



# Control Activity in Support of NASA Turbine Based Combined Cycle (TBCC) Research

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## **Abstract**

Control research for a Turbine Based Combined Cycle (TBCC) propulsion system is the current focus of the Hypersonic Guidance, Navigation, and Control (GN&C) discipline team. The ongoing work at the NASA Glenn Research Center (GRC) supports the Hypersonic GN&C effort in developing tools to aid the design of control algorithms to manage a TBCC airbreathing propulsion system during a critical operating period. The critical operating period being addressed in this paper is the span when the propulsion system transitions from one cycle to another, referred to as mode transition. One such tool, that is a basic need for control system design activities, is computational models (hereto forth referred to as models) of the propulsion system. The models of interest for designing and testing controllers are Control Development Models (CDMs) and Control Validation Models (CVMs). CDMs and CVMs are needed for each of the following propulsion system elements: inlet, turbine engine, ram/scram dual-mode combustor, and nozzle. This paper presents an overall architecture for a TBCC propulsion system model that includes all of the propulsion system elements. Efforts are under way, focusing on one of the propulsion system elements, to develop CDMs and CVMs for a TBCC propulsion system inlet. The TBCC inlet aerodynamic design being modeled is that of the Combined-Cycle Engine (CCE) Testbed. The CCE Testbed is a large-scale model of an aerodynamic design that was verified in a small-scale screening experiment. The modeling approach includes employing existing state-of-the-art simulation codes, developing new dynamic simulations, and performing system identification experiments on the hardware in the NASA GRC 10 by 10-Foot Supersonic Wind Tunnel. The developed CDMs and CVMs will be available for control studies prior to hardware buildup. The system identification experiments on the CCE Testbed will characterize the necessary dynamics to be represented in CDMs for control design. These system identification models will also be the reference models to validate the CDM and CVM models. Validated models will give value to the tools used to develop the models.

## **Introduction**

NASA is interested in developing technology leading to more routine, safe, and affordable access to space. Developing airbreathing propulsion systems for access to space vehicles has potential to meet these objectives based on recent reusable launch vehicle (RLV) system studies (Ref. 1). To this end, the NASA Fundamental Aeronautics Program (FAP) Hypersonic Project is conducting fundamental research on Highly Reliable Reusable Launch Systems (HRRLS) (Refs. 2 and 3). The HRRLS element of the FAP Hypersonic Project considering airbreathing propulsion systems has led to a Reusable Airbreathing Launch Vehicle (RALV) concept for access to space. This work supports propulsion system control development for an RALV concept vehicle.

The FAP Hypersonic RALV concept vehicle targets a vehicle system that employs two separate sub-vehicles or stages—a two-stage-to-orbit (TSTO) vehicle (Ref. 4). Each stage will include its own propulsion system and fuel. The first stage will provide horizontal takeoff capability, and its propulsion system would further accelerate both stages to a staging point. At staging, the second sub-vehicle will disengage from the first stage. After separation, the second stage will use its propulsion system for further acceleration and insertion into space. The propulsion system concept for the first stage is proposed to be an airbreather including a turbine engine cycle and a ram/scram Dual-Mode combustor (DMSJ) cycle. This combination of propulsion systems is referred to as a Turbine Based Combined Cycle (TBCC) system. For insertion into orbit, the second stage propulsion system can be rocket-based or a rocket-based combined cycle (RBCC) system. The RALV TBCC concept is a fully reusable, horizontal takeoff, and return vehicle. This work considers a TBCC propulsion system for the first stage of the RALV concept TSTO system.

The RALV first stage is anticipated to incorporate an airbreathing TBCC propulsion system. For takeoff, the first stage of the RALV will employ a turbine engine as a source to accelerate the vehicle and the DMSJ flow path will be cold-flowed (no fuel applied to the DMSJ). While accelerating past transonic and through supersonic to the staging point, escalating temperature will limit the operability of the turbine system. To continue further acceleration to the staging point, the propulsion system will transition from the turbine source to the DMSJ source. The propulsion system transition from one source to another is referred to as mode transition. Passing through the mode transition window is a critical event for enabling vehicles to travel at hypersonic speeds using TBCC propulsion systems.

