subscale-sized fine mesh, even for unsymmetric panels. In addition, panel concepts can be differentiated and selected based on their thermoelastic formulations, failure modes and materials, all within a preliminary/conceptual-level design.

Figure 8 compares the results of the traditional and enhanced ST-SIZE methods on the same global-sized 2-D element mesh for a Mach 10 vehicle. Using a traditional 2-D panel method with MSC/NASTRAN, the predicted thermal moment, for example, shows a 25% error as compared to that for a fine 3-D subscale-sized

mesh. The resulting panel weights are shown in the lower left-hand corner. Using the enhanced ST-SIZE code, with its correction terms for membrane-bending coupling input into MSC/NASTRAN, the thermal moment is only 1% different than that predicted by the fine 3-D subscale-sized mesh. The other element loads show similar error comparisons. The resulting panel weights for this calculation are shown in the lower right-hand corner. Note that the more accurately predicted weights are significantly different than those for the standard 2-D panel calculation. Thus with the enhanced ST-SIZE code it is possible to produce accurate structural weight predictions for airbreathing hypersonic vehicles in a rapid preliminary/conceptual level design. This method also lends itself to the loose-coupling of a FEA code with an aerothermal CFD code, enabling accurate predictions of a vehicle's aerothermoelastic response. This approach is currently being pursued by SAO.

• ENHANCED ST-SIZE ACCURATELY ANALYZES ALL PANEL CONCEPTS WITH 2-D FEA

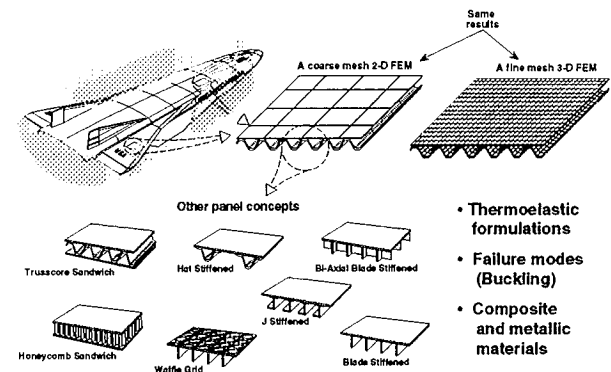


Figure 7. Enhanced ST-SIZE Method.

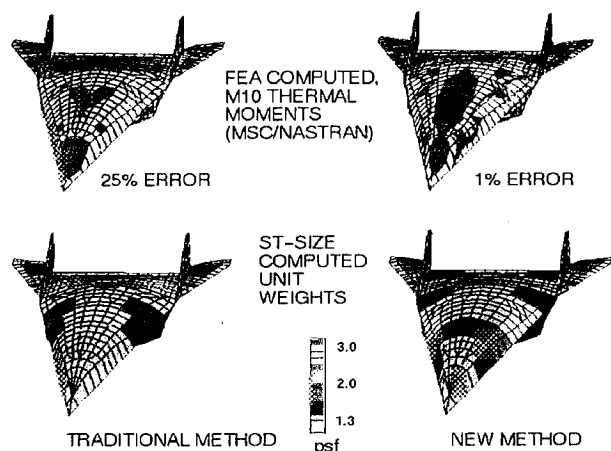


Figure 8. Traditional and Enhanced ST-SIZE Method Applied to a Hypersonic Vehicle⁶.

Thermal Management

The following discussion on the thermal protection system (TPS) is presented from an SSTO perspective, where the sizing of the TPS is dependent on the transient nature of the heat loading. For longer flight times, such as for cruise vehicles, alternative systems are considered. Figure 9 shows the under-surface of a Mach 12 vehicle color coded by the appropriate thermal protection thicknesses. It is necessary to accurately determine the thickness of the TPS to yield an accurate prediction of its weight, its volume for packaging considerations, and the heat flux through the surface such that fuel boil-off rates can be determined. The heat flux into each of the panels at several points along the trajectory is known from the results of aerothermal calculations, for example from a code like S/HABP. Figure 10 shows the cross-sectional view of one panel, or plug. Node 1 is the surface of the vehicle. The TPS is located between Node 1 and Node 7. Node 7 represents the bond between the TPS and the fuel tank insulation. Below Node 9 is the structural panel described in the above section.

