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**SYSTEM CONTROLS CHALLENGES
OF HYPERSONIC COMBINED-CYCLE ENGINE
POWERED VEHICLES**

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INTRODUCTION

Hypersonic aircraft with air-breathing engines have been described as the most complex and challenging air/space vehicle designs ever attempted. This is particularly true for aircraft designed to accelerate to orbital velocities. The aerodynamic extremes of hypersonic flight will users in new parameters and requirements for effective vehicle control. The propulsion system for the National Aero-Space Plan will be an active factor in maintaining the aircraft on course.

Typically addressed are the difficulties with the aerodynamic vehicle design and development, materials limitations and propulsion performance. The propulsion control system requires equal concern. Far more important than merely a subset of propulsion performance, the propulsion control system resides at the crossroads of trajectory optimization, engine static performance and vehicle-engine configuration optimization. To date, solutions at these crossroads are multidisciplinary and generally lag behind the broader performance issues. Just how daunting these demands will be is suggested in this brief, somewhat simplified treatment of the behavioral characteristics of hypersonic aircraft and the issues associated with their air-breathing propulsion control system design.

CONSIDERING HYPERSONIC AIRBREATHING PROPULSION

The technology that is central to single-stage-to-orbit (SSTO) hypersonic aircraft is the ramjet-scamjet engine that propels the vehicle from roughly Mach 3 to orbital speeds. Characteristically, the vehicle is long, with a large fuselage volume for the fuel, and a relatively small wing area. Conventionally, the engines are mounted horizontally beneath the fuselage, where the high velocity and attitude of the vehicle, along with the shape of its forebody, compress air entering the engine inlets. Thus, the entire forebody is fundamentally part of the engine inlet. Equally important, the vehicle aftbody serves as a part of the engine nozzle.

Combustion performance in the engine is directly tied to the efficiency with which the forebody-engine inlet combination captures air. Forebody shocks and early boundary layer transition dissipate total energy, reducing efficiency. Buildup of thick laminar boundary/entropy layers along the forebody creates stratification of the entering air, reducing the total air capture and

thus affecting combustion performance.

Figure 1 illustrates aspects of ramjet and scramjet mode operation. In the upper illustration, the "start" and "unstart" conditions are depicted in the start condition, supersonic flow and the "normal shock" - where it slows to subsonic velocities - is established well into the engine; unstart describes a condition in which the normal shock moves forward and "stands" in front of the inlet. When this occurs, airflow into the engine is greatly reduced, high forces downstream of the shock cause severe pitching movements of the aircraft, and air spillage interferes with the other inlets. In the lower two illustrations, airflow in a ramjet configuration is compared with that in a scramjet. Ram mode of operation commonly begins at Mach 2 to Mach 3, while the transition to "scram" operation begins at about Mach 5 to Mach 7.

The inlet is considered "started" when supersonic flow is established all the way into it. "Unstart" refers to a condition in which a shock "structure" associated with a breakdown to subsonic flow moves out of the inlet and stands in front of the engine. When this occurs, airflow into the engine is substantially reduced, forebody pitching moments are greatly increased, and spilled air may interfere with adjacent inlets, giving rise to the so-called "zipper effect" in which all inlets are unstarted. The two principal factors affecting unstart are inlet disturbances (atmospheric changes, gusts, boundary layer separation, etc.) and back pressure from the combustor or engine geometry. Thus, mastery of disturbance effects and combustor back pressure can be especially important in controlling engine start/unstart conditions.

The ramjet engine differs from the scramjet engine in that the inlet air is decelerated to subsonic velocities inside the engine flow path before it is mixed with the fuel for combustion. This deceleration, of course, requires a normal shock or dynamic inside the engine with attendant high stagnation temperatures and pressures ahead of the engine combustion zone. The ram mode of operation commonly begins around Mach 2 to Mach 3. At about Mach 5 to Mach 7 the engines begin a transition to the scram mode of operation. In this mode, air remains at hypersonic velocities all the way through the engine (there is no normal shock), thus, its name, "scramjet," for *supersonic combustion ramjet*. Scramjet operation can continue up to altitudes in excess of 200,000 feet and at Mach numbers in excess of 16. The National Aero-Space Plane (NASP) design concepts all use hydrogen as the fuel, primarily because it is the only fuel which can burn fast enough to go to complete combustion inside the engine at very high air velocities.