TBCC propulsion for the RALV system will include the following elements: a forebody compression surface, a turbine engine, an inlet for the turbine engine, a DMSJ combustor, an inlet for the DMSJ, an isolator for the DMSJ, and an aft nozzle system for both thrust generating systems. As the RALV system accelerates from takeoff through mode transition and to the staging point, a TBCC control system is needed to ensure the propulsion system maintains operability and safety margins while maximizing specific impulse and thrust. Control system research to support the RALV propulsion system is the focus of the FAP Hypersonic Guidance, Navigation, and Control (GN&C) discipline team. Control system research requires the following four elements: computational models (hereto forth referred to as models), specific objectives, a set of admissible controllers, and a means to evaluate controller performance. This paper focuses on the first of these elements—developing suitable control design models (CDMs) and control verification models (CVMs) necessary for TBCC control design activities. The NASA plan is to develop an overall airbreathing propulsion model for an RALV system that includes each of the propulsion system elements, along with a simulation for the free stream conditions, under a common programming format. The programming format chosen for this activity is the commercially available MATLAB (The Mathworks, Inc.) and Simulink (The Mathworks, Inc.). Of the TBCC propulsion system elements that will be represented in the model, initial attention is focused on developing models and controllers for the inlet system, including the forebody compression surface, for the following two reasons: The inlet system is a critical component for enabling mode transition, and, an inlet system has been designed to test a mode transition event for a TBCC type propulsion system in the NASA Glenn Research Center (GRC) 10 by 10-Foot Supersonic Wind Tunnel (10x10 SWT) (Ref. 5).

A large scale inlet system has been aerodynamically designed (Refs. 6 and 7) based on experimental results from small-scale screening experiments. This mixed compression inlet system that is suitable for experiments focusing on mode transition studies is referred to as the Combined-Cycle Engine (CCE) Testbed (Ref. 8). This inlet system, illustrated in Figure 1 as it will be mounted in the GRC 10x10 SWT, has two flow paths—a Low-Speed Flow-Path (LSFP) and a High-Speed Flow-Path (HSFP). The LSFP will direct airflow to a high-Mach turbine engine. The HSFP will direct airflow to a DMSJ. The dual flow-path inlet system is configured in

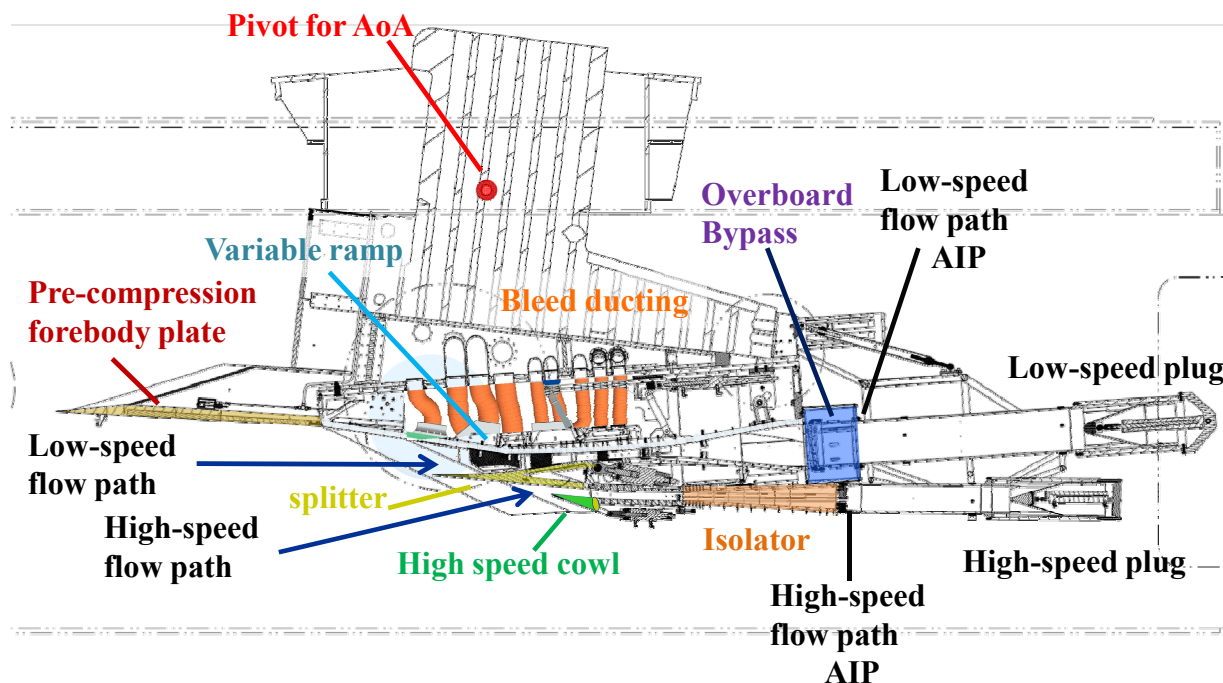


Figure 1.—The CCE Testbed as it will be installed in the NASA GRC 10 by 10-Foot Supersonic Wind Tunnel with cold pipes and plugs in lieu of a turbine engine or a Dual Mode Scramjet Combustor. This is the inlet configuration for the Inlet Characterization and System Identification experiments.

