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Hypersonic Vehicle Propulsion System Control Model Development Roadmap and Activities

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Summary

The NASA Fundamental Aeronautics Program Hypersonic project is directed towards fundamental research for two classes of hypersonic vehicles: highly reliable reusable launch systems (HRRLSs) and high-mass Mars entry systems (HMMESs). The objective of the hypersonic guidance, navigation, and control (GN&C) discipline team is to develop advanced guidance and control algorithms to enable efficient and effective operation of these challenging vehicles. The ongoing work at the NASA Glenn Research Center supports the hypersonic GN&C effort in developing tools to aid the design of advanced control algorithms that specifically address the propulsion system of the HRRLS-class vehicles. These tools are being developed in conjunction with complementary research and development activities in hypersonic propulsion at Glenn and elsewhere. This report focuses on obtaining control-relevant dynamic models of an HRRLS-type hypersonic vehicle propulsion system.

I. Introduction

The overall modeling goal for the NASA Glenn Research Center hypersonic guidance, navigation, and control (GN&C) team is to develop tools and to streamline procedures for generating control-relevant, simplified, dynamic models (hereto referred to as control models) for air-breathing hypersonic vehicle propulsion systems that incorporate the following subsystems: forebody compression surface, inlet, isolator, combustor, and aft expansion nozzle. The combustion process in the combustor may be subsonic (ramjet), supersonic (scramjet), or capable of transitioning from subsonic to supersonic combustion and back (dual-mode combustor). The control model may be iterative, map-driven, or nonlinear; however, the model should be linearizable about desired operating points, and it must include all important dynamical elements. Ideally, the propulsion system control model will be MATLAB-based (The MathWorks, Inc.) to facilitate control system development. The resulting control models, derived from the use of the developed tools and procedures, will be applicable to propulsion control studies and GN&C flight-system simulations for the vision hypersonic vehicle.

The vision hypersonic vehicle illustrated in Figure 1 is a two-stage-to-orbit (TSTO) vehicle, supporting highly reliable reusable launch system (HRRLS) class missions (Ref. 1). A viable propulsion system for the vision vehicle could be one that incorporates a turbojet engine for low-speed operation, a dual-mode combustor for high-speed operation, and a rocket-based propulsion system for ascent to space. The first stage of the vehicle will employ a low-speed air-breathing propulsion system to enable horizontal takeoff and landing. The first stage will also have a high-speed air-breathing propulsion system to accelerate the vehicle to hypersonic velocities. Second-stage access to space may be attained with a rocket-based propulsion system.

This report describes the air-breathing propulsion control model development roadmap and current activities at Glenn supporting hypersonic GN&C. The overall propulsion system modeling roadmap is a multistep process, and the task plan described in this report addresses only the first step—short-term modeling goals. The report begins with the short-term modeling goal. Next, a general description of the desired control model is presented along with heritage simulations that are available to varying degrees. These heritage simulations may be available in electronic format (FORTRAN, computational fluid

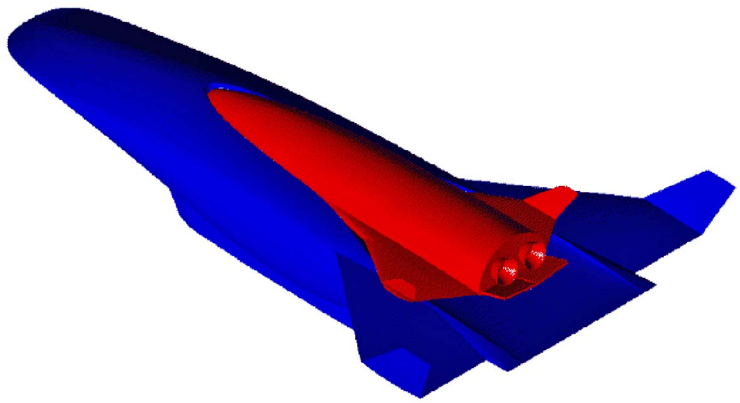

Figure 1.—Hypersonic program two-stage-to-orbit (TSTO) vision vehicle with a turbine-based combined cycle (TBCC) propulsion system.

dynamics (CFD), MATLAB, etc.) or in published papers. Finally, a roadmap outlining a possible avenue towards realizing the propulsion control model is presented.

II. Short-Term Modeling Goal

The air-breathing propulsion system for the hypersonic vision vehicle will be expected to accelerate from horizontal takeoff through subsonic, transonic, supersonic, and into hypersonic velocities. To efficiently and effectively span this range, the employed propulsion system may consist of turbine engines, afterburners, ramjets, scramjets, dual-mode (ramjet and scramjet) combustors, rockets, or a combination of these (multicycle). Ferri (Ref. 2) presents the following operating speed regimes for each propulsion system cycle: The turbine engine range is from Mach 0 up to Mach 5 or 6. The subsonic burning ramjet Mach window is from approximately Mach 1.3 and extends up to Mach 6 or as high as Mach 8. The window for the supersonic combustion scramjets can be as low as Mach 5 to 6 and faster.