Combustion efficiency is most dependent upon how well and how quickly the fuel mixes with the air as the combustion reaction goes to completion. Stratification of the air entering the combustor results in a vertical imbalance of air mass distribution in the combustor. Unless compensated for, this imbalance can result in an incomplete combustion of fuel in boundary layer regions. Matching fuel flow to inlet airflow is important to overall system efficiency in achieving the orbital mission objective. Fuel that goes unburned, either because of low air capture by the forebody/inlet or as a result of poor mixing in the combustor, does contribute to thrust -- but far less effectively.

Conservation of energy and momentum principles define the gross thrust produced by the engine, but the effectiveness with which the combustion products are expanded in the engine

nozzle and against the aftbody of the aircraft is important for maximizing the conversion to net thrust and minimizing vehicle drag. Inlet flow fluctuations, when uncompensated by engine design or engine control actions, will be reflected and/or amplified in the exhaust flows. Because the forebodies and aftbodies constitute an asymmetrical inlet-engine-nozzle combinations, they jointly affect the vehicle lift and moment balances, as well as the usual thrust-drag balance. The decoupling or compensating of outflow from inlet fluctuations is a major function of the engine controls.

High ram and scram operation produces high total temperature air that, even in the inlet before combustion, may greatly exceed the safe operating limits of the flow path materials. In fact, the hydrogen required to satisfy the cooling requirements of the engine and airframe actually exceeds that needed for thrust over much of the flight envelope. The thermal management problem is further exacerbated by the fact that the relative heat flux experienced by the various portions of the aircraft and engine can change significantly and non-uniformly due to the higher air velocities and shifting shock-zone locations over the SSTO trajectory. Static design practice requires that each coolant circuit be designed to provide flow to accommodate the peak heat flux at that location. Unfortunately, at all other points of the flight envelope that location would then be overcooled. In regions of the SSTO trajectory where the total coolant demand by the vehicle exceeds thrust demands, excess fuel from overcooling of low heat flux regions in the engine is burned, further lowering engine performance. For this reason, certain features may be included in the engine/vehicle design to actively balance (control) the flow of coolant to various parts of the vehicle during flight in order to maintain thermal margins and minimize the use of excess hydrogen for cooling.

Aircraft and engine inlet aerodynamicists and the combustor designers, therefore, must engage in refined and systematic trade studies to optimize the integrated configuration with a "best" trajectory which will satisfy the mission requirements. However, a perplexing situation has developed with the selected X-30 SSTO configuration. The same air providing the bulk of the aerodynamic lift and drag to the vehicle is also consumed by the engines in order to produce thrust, causing a degree of interaction heretofore unprecedented. An added complication is the three-dimensional nature of the flow under the forebody of the example aircraft. Figure 2 compares this overall airflow situation for a typical subsonic aircraft and a lifting-body type hypersonic vehicle. Considered here, the local angle of attack and sideslip of the air at the entrance of the center engines is *not* the same as that at the inlet to the outer engines.

ENGINE/VEHICLE INTERACTIONS

For example, consider the engine-vehicle interactions from the aircraft flight control designer's point of view. With an underbody configuration, the engine provides a significant lift component from both the inlet and exhaust streams, which can be modified by changes in throttle setting and Mach number. The vehicle trim is consequently affected and the several stability derivatives (e.g., pitch moment) are changed as well. With a nozzle that comprises external expansion along the aftbody, there is an effective thrust vector angle. This angle must be trimmed out by the aircraft controls, since it will add an increment in pitch moment with speed change.

Now, consider these same interactions from the point of view of the engine controls designer.

The engine inlet will be continuously subjected to perturbations at nominal performance. These perturbations occur in free-stream air density (pockets of 50 percent variations possible at higher altitudes) and in angles of attack and sideslip resulting from aircraft maneuvers over its flight trajectory. Involved are flight control system adjustments for shifting center of gravity, fuel slosh and even aircraft bending modes. With air-residence time in the engine on the order of 1 to 10 milliseconds and combustion rates measured in 10th of a millisecond, bending modes up to several hertz may be considered low frequency to the engine. These perturbations affect the quantity of air captured by the engine inlet.