an over-and-under arrangement, LSFP over the HSFP, to take advantage of a common forebody compression surface and to save weight. The CCE Testbed also includes variable geometry to enable operation across a flight regime. The variable geometry includes a rotating Splitter, a Variable Ramp for regulating LSFP throat height, a rotating High-Speed Cowl, and Overboard Bypass Gates. The upper surface of the splitter, exposed to the LSFP, serves as the LSFP cowl; whereas, the lower surface of the splitter serves as a HSFP compression ramp. The Overboard Bypass Gates, consisting of four engine bypass doors, are actively used to regulate pressure at the aft end of the LSFP. Controllers are used for the Overboard Bypass Gates to prevent the LSFP from unstating. Also, the CCE Testbed incorporates a passive stability bleed system with controllable plenum back pressure. The passive stability bleed system are patterns of holes in the LSFP ramp, cowl, and sidewall surfaces leading to bleed plenums that also help prevent the inlet from unstating. Thrust producing hardware, such as the turbine or DMSJ, can be installed at the aft planes of the inlet flow-paths. The plane defining the aft end of the inlet flow path and the upstream end of the engine is referred to as the Aerodynamic Interface Plane (AIP). In lieu of installing a turbine engine or a DMSJ, calibrated cold pipes and plug assemblies can be installed at the AIP to promote steady-state back pressuring of the inlet (Refs. 9 to 12). The Figure 1 illustration has the airflow entering the inlet from the left and exiting on the right. Also, the mounted inlet model will have a selectable Angle of Attack (AoA).

The CCE Testbed, with engines or cold-pipes, was designed to enable simulated acceleration of a vehicle from lower supersonic Mach numbers to DMSJ take-over speeds. At scramjet take-over speed, this inlet is designed to employ the rotating splitter to cut-off airflow through the LSFP. The most significant event during the propulsion system mode transition is the splitter rotating to cut off the LSFP airflow, reducing LSFP airflow and increasing HSFP airflow. Other significant mode transition events include lighting the DMSJ and spooling down the turbine. Mode transition control is necessary to maintain propulsion system operability throughout the mode transition events.

The primary objective for the CCE Testbed is to experimentally investigate and develop methods of mode transition for a TBCC type propulsion system (Ref. 13). Ideally, these hardware tests will result in a demonstration of an inlet system capable of maintaining inlet operability and safety margins with maximum performance through all flight conditions including mode transition. Inlet operability is defined as supplying airflow demand with acceptable distortion while keeping the inlet flow paths started. A started inlet LSFP will maintain a normal shock, or terminal shock, located downstream from the aerodynamic throat. The normal shock is where the airflow nonlinearly decreases from supersonic to subsonic. Ideally for maximum performance, the normal shock is maintained near the inlet throat. A started inlet HSFP will maintain the location of the shock train leading edge within the HSFP isolator. To this end, the CCE Testbed will be subject to a series of ground-based testing that initiates with an Inlet Characterization (IC) test.

IC testing will be conducted at various boundary conditions and inlet geometries. Inlet boundary conditions would be free stream conditions (Mach number, temperature, and pressure), AoA, bleed plenum back pressure, and the AIP pressures. The inlet boundary conditions and geometry define a specific inlet operating point. The IC tests will support designing an inlet operating schedule to appropriately configure the inlet geometry with respect to the free stream conditions and AoA. This schedule will also define the geometry manipulation procedure to be followed during mode transition. The mode transition geometry manipulation procedure will be developed based on steady-state IC test data, will be time independent, and it will not consider dynamic disturbances. The IC test data will give insight into the approximate normal shock location in the LSFP for each inlet operating point. Also, data will be recorded during the IC testing to map inlet operating points of high distortion at the AIP of the LSFP. Turbine engines require clean airflow (Ref. 14) through all flight conditions. Clean airflow will be determined based on the distortion analysis. Therefore, the IC test data will reveal a geometry reconfiguration schedule suitable for simulating the mode transition event that will avoid inlet unstart, maximize inlet performance, and steer clear of configurations associated with high LSFP distortions. Finally, dynamic data will be measured to access the noise level of the dynamic pressure sensors at each operating point. These noise level assessments will be helpful for future dynamic experiments.

The data from the IC tests, necessary for control schedule development, are represented in “cane-curve” maps. An example cane-curve map, with several cane-shaped data traces, is illustrated in Figure 2. The data used to generate the cane-curve map illustrated in Figure 2 is from experiments with a smaller model of the CCE Testbed (Ref. 15). Figure 2 is a typical map of inlet performance, operability and mode transition sequence. The cane-curve map abscissa is a mass-flow ratio of the mass-flow at the AIP ( $m_2$ ) to a reference mass-flow ( $m_{hs}$ ), and the ordinate is the ratio of total pressure at the AIP ( $P_2$ ) to a reference free stream total pressure ( $P_0$ ). The value for  $m_{hs}$  is the mass captured with the inlet geometry configured for a specific mach number. The span of the cane-curve traces on both the abscissa and the ordinate will be less than one.