The transient analysis proceeds, as illustrated in Figure 11, as follows. Knowing the heat flux at Node 1 from the aerothermal code at representative points along the trajectory, and an initial value of TPS thickness, a transient analysis is performed starting at the initial conditions on the ground and marching along the trajectory. If at some point along the trajectory, the temperature limit at Node 7 is exceeded, for example in this case the temperature limit is set at 400°F due to the temperature constraints imposed by the bonding material, then the analysis is stopped, the TPS thickness is increased, and the transient analysis begins again. This process continues until the appropriate TPS thickness is determined such that the temperature limit at Node 7 is not exceeded by the end of the trajectory. This analysis is repeated for each plug on the vehicle in an automated manner, where a typical vehicle is composed of over 1000 plugs.

Once the TPS thickness is known for each plug, the heat flux at Node 9 can be determined from the same transient analysis. Note that where fuel

tanks are adjacent to the vehicle skin, fuel is located just below Node 9. Knowing the integrated heat load into the fuel tank, the amount of fuel that must be boiled-off to maintain the tank pressure can be determined. The transient analysis also predicts whether or not active cooling, as opposed to TPS, is required for any portion of the vehicle surface. If at any point along the trajectory the temperature at Node 1 exceeds the material temperature limit of the TPS, for example 2500°F for FRICI-12 and 2300°F for TABI, or if the TPS thickness is greater than some predefined maximum allowable thickness, then active cooling is required at that location on the vehicle.

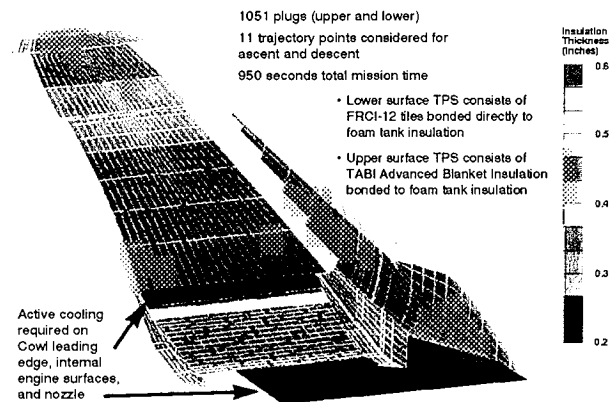


Figure 9. Mach 12 Staging X-34 Concept Thermal Protection System Thickness.

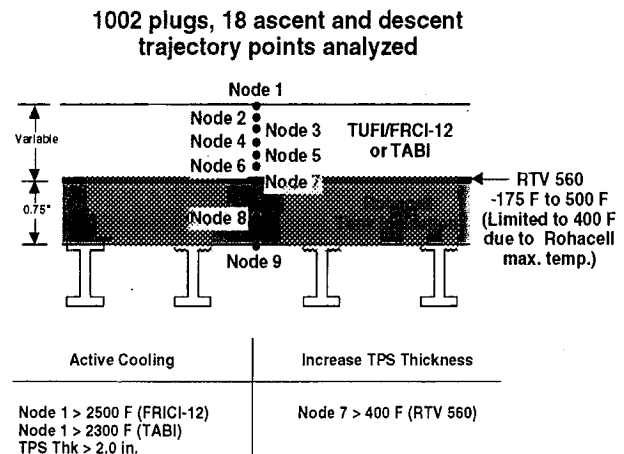


Figure 10. Access-to-Space SSTO Thermal Analysis Plug Model for Sizing TPS.

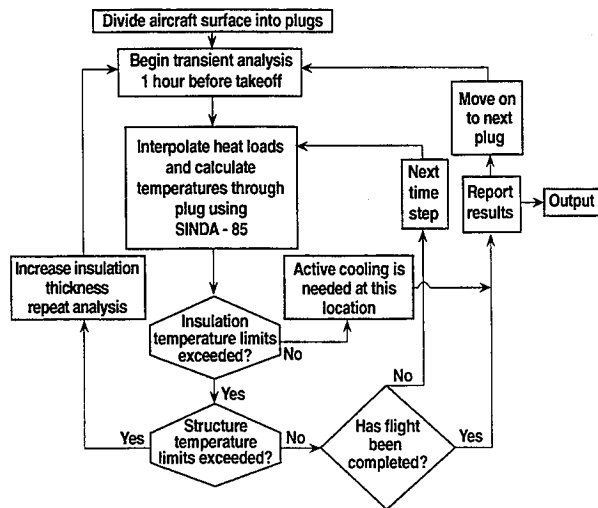


Figure 11. Automated Insulation Sizing.