Additionally, as shown in Figure 3, these effects will in all likelihood be non-uniform across the array of engines, further lowering engine performance. For this reason, certain features may be included in the engine-vehicle design to actively balance (control) the flow of coolant to various parts of the vehicle during flight in order to maintain thermal margins and minimize the use of excess hydrogen for cooling. For example, consider that the engine/vehicle inlet flow fluctuations will perturb the internal flows and shock structures of each engine uniquely. Unchecked, these effects may cause incomplete combustion, fluctuations in thrust and exhaust flows, unstarted inlets and thermal imbalances. These effects will also carry through to the aftbody drag and lift vectors, potentially adding to the lift-moment and thrust-drag imbalances. Depending on the vehicle configuration and the specific nature of these interactions, the open loop engine response may amplify or attenuate the perturbations seen by the aircraft. As an example, consider an aircraft perturbation yaw angle to the right, as reflected in Figure 3. Airflow to the left engines is relatively undisturbed, but that to the right engines is greatly disturbed by forebody crossflow. The left engines capture more air, increasing thrust, while the right engines sustain reduced thrust - thus amplifying the condition causing the yawing effect in the first place.

Figure 4 presents the general aerodynamics and propulsive flow conditions affecting the pitch-plane attitude control and thrust/drag forces. In combination, the forebody and aftbody constitute an asymmetrical inlet-engine-nozzle combination. Thus, they jointly affect vehicle lift and moment balances, as well as the usual thrust-drag balance.

Clearly then, guidance and control of an SSTO vehicle is an encounter of significant complexity. Engine controls will include the valves and effectors manipulating the flows and geometry of the engine, the controlling logic embodied in the real-time software, the implementing controllers/computers, and the suite of instruments feeding back control parameters from the engine. These controls must be compatible with and interact with the vehicle management system to configure the engines for delivery of the commanded thrust while imparting the desired lifts and moments to the aircraft - including correction of imbalances across the engine array. The controls must also maximize engine performance by controlling and maintaining proper engine fuel-air-equivalence ratios. And finally, they must ensure engine and vehicle safety by controlling coolant flows, providing smooth mode transitions, minimizing unstart/restart transients, effectively monitoring engine condition and stating parameters for signs of degradation, and decoupling/desensitizing outlet flows from inlet fluctuations.

Development of candidate control system concepts must, therefore, include definition of the control features to be incorporated in the physical engine, along with analysis of performance

requirements for all elements of the control system, coordinated total aircraft-engine controls integration and logical interface structure definition. Driving the development planning will be the key issues of vehicle weight, various performance phenomenology, vehicle integration and, finally, control performance assessment.

The aircraft-engine description presented here implies an engine concept with a large number of control effectors and control measurements. The speed of the physical processes drives up the computational speed requirements. In parallel, system requirements for safety, reliability and supportability drive the redundancy requirements and the complexity of the engine monitoring system. Accordingly, the various measures of control system complexity and difficulty (throughput, memory, source lines of code, environment, etc.) in the hypersonic air-breathing engines generally range from 2 to 10 times that for the Space Shuttle Main Engine, as an example. As a result, substantial effort is mandated to define the minimum necessary control requirements and to bring the most advanced, ultra-lightweight control system technologies to bear on the implementation concept. Included is everything from lightweight composite materials in structural applications to very high-speed integrated circuits (VHSIC) and very large-scale integrated circuit (VLSIC) technologies in electronics.

STATIC CONTROL ACCURACY

One aspect of this is the effect of static control accuracy. Ignoring the dynamics of perturbations response, this factor affects how accurately key engine performance parameters can be measured in relation to a given mission. The SSTO mission has two such parameters. The first is specific impulse, I_{sp} - the thrust divided by fuel flow rate. Higher I_{sp} means lower fuel flow rate for a given thrust, or less fuel consumed or a smaller vehicle. The second parameter is closely related: engine fuel to air-equivalence ratio, stated as θ . This is the ratio of actual fuel flow rate to that required for *stoichiometric combustion* -- where both oxygen and hydrogen are completely consumed in the combustor. This maximum of engine performance is expressed as $\theta = 1$. Thus, when coolant demands exceed thrust demands on fuel flow, θ is greater than 1 and I_{sp} is reduced as some fuel leaves unburned. At $\theta < 1$, some are unburned, combustor temperatures are generally lower and I_{sp} is reduced.