For a typical IC test, the environmental boundary conditions are set first. Next, the inlet actuators will be used to manipulate the inlet to a desired geometry. After the inlet is configured as desired and the dynamic pressure sensors have settled to a steady-state condition, the inlet AIP back pressure ratio is incrementally increased with the use of a calibrated cold-pipe and plug assembly. The LSFP cold-pipe plug will incrementally progress from a completely withdrawn position towards a cold-pipe close-off position. As the cold-pipe plug approaches a close-off position, the inlet AIP back pressure will increase, and the normal shock will move upstream.

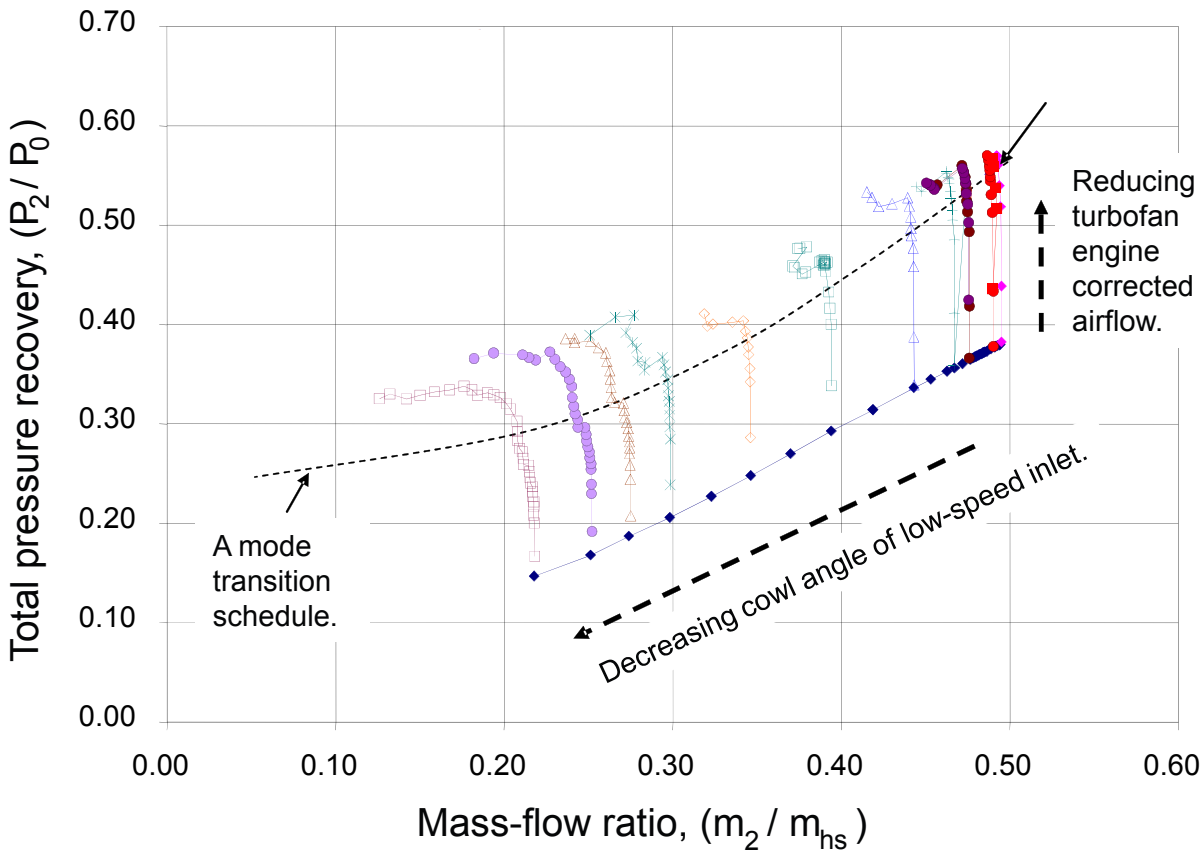


Figure 2.—Example of a large number of Performance ‘Cane’ Curves. Each curve is representative of a specific low-speed cowl angle. These curves illustrate inlet pressure recovery versus flow ratio (Ref. 15).

Each incremental movement of the cold-pipe plug will define a new inlet operating point. Steady-state data from axially distributed static pressure sensors and dynamic pressure sensors will be measured and recorded at each operating point. These measurements will give an axial static pressure distribution, including an AIP pressure ratio, at each operating point. Furthermore, a rake of dynamic pressure taps located at the AIP will be measured and recorded for assessing AIP pressure distortion. The axial pressure distribution will reveal an approximate LSFP normal shock position and margin of safety. The LSFP margin of safety is the approximate measurement between the aerodynamic throat and the normal shock location. Likewise, the approximate location of the HSFP shock train leading edge and margin of safety will also be known at each inlet operating point. The HSFP margin of safety is the approximate measurement between the isolator entrance plane and the leading edge of the shock train. Based on this information, an appropriate inlet back pressure ratio schedule can be identified to place the shock, normal or leading edge, at desired locations for every inlet operating point. This knowledge makes way for developing a bypass valve control schedule that would be useable for running the inlet steady state with low AIP distortion suitable for the GRC 10x10 SWT environment given no external disturbances. The procedure to incrementally increase the back pressure ratio, by further advancing the cold pipe plug, continues until unstart is imminent. This process can be stopped prior to unstart to avoid applying unnecessary high unstart loads to the inlet hardware.