Selection of an optimum propulsion cycle is mission-dependent. Two factors of interest for HRRLS-type vehicles are range and accelerative ability. Both of these performance factors are directly related to specific impulse (I_{sp}), which is the thrust produced per unit rate of fuel consumption (Ref. 3). As per Billig's (Ref. 3) specific impulse versus flight Mach number illustration, reproduced in Figure 2 for the abovementioned propulsion systems, the turbojet is most efficient for speeds up to Mach 2.5. Afterburning turbojets have a significantly lower I_{sp} than that of turbojets and fall below the ramjet I_{sp} beyond Mach 2. As velocity increases beyond Mach 2.5, the ramjet cycle becomes the optimum choice. The I_{sp} of the scramjet surpasses the ramjet at speeds above Mach 5. However, Billig's illustration also reveals that the turbojet and the afterburning turbojet have higher I_{sp} values than that of dual-mode combustors for speeds below Mach 3. Given the limited performance ranges of these propulsion systems, to span the desired flight range, the vehicle's propulsion system must employ a multicycle system: a turbojet or afterburning turbojet for low Mach number operation, a ramjet for high supersonic velocity, and a scramjet for hypersonic velocity.

The vehicle propulsion system also may consist of a turbojet or afterburning turbojet and a dual-mode combustor. These two engine combinations are referred to as turbine-based combined cycle (TBCC) propulsion systems. Employing a turbine engine in the vision vehicle's propulsion system is desirable because turbine engines are much more efficient at low speed than rocket systems. Furthermore, ramjets, scramjets, and dual-mode combustors produce no thrust at subsonic speeds (Ref. 4). To efficiently accelerate above Mach 3, the HRRLS will need either a combination of ramjet and scramjet combustors or a dual-mode combustor. To accelerate a vehicle from ground takeoff to hypersonic velocities, the propulsion system must be able to transition safely from one engine system to another on demand.

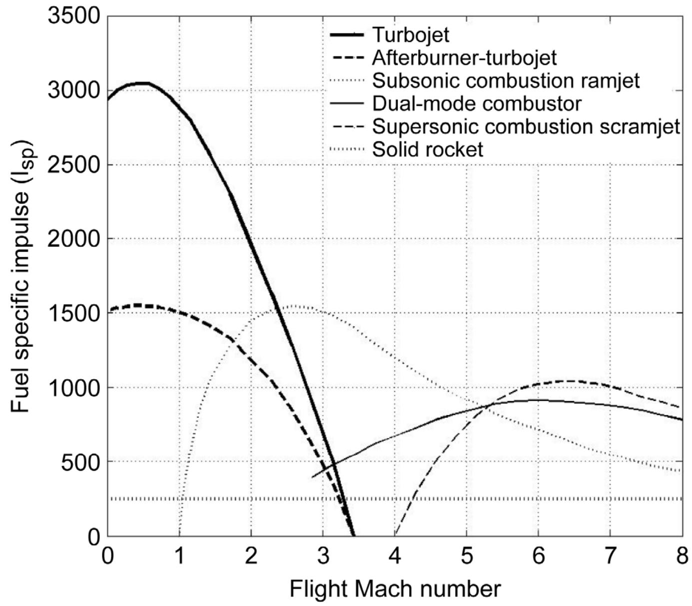

Figure 2.—Fuel specific impulse (I_{sp}) for various propulsion systems (Ref. 3).

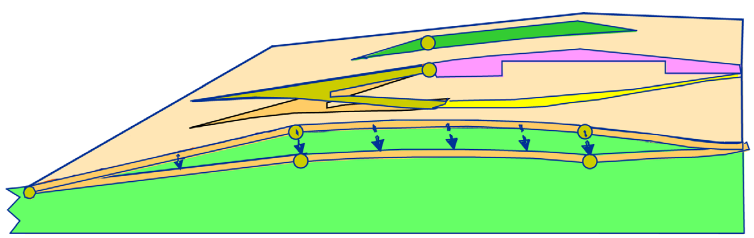

Figure 3.—Large-scale inlet to study mode transition (L–IMX).