Fuel flow is simple to measure with a reasonably high degree of accuracy. To get I_{sp} , thrust is measured. To get θ , airflow rate is measured through the flow path. Systems to measure these parameters generally involve a collection of intrusive and/or non-intrusive sensor, signal and data processing circuitry and calculation algorithms, anchored by test data or CFD. The hostile environment of the flow path limits the available sensor technology, and the lack of test data over the flight envelope adds uncertainty to the calculation algorithms. Nevertheless, given the elements of the measurement systems, one can statistically determine the uncertainty that can be expected in measured engine performance over the SSTO trajectory.

If the control system is trying to hold an θ of 1 and the θ measurement says that the engine is operating at an θ of 1, *but the real θ is 1.1*, then the vehicle designer either must have compensated for the resulting reduction in I_{sp} with additional fuel or accepted the risk of not achieving orbit. Control feasibility, therefore, depends on a favorable uncertainty analysis, and performance accounting will eventually require consideration of these uncertainties.

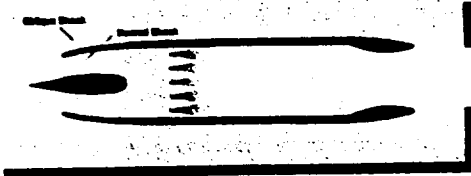
CONCLUSIONS

The challenge, then, is formidable. A ramjet-scrumjet engine and hypersonic vehicle combination will be a total systems integration, characterized by sensitive and strong interactions between nearly every key variable - from the forebody motions associated with aircraft bending to engine exhaust flows on the aftbody of the aircraft. Multiple disciplines from aerothermodynamics to heat transfer to electronic software design will be employed to derive a control system concept that is capable of delivering commanded thrust while optimizing engine performance and ensuring engine-vehicle safety.

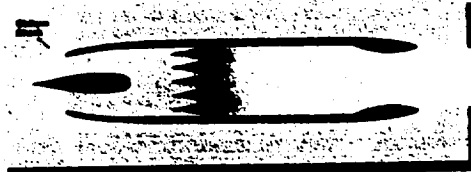
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Start Condition



Unstart Condition



Typical Ramjet $V_1 > V_2 < \text{Mach } 1$



Typical Scramjet $V_1 > V_2 > \text{Mach } 1$

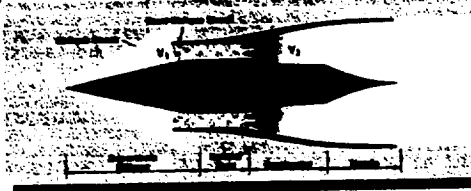


FIGURE 1. - AIRFLOW CONDITIONS FOR ENGINE RAMJET AND SCRAMJET OPERATING MODES.

**Airflow Thrust and Lift Blend to Unprecedented Levels
Propulsion-Aerodynamics Interactions Are More Challenging To Control**