Each cane-shaped trace on the cane-curve map, in Figure 2, is a collection of points obtained for a given inlet geometry and free stream condition at various cold-pipe plug positions. The first data point acquired on a particular cane trace is located at the bottom of the cane-shaped trace. As the cold-pipe plug progresses towards cold-pipe close-off, the data points are plotted higher on the cane-curve trace—corresponding to an increasing pressure ratio and relatively constant mass flow ratio. The data points located on the vertical segment of the cane-curve trace represent inlet super-critical operating conditions—normal shock located downstream from the passive stability bleed region. As the plug further progresses towards close-off, AIP back pressure increases and the normal shock will move upstream and pass over the passive stability bleed region. For inlet operating conditions where the normal shock is passing over the bleed region, the pressure ratio and mass ratio data points will form the arc and subsequent horizontal segment of the cane trace. The last point plotted on the cane trace, the left end of the cane trace horizontal segment, has the exit cold-pipe plug positioned just prior to a position that will result in inlet unstart—the minimal stable operating condition.

For IC testing, data is collected to populate the right most cane-curve trace first. This data corresponds to the cowl being opened to a maximum operating position. As the splitter moves towards LSFP close-off, the LSFP cowl capture area decreases, and data to populate cane-curve traces to the left will be acquired. Therefore, the cane-curve traces from right to left are representative of inlet operating points with decreasing cowl capture area. Potential inlet pressure recovery also reduces for the cane-curve traces displayed from right to left. This reduction is probably due to both lower internal compression and proportionately greater ingestion of low momentum forebody boundary layer (Ref. 15). Optimal inlet operation, for a given geometry and free stream condition, is the knee of the cane-curve—mass flow and total pressure ratios are maximized. Therefore, for a given inlet geometry and free stream condition, the optimal AIP pressure, while rotating the splitter to close off the LSFP for mode transition, would be the locus of points that define a line that would pass through or just below the knees of these cane-curve traces. The dash trace illustrated in Figure 2 is such a trace, and it represents the probable best inlet geometry mode transition schedule.

The TBCC propulsion system for an RALV concept vehicle will employ a control system to follow a defined schedule optimized to a flight trajectory. The schedule will be developed to suitably configure the propulsion system geometry throughout the flight trajectory. Included in the schedule will be the capability to move multiple actuators synchronously to accomplish mode transition. This controller will include a closed loop feedback system to reject or dampen the effects of disturbances on the operation of the TBCC propulsion system. Therefore, the TSTO system will need a control system that can manage a propulsion system schedule based on boundary conditions and the status of the propulsion system, while maintaining propulsion system stability and performance. This paper will focus on activities to design feedback TBCC controllers to maintain propulsion system stability and maximize performance throughout a mission including the mode transition event.

The discussion in this paper initiates by describing a plan to develop an architecture suitable for simulating a propulsion system. The propulsion system simulation architecture will be useful for computational verification of controller capability. This architecture will consist of a collection of independent system component models and component controllers that can be united to simulate a complete propulsion system. Because the inlet system is a critical propulsion system component for enabling mode transition, ongoing modeling and control activities associated with the propulsion inlet system are discussed with attention given to the CCE Testbed design. The CCE Testbed will be subject to ground-based IC testing and dynamic System Identification (SysID) experiments for control studies. These SysID experiments that will support controller design activities for the CCE Testbed will be discussed.

# Control Design Model Development

## Modeling and Control Architecture

The propulsion system simulation development plan is to make available a controllable computational simulation of an overall hypersonic vehicle airbreathing propulsion system. The propulsion system simulation will include capability to computationally model atmospheric free stream conditions representative of a mission profile or wind tunnel conditions. A block diagram description of this architecture is illustrated in Figure 3. The architecture includes an element, represented with an oval shape, from which free stream conditions can be applied to the propulsion system model. Elements illustrated with a rectangular shape represent propulsion system component models. Elements represented with small square shaped elements, that include a "C," are controllers applied to a specific component. The large square element represents an overall controller. The line segments with arrows in the Figure 3 illustration represent communication paths between components. The need to apply an individual controller to each of the propulsion system elements, as implied by the illustration in Figure 3, may not be necessary.

A propulsion system simulation as illustrated in Figure 3 can have elements removed, modified, or replaced without dismantling the overall simulation. Furthermore, each element can be removed and studied for controller design exercises and then reinserted back into the simulation with a new control algorithm. Finally, the architecture illustrated in Figure 3 can adapt to represent a propulsion system with a similar but different configuration of elements by rearranging the blocks, removing blocks, adding new blocks, and implementing cross interactions. A populated simulation will be a useful tool for airbreathing hypersonic vehicle propulsion systems control system design activities.