Generally it is known a priori that the engine flowpath requires active cooling.⁷ The upper left-hand corner of Figure 12 shows an example of a coolant routing along the keel-line of the inlet, combustor and nozzle. Schematically, the active cooling network is shown in the middle of the figure. Inputs to the network analysis include the initial coolant system architecture, propulsion heat loads and flowpath geometry, coolant supply temperature, coolant and material properties, and the total pressure drop through the network, based on the pumping system and the desired fuel injection pressure. From this, the coolant mass flow, temperature and pressure distribution, along with the panel temperature distribution are determined. The panel temperatures are checked to ensure that they remain below the material temperature limits. Also, panel stresses are calculated. For example, if a hole is punctured in one of the cooling panel walls, the stress on that wall must not be high enough to cause the panel to “un-zip.” The network architecture and panel designs are modified until the overall cooling system weight and coolant flow rate are minimized, while meeting the above constraints. As noted in the propulsion section, the coolant flow rate and the fuel injection properties have a significant impact on the net propulsive thrust.

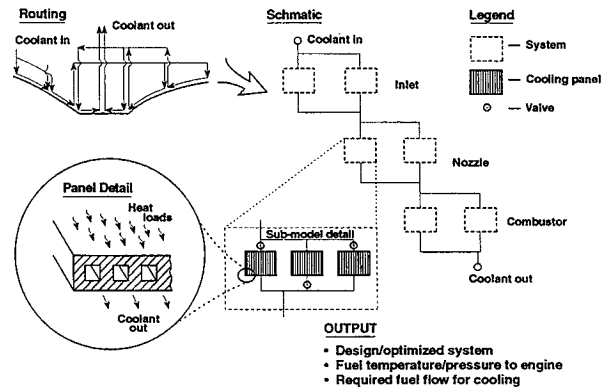


Figure 12. Cooling System Design/Analysis.

Discipline Interdependence

As previously mentioned, the areas of propulsion, structures and thermal management are unique to air-breathing hypersonic vehicle design. However the other disciplines are also critical to resolving a hypersonic vehicle. Figure 13 illustrates the complex interdependence among the disciplines in airbreathing hypersonic vehicle design. For example, aerodynamics inputs surface coordinates from geometry; interacts with propulsion in defining the entire vehicle configuration; outputs heat loads to the thermal management analysis; outputs forces and temperatures to structures; and iterates with the trajectory to yield flight conditions, forces and moments. As noted previously, not only are there a large number of couplings, but the sensitivities are high and the system is highly nonlinear. For these reasons, the disciplines are resolved to the high degree of accuracy described in the sections above. This detail is necessary just to capture the impact of the key factors in airbreathing hypersonic vehicle design.

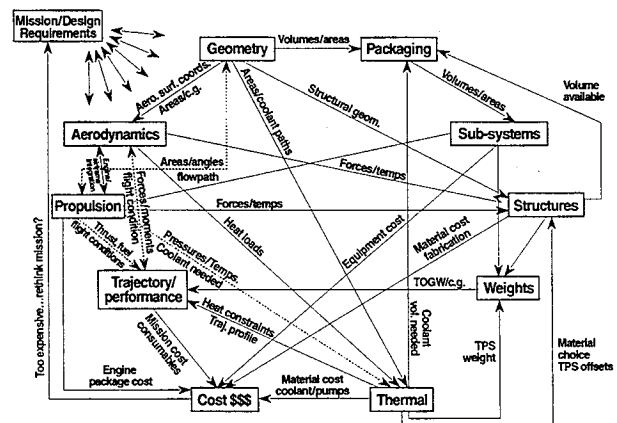


Figure 13. Discipline Interdependence.