Conceptual designs for TBCC propulsion systems typically employ a dual flow-path system: a low-speed flow path with a turbine engine and a high-speed flow path with a ramjet, scramjet, or dual-mode combustor. The low-speed flow path incorporates variable inlet cowl and ramp geometry, multiple bleed regions, and bypass-flow valves suitable for controlling airflow to a turbine engine. The high-speed flow path, designed with minimal variable geometry, applies airflow to a ramjet, scramjet, or a dual-mode combustor system (Ref. 5). The process of transitioning airflow from one flow path to the other is referred to as mode transition. For meeting the capability of the vision hypersonic vehicle to accelerate from horizontal takeoff to hypersonic velocities, with air-breathing propulsion systems, the hypersonic program's propulsion discipline team will be testing a large-scale inlet to study mode transition (L–IMX) in the Glenn 10-by 10-Foot Supersonic Wind Tunnel. The L–IMX, illustrated inverted in Figure 3, is a dual flow-path inlet model. The inlet illustrated in Figure 3 is inverted as it is typically described by Sanders (Ref. 6) in the aerodynamic design document for this inlet. The L–IMX upper airflow path (lower flow path in Fig. 3) with variable ramp geometry, is designed to support turbine-based low-speed air-breathing propulsion. The L–IMX lower airflow path (upper flow path in Fig. 3) is designed to support a high-speed dual-mode combustor for high supersonic and hypersonic velocities. These inlet tests are designed to demonstrate safe and effective mode transition.

To complement the L–IMX hardware tests in the wind tunnel facilities and to support advanced propulsion system control research, analysis and control computational dynamic models are desired (Ref. 7). Analysis and control dynamic models must be designed, developed, and validated with ground tests. The short-term objective of the Hypersonic GN&C discipline team is to develop analysis and control models that adequately represent the L–IMX mode-transition dynamics in the Glenn 10×10 wind tunnel. Initially, these models will be used to study various mode-transition schedules. The test-validated models will also support developing closed-loop control algorithms, capable of improving mode transition with weighted optimization on performance, stability, and disturbance rejection. The control model will include the following basic hypersonic vehicle propulsion system components: forebody compression surface, inlet, and isolator. These tools and procedures will be assets for developing flight propulsion control models for hypersonic vehicles.

III. Analysis and Control Model Development

This section begins with a brief description of the L–IMX control model's desired elements. Next, available simulations are presented. The term "available" includes a broad span of sources ranging from publications of equations, tables, and charts for compressible flow (Ref. 8) to codes such as the large perturbation inlet model (LAPIN) (Refs. 9 to 12) and SRGULL (Ref. 13) that are available in computer-executable files. Included below are brief descriptions of the simulation codes that are considered to be of interest. The brief descriptions include some accounting of the simulation capabilities. The simulations available in electronic form, such as LAPIN and SRGULL, are presented first. Next, brief descriptions of simulations that are available only in open literature papers are presented.

A. Desired L–IMX Control Model

The simplified computational simulation development activity for the L–IMX will result in a code that timely captures pertinent dynamics for stability and efficiency analysis with respect to input parameter variations. The applicable dynamics (model feedback) will be a sensitivity study against the model input parameters (control effectors). To aid controller design and development activities, it is desirable to have the simulation be MATLAB- or Simulink-based (The MathWorks, Inc.). For the L–IMX hardware, the simplified model-control effectors and feedback signals are as follows:

(1) Control effectors
- a. Low-speed path cowl position
- b. Low-speed path ramp position
- c. Low-speed path bleed flow
- d. Low-speed path bypass valves
- e. Low-speed path back flow rate
- f. High-speed cowl position
- g. High-speed path back flow rate
- h. Freestream conditions

(2) Feedback
- a. Low-speed path normal shock position
- b. Low-speed path axial pressure distribution
- c. Low-speed path axial temperature distribution
- d. High-speed path axial pressure distribution
- e. High-speed path axial temperature distribution

B. Available Simulation Codes

The software codes SRGULL and LAPIN have been used to model propulsion system components that are suitable for hypersonic vehicles. The SRGULL code evaluates the forebody compression surface, inlet, isolator, ramjet and scramjet combustor, and aft nozzle for a hypersonic vehicle. The LAPIN code is focused on dynamic inlet modeling. These two codes are the only known codes that can be readily employed as source code or executables. A suitable and available code that may be useful for incorporating the propulsion simulation into an overall hypersonic vehicle is the Air Force Research Laboratory (AFRL) 3-degree-of-freedom flexible hypersonic dynamic vehicle model (Ref. 14).

The SRGULL code (a hybrid of codes named SCRAM and SEAGULL), is a hypersonic propulsion modeling and analysis code that was developed by combining a combustor program and a flow-field analysis program (Ref. 13). It was developed by researchers from NASA Langley Research Center, S.Z. Pinckney, S.M. Ferlemann, and G. Mills (Vigyan, Inc.). It consists of FORTRAN code that reads multiple text documents in FORTRAN card-reader format, which describe the design parameters of the proposed propulsion system, environment, and boundary conditions. It creates output text files that are suitable for postprocessing activities. This code computes the steady-state operating point for a hypersonic propulsion system from tip-to-tail (i.e., forebody compression surface, inlet, isolator, ramjet and scramjet combustor, and nozzle). It can also be used to evaluate the offdesign steady-state operating points. SRGULL is an Agency-accepted code with success deeply rooted in the Hyper X–43 program (Ref. 15). The SRGULL code simulation results are fast and could be run as an executable on a standalone computer.