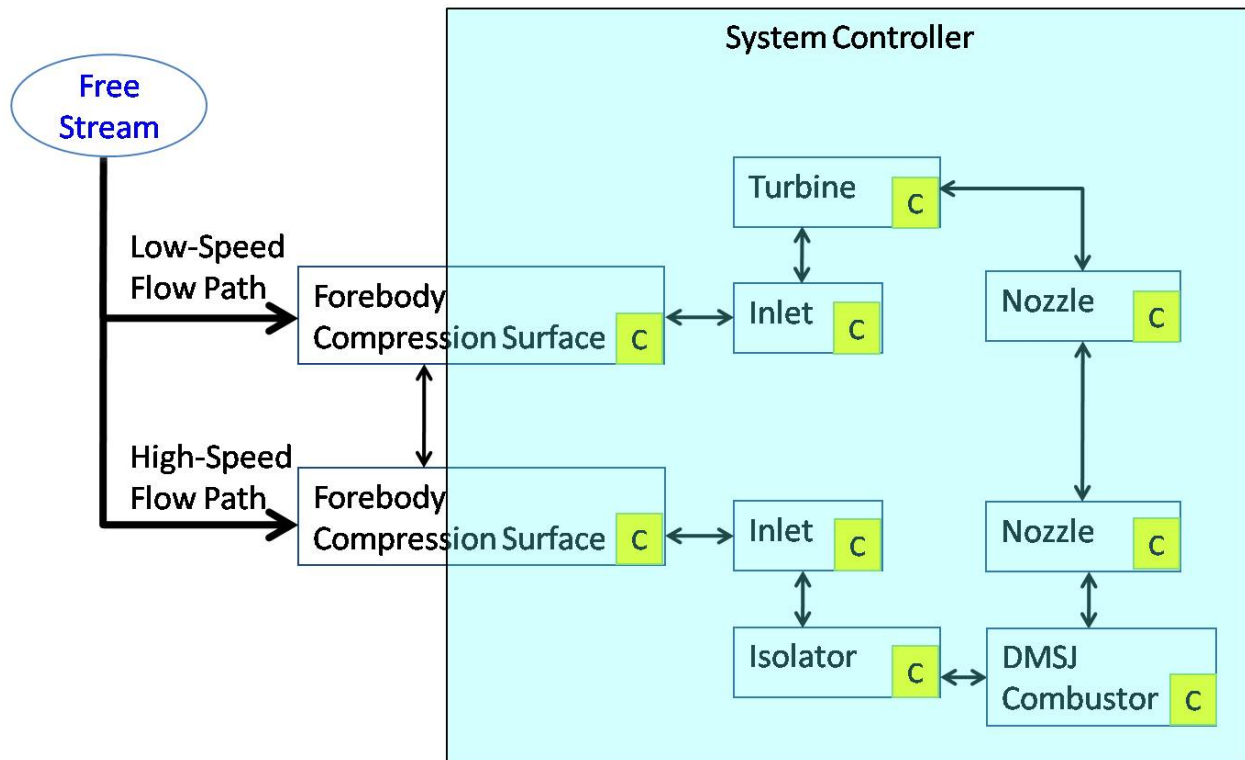


Figure 3.—Block diagram for a hypersonic vehicle propulsion system simulation and control architecture.

Attention is focused on a path towards developing an inlet simulation applicable to the overall architecture described in Figure 3. The inlet system model will be representative of the CCE Testbed. The objective is to design the “C” block in the “Inlet” rectangles in the Figure 3 illustration. The first step towards designing this control system is to assemble CDMs that capture the pertinent dynamics associated with the inlet operation. Dynamics of interest include: internal shock position, aeroservoelasticity of control surfaces, hydraulic actuator response, seal friction, aero loads, and couplings between captured air flow and the actuator dynamics. Therefore, the first step will focus on designing the “Inlet,” “Forebody,” and “Isolator” simulations represented with rectangles in the Figure 3 illustration.

To simulate the CCE Testbed design testing in the GRC 10x10 SWT, the architecture illustrated in Figure 3 is reorganized to a configuration as illustrated in Figure 4. The configuration in Figure 4 includes cold pipes simulations instead of a turbine or DMSJ and only one forebody compression surface simulation. A splitter element is added to regulate airflow from a common forebody compression surface to each flow path. The LSFP component of the inlet will include a rotatable cowl flap, a variable throat height ramp surface, bypass valves, and passive stability bleeds. The HSFP component of the inlet will include a rotatable cowl flap and a variable forebody compression ramp surface. The LSFP cowl and the HSFP ramp will be dependent on the position of the splitter.