HOLIST

HOLIST is SAO's working environment for the multidisciplinary design, analysis and optimization of airbreathing hypersonic vehicles. It is being developed by SAO in part through a contract with McDonnell Douglas.⁸ HOLIST will help to eliminate disconnects between disciplines, enable rapid multidisciplinary parametrics, allow the evaluation of design sensitivities, and will enable the optimization of the vehicle design and trajectory. Currently a parametric geometry model, Pro/ENGINEER, is being incorporated into HOLIST. This will enable the entire vehicle configuration to be represented with a number of specified design variables. HOLIST is constructed modularly such that when improvements are made in any of the discipline tools, or new tools are available, these can be easily incorporated. A user-friendly optimizer, Optdes-X, has been integrated into the environment. And the entire system is set up on workstations, complete with graphical user interfaces.

Figure 14 is a simplified flowchart illustrating how an optimization proceeds in HOLIST. In the upper left-hand corner, the process set-up includes defining the design variables, objective function, constraints and convergence criteria for a run. The baseline vehicle geometry and packaging, together with a definition of the mass and thermo properties, follow. Analysis of the configuration proceeds with aerodynamics, propulsion, etc. (Note that for simplification of the diagram several disciplines are not represented here, including structures and thermal management, for example.) The analysis can either be performed in real time, i.e. by running an analysis code, or a database can be accessed to obtain the discipline results. It is important to note that there is more than just one result being passed through this flowchart. In other words, since the vehicle will fly some trajectory, matrices of aerodynamic and propulsion data representing the coefficients of lift, drag, and thrust, and fuel flow rate, for example, at appropriate values of angle of attack and Mach number, must be passed through the loop. In addition, the vehicle geometry may be variable along a trajectory requiring multiple geometry definitions.

Once the analyses are completed the vehicle is

flowed as represented by the "Analyze Mission" box. From the mission results, the vehicle is sized. (It is also possible to define a scaling factor as a variable and use $|PFR-PFA| \leq .1$ as a constraint. This would eliminate the need to perform the sizing process in the extra loop.) At this point, if only a single vehicle analysis were required, the process would be complete. However, if it is desired to optimize the vehicle, the optimization process begins. Finite differences are used to calculate the derivatives of the objective function with respect to each of the design variables. Thus, for the perturbation of each design variable, one pass through the loop is made. Based on the derivative information, the vehicle design for the next iteration is defined. The objective function for the new design is evaluated, the derivatives at the new point in the design space are determined, and the process continues with the vehicle definition for the next iteration. Iterations continue until the convergence criteria and all the constraints are satisfied, yielding the optimum vehicle configuration.

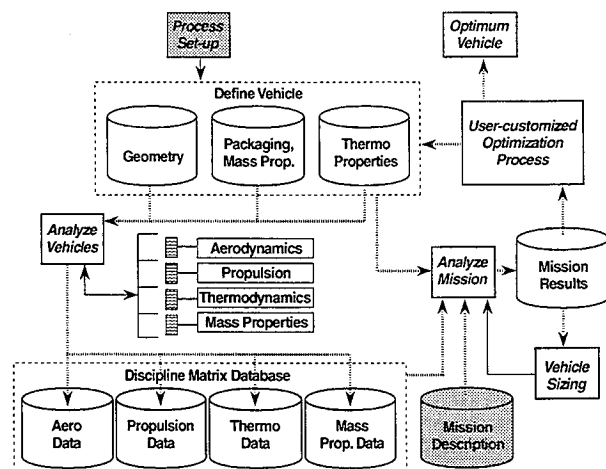


Figure 14. HOLIST Design Optimization.

Current Status and Demonstration Example

Currently, the basic synthesis system of HOLIST is in operation. The capabilities include aerodynamics and propulsion analysis for Mach 6 to 25, and vehicle performance methods such as energy-state, 3-DOF and GATMIS, which can perform various mission segments such as cruise, maneuvers, descent, etc. Also included are methods for packaging, mass property definition and vehicle

sizing. Optdes-X has been integrated into HOLIST and can be accessed by any of the disciplines individually, as well as from the system as a whole.