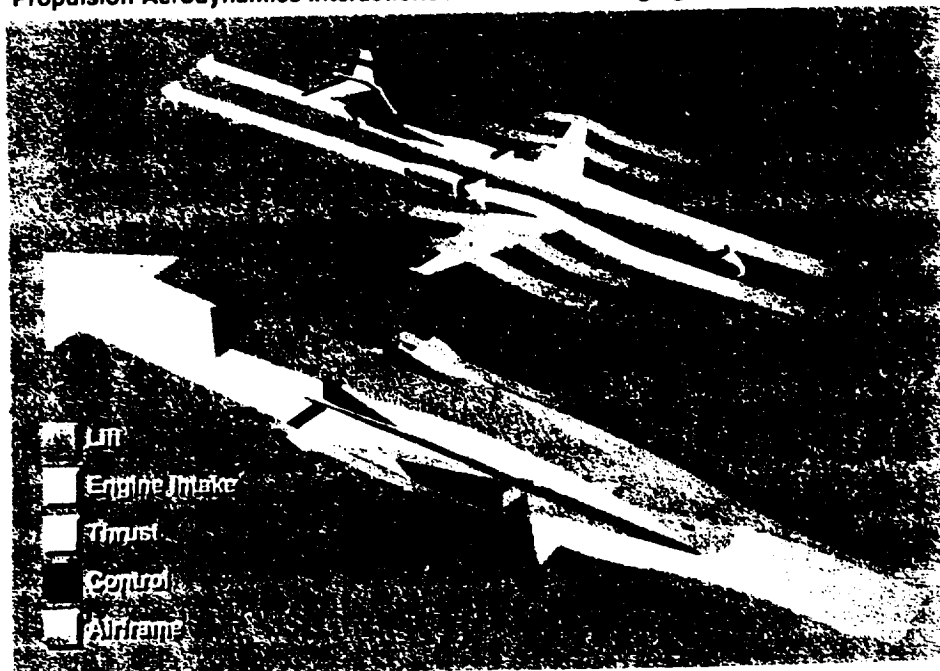


FIGURE 2. - AIRFLOW COMPARISON FOR TWO VEHICLES.

Perturbed Flow Condition

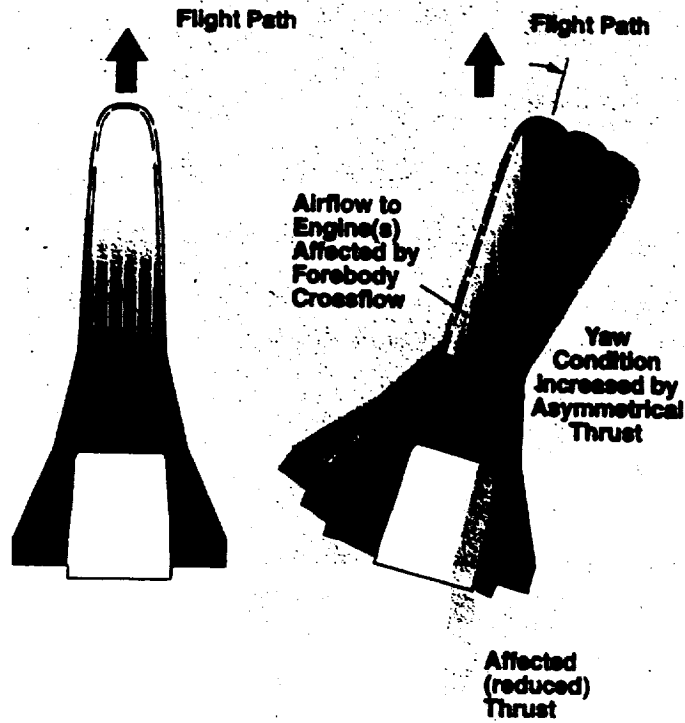


FIGURE 3. - VEHICLE ATTITUDE AND ENGINE OPERATION INTERACTIONS.

Engine-Vehicle Interactions

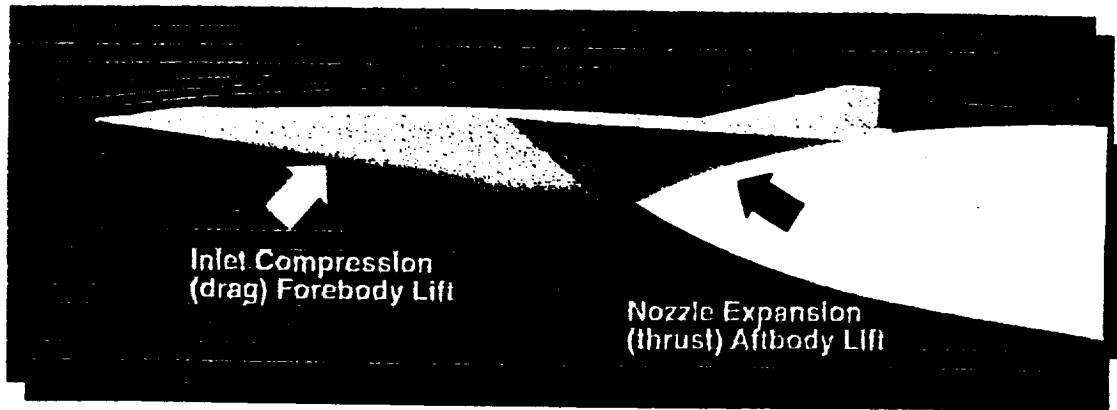


FIGURE 4. - ENGINE-VEHICLE INTERACTIONS.