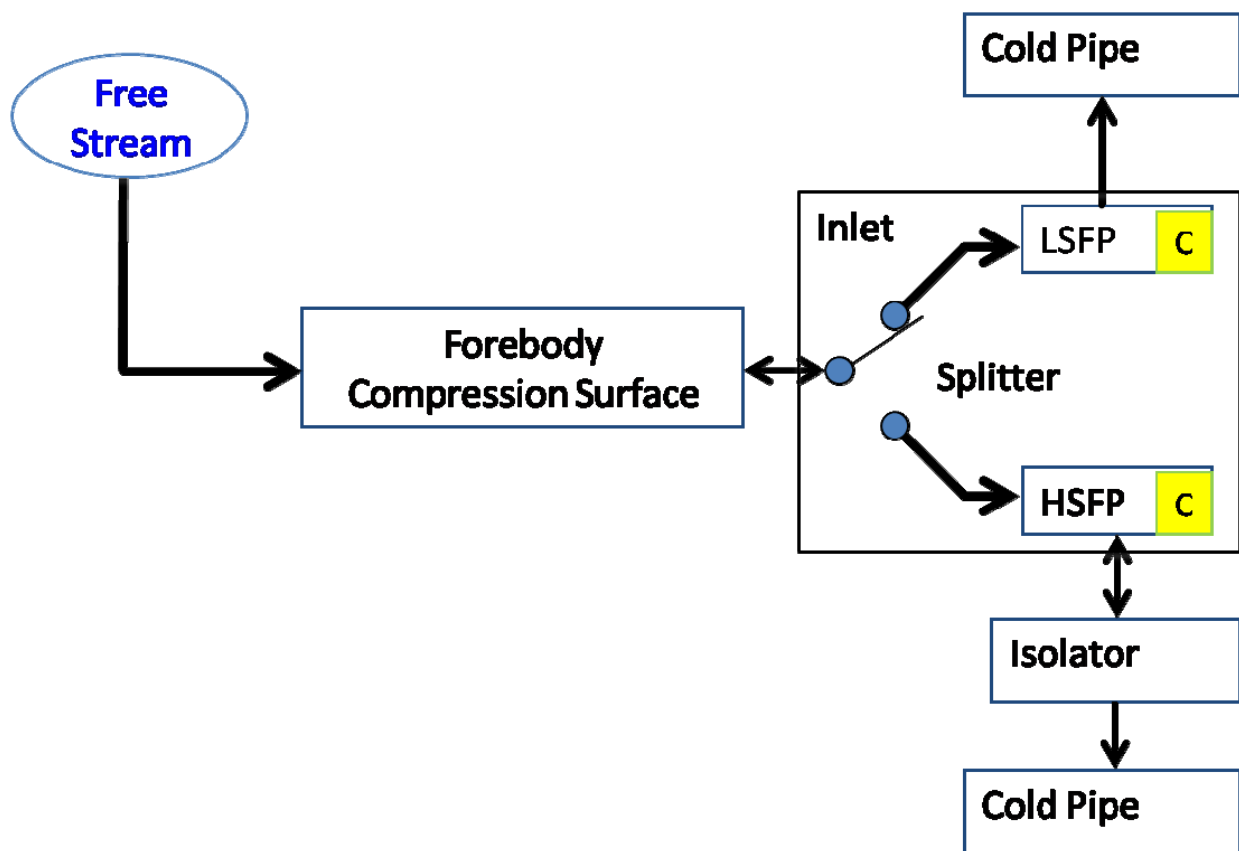


Figure 4.—Block structure simulation of the CCE Testbed as it will be configured to represent the IC and SysID testing in the GRC 10x10 SWT.

The two dominant modeling tools available for simulating inlets are multidimensional Computational Fluid Dynamics (CFD) and the Large Perturbation Inlet Model (LAPIN) (Ref. 16). For control design purposes, a full three-dimensional CFD simulation is too slow or impractical on current computer systems. LAPIN is a one-dimensional CFD legacy code primarily used for simulating supersonic propulsion inlets for control studies. However, LAPIN is a complex, stand-alone, executable FORTRAN 77 code written to run from a command shell. What is desired is a simulation capable of flow analysis and capturing shock dynamics that can be run in MATLAB Simulink integrated with the other dynamic simulations of interest.