A demonstration of the optimization capability of HOLIST has been completed. A single-stage-to-orbit vehicle with the baseline configuration shown at the top of Figure 15 was selected. As illustrated in the lower left-hand, the design variables include the vehicle forebody angle, nozzle chordal angle, the planform exponent and scalar, and the upper surface maximum height. The vehicle length was held constant. With these five variables, the entire vehicle configuration is defined. The shape can be viewed on-screen, changing while the optimizer proceeds, if desired. The primary analyses represented in the demonstration are aerodynamics, propulsion, a simplified trajectory calculation, packaging and weights. The objective function was PFR-PFA for an unsized vehicle. Thus as PFR-PFA is minimized, the value will be driven from a positive value, for example, towards a negative value. Once the final vehicle is sized, the TOGW will also have been minimized. Note that in another approach, TOGW could be defined as the objective function with $|PFR-PFA| \leq .1$ as a constraint.

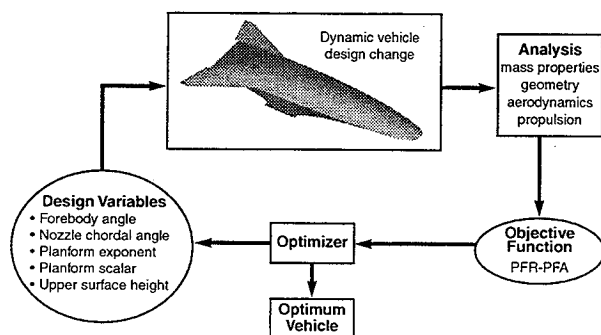


Figure 15. HOLIST Demo Problem.

Figure 16 shows the actual flowchart for the demo problem. At the top of the figure, the geometry is defined based on the five design variables. The geometry is transformed into a format that can be read by the propulsion and aero disciplines. Propulsion data is supplied from a database and aerodynamic data is obtained from the S/HABP code while it runs in real time. The trajectory iterates with the propulsion and aero data, finally resulting in a

completed trajectory and the value for the PFR. From the mass properties and packaging, PFA is determined. Thus the objective function, PFR-PFA is known. Using the differencing method described above the optimization proceeds with finite difference derivatives being determined for each of the five design variables, followed by a new vehicle geometry for the next iteration. In this example the number of iterations was predefined to be twenty, without the selection of a convergence criteria.

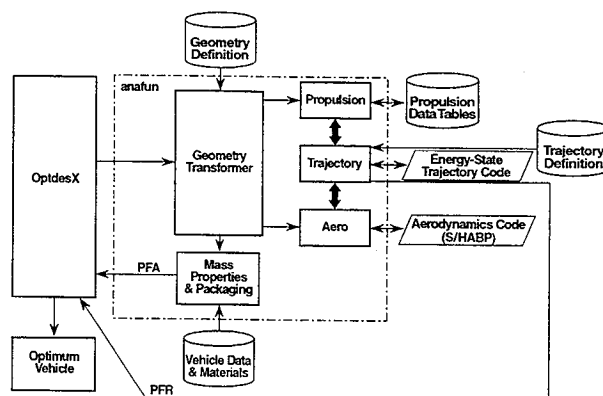


Figure 16. Demo Problem Flowchart.

The plot of TOGW and PFR-PFA versus iteration in Figure 17 illustrates the results of the optimization. The baseline configuration began with a TOGW of 606,000 lbs with a positive PFR-PFA, and thus an even heavier sized vehicle. After 20 iterations the final configuration had a TOGW of 389,000 lbs, with a negative PFR-PFA. Thus, if this configuration is sized for the mission, the final vehicle TOGW will actually be less than 389,000 lbs. A significant reduction in TOGW is achieved.

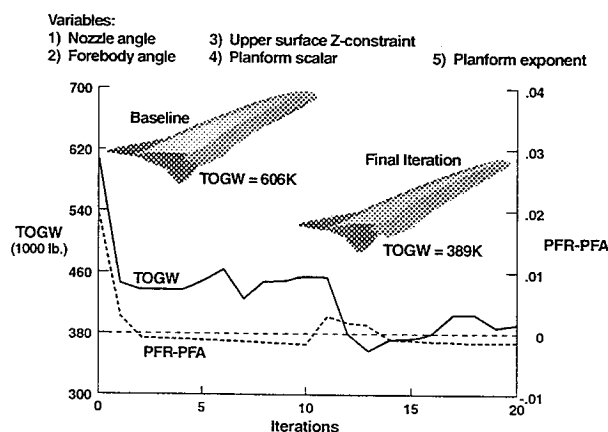


Figure 17. Results and Iteration History.