Efforts are underway at Langley to integrate the SRGULL executable with the TechnoSoft adaptive modeling language (AML) (TechnoSoft, Inc.) for use with NASA's multidisciplinary analysis and optimization exercises. AML is an object-oriented, knowledge-based engineering modeling framework. AML provides a geometry-centric environment with support for solid, surface, and wire-frame modeling capabilities (Ref. 16). Essentially, the necessary SRGULL input text documents are automatically generated and FORTRAN-formatted within AML. Then, the SRGULL executable is called to solve the simulation with respect to the input text documents. SRGULL results are also saved within text documents. Finally, AML filters the SRGULL output documents and proceeds with an optimization routine.

LAPIN was developed by M.O. Varner, et al. (Sverdrup Technology, Inc.), and G.L. Cole (Glenn) (Refs. 9 to 12). Using FORTRAN code, it reads a text document in FORTRAN card-reader format that describes the design parameters of the proposed inlet system, environment, and boundary conditions, and creates an output text file that is suitable for postprocessing activities. This code is used for simulation analysis of supersonic mixed-compression inlets with large flow-field perturbations. It uses a quasi-one-dimensional, inviscid, unsteady formulation, with time-dependent equations of motion that include engineering models of unstart and restart, bleed, bypass, and geometry effects. LAPIN is a valuable resource because it is a dynamic simulation for supersonic inlets, the simulation results are fast, it can be run as an executable on a standalone computer, and the source code is available to enable code modifications.

The AFRL has developed a simulation that is considered state-of-the-art for hypersonic vehicle flight dynamics (Ref. 14). This model addresses some of the limiting assumptions that were inherent in an earlier comprehensive analytical model for hypersonic vehicles—the Chavez and Schmidt model (Ref. 17). The Bolender simulation calculates a time-varying oblique shock structure considering forebody flexibility. Therefore, the propulsion system mass-capture and thrust will be time-varying with the flexible vehicle structure. These models capture the overall hypersonic vehicle perspective; we are interested in a model that focuses on the dynamics of a variable geometry inlet, combustor, and a variable geometry nozzle. Nevertheless, this model provides an interesting platform to test propulsion systems and propulsion system controllers while considering the overall hypersonic vehicle flight dynamics.

The generic hypersonic aerodynamic model example (GHAME) represents a hypothetical aircraft and is intended to provide simulation models for trajectory study and optimization and for control system design (Ref. 18). The model includes turbojet, ramjet, and scramjet engines. The generic engine model assumes the engine will automatically change from one engine cycle to the next and that a variable geometry inlet is used. The GHAME paper also explains that the engine model uses only angle-of-attack, Mach number, and pilot throttle commands to determine thrust and was designed only to be sufficient to operate the simulation. The mission to be performed by GHAME is that of a single-stage-to-orbit.

Therefore, this vehicle would takeoff horizontally from a runway, accelerate to orbital velocity, and insert into orbit. This code is referenced here only because it is another example of previous work in the area of hypersonic vehicle propulsion system simulation.

C. Open Literature Simulations

This section attempts to identify all major published efforts to simulate supersonic or hypersonic inlets. The efforts listed pertain to publications that give either source code or first-principles equations that can be harnessed to create a simulation.

National Advisory Committee for Aeronautics (NACA) reports are excellent sources of equations that describe compressible flow (Refs. 8, 19, and 20). The equations from these reports have been compiled into a convenient Compressible Flow MATLAB Toolbox (Ref. 21). This toolbox solves linear and nonlinear classical compressible flow relations for analysis of one-dimensional steady flow with constant entropy, friction, heat transfer, and shock discontinuities. These NACA reports and the Compressible Flow MATLAB Toolbox can be used to map the shock structure and flow-field conditions on the forebody compression surface of the hypersonic vehicle. Figure 4 illustrates the L–IMX low-speed flow-path shock structure using this toolbox. The MATLAB script files used to generate the illustration in Figure 4 was designed to read an Excel (Microsoft, Inc.) spreadsheet to obtain freestream condition, ramp geometry, and cowl geometry. The illustration in Figure 4 is representative of the L–IMX in the 10×10 wind tunnel with a 0° angle of attack and a 6.5° compression angle at the bow of the vehicle. The Compressible Flow Toolbox is used to define the oblique shocks, Prandtl-Meyer expansion shocks, reflection shocks, and flow conditions downstream from each shock. Not illustrated in Figure 4 are the following numerous oblique and Prandtl-Meyer expansion shocks—shocks that originate within the inlet on the cowl surface because the contour of the cowl, shocks that originate within the inlet on the ramp surface because of the contour of the ramp, and reflections off the cowl and ramp from the previous two sources. One interesting note on this inlet geometry and freestream condition is that the oblique shocks originating from forebody compression surface do not intersect with the cowl lip. The gap between the oblique shock and the cowl lip represents spilled compressed air that will not be contributing to thrust production.

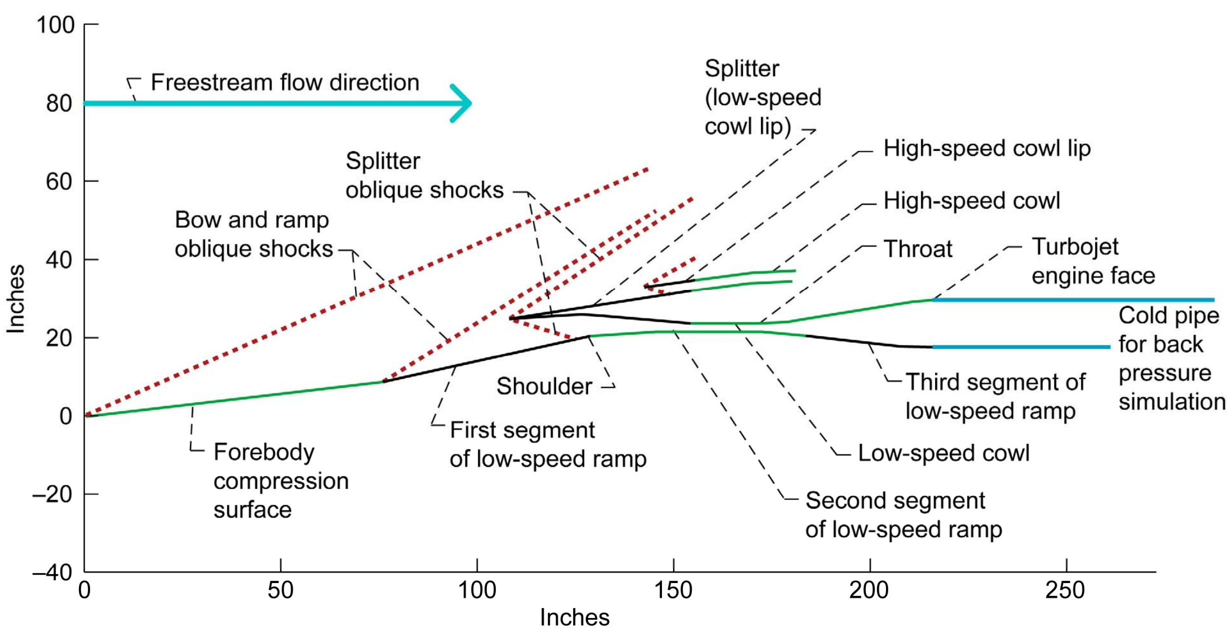

Figure 4.—Oblique shocks (dot traces) originating from the large-scale inlet to study mode transportation (L–IMX) forebody tip, forebody compression surface break point, the low-speed cowl lip, and the high-speed cowl lip.

In 1965, Virginia L. Sorensen (Ref. 22) published a computer program for calculating flow fields in supersonic inlets. The Sorensen paper includes the following information: FORTRAN IV source code, flow charts, program usage, illustrations describing the type of inlets the code will simulate, and a sample case. The source code employs the method of characteristics (MOC) for a perfect gas for axisymmetric or two-dimensional inlets. The code output consists of a uniform field of points, at each of which the total pressure, Mach number, local flow angle, and static pressure ratio are printed. Also using MOC, a FORTRAN IV computer program was written by Anderson (Ref. 23) to assist in designing supersonic inlets. This code takes engineering design quantities, such as throat Mach number and flow angle, and calculates the surface contours required, with minimal inviscid throat distortion. The Sorensen or Anderson work is applicable for determining steady-state inlet operating conditions. This type of research would help identify sensitivities.

The flow-field modeling work by Sorensen is helpful for steady-state point design analysis. Therefore, the Sorensen model would be useful for inlet design exercises. For controller design, a simplified model that includes dynamics is desired. Dynamics are of particular interest for the L–IMX model development because the focus of the study is mode transition. In 1968, Lewis Research Center, now Glenn, published mathematical analysis of supersonic inlet dynamics (Ref. 24). The Willoh method is a mathematical representation suitable for simulating shock-position frequency response. Willoh presents a set of linearized equations across the normal shock with an exact solution of the linearized wave equation. Here, the subsonic portion of the inlet is represented by one-dimensional wave equations that are integrable along constant-area portions of the subsonic duct. The movable normal shock is the upstream boundary condition, and a choked station is assumed for the downstream boundary condition. Bleed and bypass airflow equations can also be applied to the Willoh model (Ref. 25). The equations of these models have been captured to study a two-volume mixed compression inlet model (Ref. 26). Johnson (Ref. 27) has extended the models developed by Willoh, Cole, and Melcher by adding a constant-area combustor that terminates in a thermal choke.

The Willoh mathematical analysis describing the dynamic response of the normal shock within an inlet may be suitable for the L–IMX low-speed flow path. This approach may be useful; however, the LAPIN simulation should already capture these effects (Refs. 24 and 25). The simplified model assembled by Melcher for real-time simulation may be a useful starting point for modeling the L–IMX low-speed flow path (Ref. 26).