Plans for HOLIST

There are many upgrades to HOLIST that are currently in progress. As noted previously, Pro/ENGINEER is currently being integrated into HOLIST. This will enable a CAD geometry to be represented parametrically. Also, the propulsion and aerodynamic analysis are being expanded to include low speed (supersonic and subsonic) calculations. Structures is being added in two phases. In Phase I, simple g-loading will be used to determine bending moments and ST-SIZE will be used to estimate the weight of the external structure. The internal structure will be modeled parametrically. In Phase II, a simplified FEA using Pro-E mesh and ST-SIZE will be used to more accurately determine the weight of the external structure. Thermal management will also be added in two phases. In Phase I, the active cooling network analysis, described above, will be added. This will enable the prediction of cooling system weight, the fuel flow rate required for cooling the vehicle, and the fuel injection properties. In Phase II, the thermal protection system transient analysis will be added. This will allow the calculation of TPS weight and fuel tank boil-off. Other additions include an enhanced weight, packaging and vehicle sizing capability. Figure 18 illustrates the actual flowchart for completing an optimization in HOLIST, with the additional capabilities included. In contrast to the demo problem schematic in Figure 16, structures, thermal management and less restricted trajectory calculations are included.

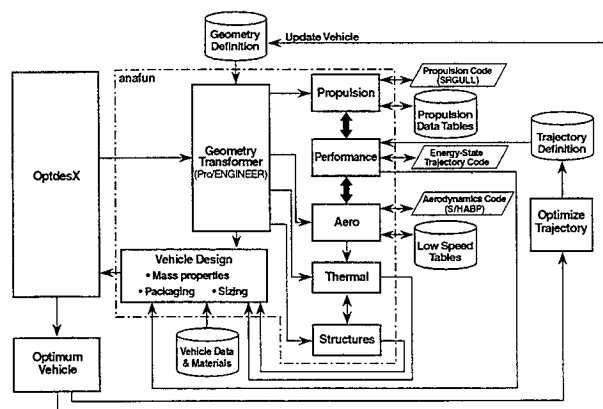


Figure 18. Planned HOLIST Design and Trajectory Optimization Flowchart.

Figure 18 also shows an additional loop on the optimization process, a trajectory optimization. Since the vehicle design and the trajectory are tightly coupled, it makes sense to optimize the two together in some manner. However, due to the high sensitivities and high accuracies necessary to resolve a trajectory, significant person-in-the-loop methods are currently required. Thus a method such as the Taguchi method or response surface method will be used to define a matrix of discrete trajectories. Vehicles will be optimized along each of the trajectories in the matrix, and the optimum vehicle/trajectory combination derived.

SUMMARY

Methods and tools are being developed to support the primary role of the Systems Analysis Office—to assess and design hypersonic airbreathing vehicles. Figure 19 illustrates some of the vehicles that are being investigated. In the Mach 4-8 range, there are cruise or accelerator-type vehicles that can be powered by either hydrogen or hydrocarbon fuel. For flight Mach numbers between Mach 8 and 18, vehicles can be either hydrogen or dual-fuel powered. They may serve as cruise configurations, or potentially as the first or second stage of a two-stage-to-orbit or three-stage-to-orbit vehicle, respectively. This class of vehicles is of current interest in the Hypersonic Vehicles Office. In particular, Mach 10 cruise and accelerator vehicles, and the possible synergy between the two, are being studied. SAO is also continuing to expand the matrix of single-stage-to-orbit vehicles.

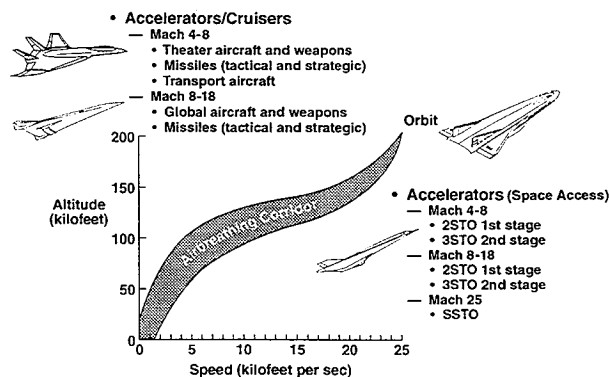


Figure 19. Air-Breathing Hypersonic Vehicle Applications and their Flight Envelopes.

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