Some one-dimensional, general flow analysis equations are given by Pratt and Heiser for a scramjet combustor, inlet, and isolator (Ref. 28). The Pratt and Heiser paper offers an approach to simulate the high-speed flow path. Although their attention is towards H–K curves, their paper may be useful for getting a high-speed flow-path simulation underway. The one-dimensional analysis in the Pratt paper may be coupled with the NACA method discussed above. The NACA method that generated Figure 4 could be used to identify flow characteristics going into the inlet.

A NASA grant was awarded to the University of Akron, Department of Electrical Engineering to develop a method for generating linear models for control design from steady-state CFD results (Refs. 29 to 31). The result of this research is a procedure for creating small perturbation models that can be used for control applications and real-time simulations. Information is extracted from CFD results and used to create simulations using linearized CFD equations. The small perturbation model will only be valid when operating within a small region around the steady-state value. The small perturbation models will have as many matrix points as the CFD model has grid points. The size of the system matrix will be 3N-by-3N, where N is the total number of grid points. Therefore, model reduction is necessary so that linear models can be transformed into a manageable size. Chicatelli's (Refs. 29 to 31) work identifies the following approaches for model reduction: singular perturbation, balancing, Schur method, and square root method. This method may be fruitful for developing high-fidelity control evaluation models. However, the need to identify, setup, and run CFD simulations is not cost-effective and does not meet our immediate need to simulate the L–IMX.

Ajay Kumar (Refs. 32 and 33) developed a three-dimensional Navier-Stokes-based computer program to numerically calculate flow fields in supersonic combustion ramjet (scramjet) inlets. These papers present the governing equations and discuss simulation results. The code can be used to analyze inviscid and viscous (laminar and turbulent) flows. This code would only be useful for solving steady-state solutions that can also be determined with SRGULL.

An integral method for predicting boundary-layer development in transition and turbulent flow regions on two-dimensional or axisymmetric bodies has been developed by Pinckney (Ref. 34). The method has the capability of predicting nonequilibrium velocity distributions. Pinckney (Ref. 35) also reported on an approach towards predicting the heat flux in a compressible turbulent boundary layer in the presence of a large pressure gradient. This method is useful for predicting heating and cooling requirements for an engine sized by estimates of vehicle drag at a range of altitudes and Mach numbers. Boundary layer buildup is a fundamental concern for both flow paths. The Pinckney paper offers a computational solution that may help the dynamic modeling development activity. The Pinckney method could also be used to predict cooling requirements.

A Northrop Corporation Aircraft Division report consists of a one-dimensional mathematical dynamic simulation model for predicting the transient behavior of air induction systems in the supersonic spectrum (Ref. 36). A lumped parameter concept is used in simulating the dynamic response of the subsonic duct downstream of the normal shock. The code is presented in block-diagram format, which may make it convenient for translating to MATLAB Simulink. This report is a good starting point for developing a parallel high-speed flow-path simulation with the low-speed flow-path simulation.

D. Roadmap for Modeling the L–IMX

The L–IMX control model is expected to simulate the low-speed and the high-speed flow paths along a mode-transition schedule. Needed to be captured in the simulation are the dynamics pertaining to the airflow and potential aeroservoelasticity effects on the two cowl flaps and the low-speed flow ramp. To this end, tools and procedures will be established to model cowl and ramp motions and flexibility dynamics, hydraulic actuator dynamics, control servodynamics, and seal frictions. Potential couplings between the aerodynamic loads in the two flow paths of the L–IMX could be adequately represented based on CFD analysis. Nonsteady aerodynamic effects, such as flow separation and inlet unstart, are difficult to predict and need to be avoided via robust control design or conservative operation based on exhaustive inlet performance operability tests.

The LAPIN code will be employed to simulate the normal shock dynamics of the low-speed flow path. There are two efforts underway at Glenn to leverage the capability of LAPIN to support the modeling and control development activities. The first effort is a brute-force approach to streamline the setup, running, and analysis of LAPIN with MATLAB tools. The MATLAB tools leverage the capability of a Microsoft Excel spreadsheet to simplify simulation setup descriptions. The Excel spreadsheet is configured to provide a convenient user interface to enter and save all necessary information for loading a LAPIN input file—boundary layer conditions, geometry, freestream conditions. Custom MATLAB code is designed to read the spreadsheet and populate a text document in FORTRAN card format. This effort will ease LAPIN use as is, that is, without interactively changing the inlet boundary conditions or geometry. Ideally, the LAPIN simulation would be the process model being controlled in a typical closed-loop control system as described in Figure 5. However, because of the current state of the LAPIN method of operation, the LAPIN code will need to be iteratively setup, run, and analyzed automatically.

The LAPIN setup would be dependent on the controller output, which will be dependent on the previous LAPIN simulation result. The bottleneck in this configuration is the LAPIN analysis and setup procedures. Currently, these steps are time-costly operations involving data reduction of text files and populating a LAPIN input text file. In an effort to effectively streamline through this method of operation, MATLAB code will be developed to reduce LAPIN-generated output text files to data useable by a controller, build LAPIN text input files based on a controller output signal, and create local linear models suitable to support linear controller design. These efforts to establish MATLAB tools to support LAPIN will improve the LAPIN method of operation; however, these tools will not remove the bottleneck.

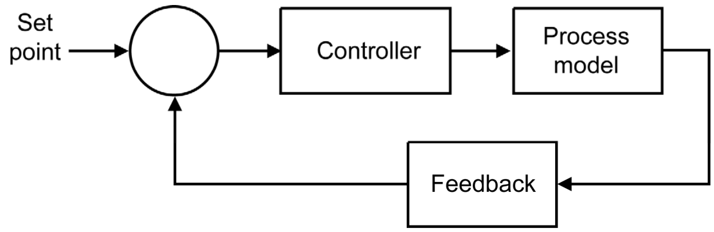

Figure 5.—General control feedback loop structure.

To work around the requirement of repeatedly setting up input text files and analyzing output text files, a simulation is needed that incorporates LAPIN into a closed-loop simulation—LAPIN-in-the-loop. This simulation would be a more substantial extension for LAPIN capability and will enable it to directly communicate feedback information to a controller and respond to controller signals. Specifically, this capability will enable LAPIN to run and test controllers designed using MATLAB Simulink, that is, create a LAPIN-in-the-loop inlet-control simulation. This idea leads to the second effort underway to leverage LAPIN capability. In essence, LAPIN code in operation will be affected by periodic signals from a Simulink control model. Likewise, the Simulink control model will receive data periodically from the LAPIN simulation. This task plan is parallel to the LAPIN tool development activity as described above. The path for this task involves getting the FORTRAN code LAPIN to execute in a cooperative way with MATLAB Simulink.

A promising scheme to carry out the data exchange between these two processes that is fast and reliable is a method of data exchange called memory mapped file (MMF). This scheme uses system calls to set up an arrangement, similar to a RAM disk file, which two or more applications can write to and read from without the delays and overhead of actual disk reads and writes. It is available in the coding languages of C, C++, and a few others but not FORTRAN. Some C++ coded subroutines are needed that LAPIN can call to do the data exchanges with the Simulink model. The technique uses two distinct MMFs—one for Simulink to FORTRAN and the other for FORTRAN to Simulink. This enhancement to LAPIN would facilitate coupling LAPIN to the MATLAB environment. With LAPIN integrated with MATLAB, MATLAB would be responsible for populating the memory locations LAPIN reads for input (control) information. Likewise, LAPIN would populate memory locations that a MATLAB Simulink controller would read for feedback information. A key task to enable this technique is getting the data exchanges synchronized. It is vital to have the data consumer wait until the data producer has finished and placed the data into the MMF. A simple scheme using a status word inside the MMF has been employed. Finally, to enable this type of capability, some reprogramming of the LAPIN FORTRAN source code will be in order. The LAPIN code will need to make available feedback signals and receive control signals.

Another endeavor to realize a simulation for the L–IMX low-speed flow path is an effort to restart the work of Willoh (Ref. 24), Cole (Ref. 25), Melcher (Ref. 26), Johnson (Ref. 27), and Martin (Ref. 37) from the literature. These publications identify how to computationally model the normal shock position dynamics in the throat of the low-speed flow path and give normal shock dynamics from small upstream and downstream perturbations. The normal shock position, which is a parameter of system stability, is sensitive to flow conditions upstream from the shock position and pressure downstream from the shock position. The normal shock dynamic simulation will be inserted into a simulation that calculates the steady-state one-dimensional flow through the low-speed flow path. The steady-state one-dimensional flow entering the low-speed flow path will be calculated based on the freestream conditions encountering oblique shock structures as illustrated in Figure 4. The oblique shock structures and airflow state downstream from these shocks will be determined using the Compressible Flow Toolbox (Ref. 21), which is based on NACA TR–1135 (Ref. 8). Simulation results from this effort will be compared with LAPIN simulation results and CFD steady-state results. An added capability to this simulation will be the incorporation of an afterburning turbine model. The afterburning turbine model is needed to capture the inlet downstream pressure because of the turbomachinery spool-down dynamics expected at the mode-transition operating point.

The SRGULL simulation is the leading choice for modeling the L–IMX high-speed flow path. To use SRGULL for this task, procedures and tools need to be identified or designed to set up, run, and reduce SRGULL simulations. Fortunately, expert users are available for startup tutoring and automation techniques could be employed to batch run SRGULL using either the TechnoSoft AML or MathWorks' MATLAB as the platform. SRGULL being a complete tip-to-tail simulation requires a ramjet, scramjet, or dual-mode combustor to establish an appropriate downstream boundary condition for the inlet. The SRGULL has engine simulation capability in the code. The challenge will be to configure the SRGULL engine simulation to represent the engine to be applied to the high-speed flow path of the L–IMX. SRGULL simulation setup involves populating several text documents. Hand modification or setting up automatic modification of these text files using AML or MATLAB is not a trivial task. To realistically get SRGULL simulation results to support this effort, expert SRGULL operators will be needed to set up, run, and analyze the simulations. Simulation results from SRGULL will be applied parallel to the low-speed path-dynamic model to achieve a complete dual flow-path inlet system simulation. Although SRGULL is not a dynamic simulation, simulation results from SRGULL will be useful to establish trim values for a dynamic model. Furthermore, a first-step approach will be to assume that the airflow response to any disturbance will be significantly faster than the capability of an actuator response such that the aerodynamics of the high-speed flow path can be considered instantaneous.

Another feasible approach towards creating a high-speed flow path simulation is to build one based on modeling equations documented in Billig's (Ref. 38) report. Since all flow conditions for the high-speed flow path are considered instantaneous (i.e., too fast to react to with mechanical actuators), unstable steady-state conditions need to be avoided. The information within this document will be used to develop a high-speed flow-path simulation based on upstream flow conditions. The upstream flow conditions for this model will be dependent on the oblique shock structures and the low-speed flow path.

To realistically represent the L–IMX aeroservoelasticity, a two-step development is being taken. The first step is a "brute force" approach that leverages a validated CFD model to populate mechanical look-up tables of aeroloads for a few specific operating points along and about a specific mode-transition schedule. Such a transition schedule would be based on CFD parametric studies for setting proper bleed rates and back pressures as required to deliver a high-performance mode-transition profile without violating various limitations of turbine engine operation and ramjet ignition requirements. The CFD database would also be used to fine tune and validate a simplified flow dynamics model suitable for control development, which is to be developed in the second step. In the second step, the aeroloads and sensitivity tables developed in step one will be replaced by a certain simplified, sectored, one-dimensional aerodynamics model for each of the two parallel flow paths. The first iteration for this technique is basically an MOC approach. More sophisticated approaches may also be explored, if necessary, to improve the model. The first being considered is described by Amin (Ref. 36). Second, an adaptation of Willoh, Cole, and Melcher is also being considered (Refs. 25 and 26). A third possible approach is the two-dimensional version of the most recent numerical methods for compressible flows (Ref. 39); the CLAWPACK (a conservative laws package out of the University of Washington, using finite volume-type Riemann solvers) could be used for this purpose. Finally, the last approach is via brute-force merging of an L–IMX mechanical model with parallel LAPIN codes to assess the dual-path flow dynamics.

IV. Conclusions

The short-term goal of the Glenn guidance, navigation, and control discipline team is to support the NASA Fundamental Aeronautics Program Hypersonic project by developing essential tools and procedures that will be assets for creating and validating analysis models and control relevant dynamic models, referred to as control models, suitable for controller design activities and applicable to the large-scale inlet to study mode transition (L–IMX) and future flight inlet models. To this end, a description of the desired L–IMX control model was presented. The steps towards achieving this goal include using computational codes found in public-domain literature and NASA reports. The simulation codes LAPIN and SRGULL, available in electronic format, are valuable resources towards this goal. Simulation approaches published by Willoh, Cole, and Melcher; Johnson; Sorensen; Martin; Amin; National Advisory Committee for Aeronautics reports; and the Compressible Flow Toolbox are also promising to adequately simulate the airflow dynamics. Tools and procedures will be established to model cowl and ramp motions, flexibility dynamics, hydraulic actuators, control servos, and seal friction. Potential couplings between the aerodynamic loads in the two flow paths of the L–IMX could be adequately represented based on computational fluid dynamics analysis. Nonsteady aerodynamic effects, such as flow separation and inlet unstart, are difficult to predict and need to be avoided via robust control design or conservative operation based on exhaustive inlet performance and operability tests. Finally, a good simulation of the afterburning turbine engine is needed to accurately simulate the downstream boundary condition for the low-speed flow path.

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14. ABSTRACT
The NASA Fundamental Aeronautics Program Hypersonic project is directed towards fundamental research for two classes of hypersonic vehicles: highly reliable reusable launch systems (HRRLS) and high-mass Mars entry systems (HMMES). The objective of the hypersonic guidance, navigation, and control (GN&C) discipline team is to develop advanced guidance and control algorithms to enable efficient and effective operation of these challenging vehicles. The ongoing work at the NASA Glenn Research Center supports the hypersonic GN&C effort in developing tools to aid the design of advanced control algorithms that specifically address the propulsion system of the HRRLS-class vehicles. These tools are being developed in conjunction with complementary research and development activities in hypersonic propulsion at Glenn and elsewhere. This report is focused on obtaining control-relevant dynamic models of an HRRLS-type hypersonic vehicle propulsion system.

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