To meet our interest of having a simulation code for the inlet that is suitable for control design and compatible with our overall propulsion system architecture plans, the following five parallel paths were taken and will be discussed in the subsequent sections. One, develop an aeroservoelastic simulation to model and study aeroservoelasticity of the inlet, hydraulic actuator dynamics, seal friction, and couplings between air flow and actuator dynamics. This activity would yield models compatible with the overall architecture plan. Two, develop a simplified inlet model that can simulate an inlet that is compatible with the overall propulsion system architecture. This parallel path is leading towards an interactive simulation. Three, develop a methodology to facilitate communication and synchronous operation between LAPIN running from the command shell and the propulsion system architecture running in a parallel process. This methodology has been termed "LAPIN-in-the-Loop." Four, award a NASA Research Announcement (NRA) for developing a propulsion system model to simulate mode transition (Ref. 17). Finally, five, conduct hardware tests on an inlet model. Two types of hardware tests are being planned that will support the modeling activities: the IC and SysID experiments. The IC testing will identify a steady-state schedule of operating points to which SysID experiments can be conducted. The SysID experiments will lead to control design models based on reduced empirical data. These first four paths will lead to tools that can be used for control analysis of a design prior to hardware buildup. The fifth path will lead to experimental based truth models to verify the tools. Furthermore, the fifth path will also yield models suitable for designing controllers. This paper continues with further information regarding the progress towards developing models along these parallel paths.

## **Aeroservo Simulation**

This Aeroservo Simulation considers the mechanical stability and control issues not represented in the other simulations. The Aeroservo Simulation path simulates the dynamic interactions between the inlet air flow and the mechanical actuators which control the LSFP ramp, splitter, and the HSFP cowl positions. The simulated dynamics and issues are depicted in Figure 5. This model will simulate the actuation system dynamics and inlet structural and mechanical motions to predict servo control stability under aerodynamic loads. This simulation includes the following: A mathematical representation of typical servo proportional and integral (PI) control via piston feedback; Laplace transform representation of servo-valves' response to servo electrical current inputs; hydraulic volumetric flows controlled by four-way valves into and out of the two opposing volumes of the different sides of the actuator piston; and the pistons differential hydraulic pressure which is estimated from integrating the pressures' time rate-of-change, based on the assumed hydraulic fluid bulk modulus.

The aero-loads on the moving parts of the simulated inlet are computed from distributed static pressures over the "wetted" surfaces. The static pressures will be made available from LAPIN or the Interactive Simulation. The Interactive Simulation will be discussed later. The transferring of these loads onto the various hydraulic actuator rods are computed from the nonlinear kinematic constraints imposed by the mechanical linkages between the hydraulic actuator rods and the respective inlet surface. With these known constraints, the equations of motion of this system are expressible using the piston's stroke and structural bending modal

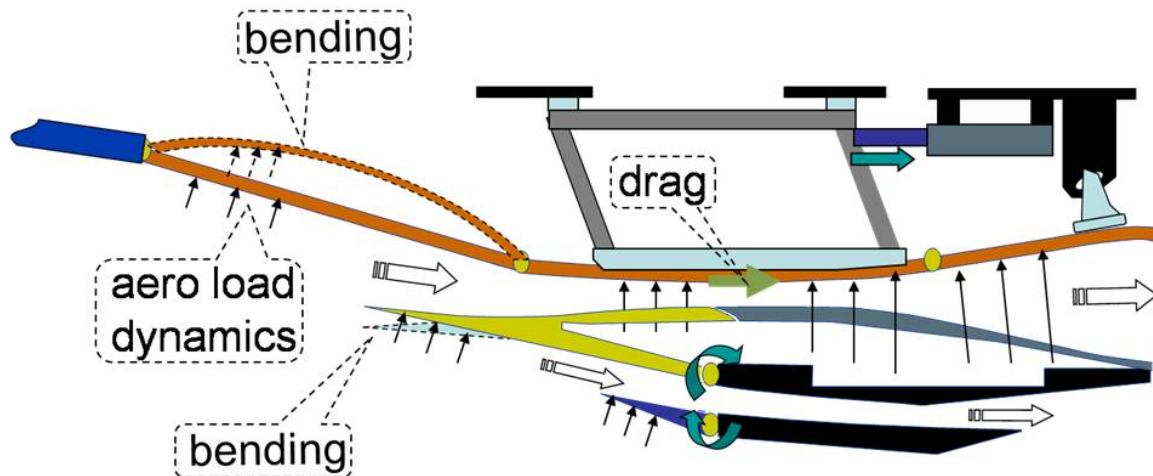


Figure 5.—Illustration of CCE Testbed actuators, loading, and aeroservo dynamic interactions.

displacements as generalized coordinates, with the generalized mass matrix dependent on the piston stroke. Aerodynamic loads from other moving ramp sections will also induce loads on the ramp actuator piston that can be computed using other kinematic constraints. Similarly, the seal frictions also impart forces on the piston through the linkages. Such seal friction effects are modeled as static and kinematic friction lumped at discrete points representing the seal contact with the sides of the LSFP ramp, splitter, and HSFP cowl.

### Interactive Simulation

The objective of the Interactive Simulation is to simulate inlet steady-state operating conditions and allow for dynamic studies of the LSFP normal shock. This capability is similar to LAPIN. The benefit of the Interactive Simulation over LAPIN is flexibility; this code is written in the same format as the overall propulsion system controller development architecture. Furthermore, this code is being designed as a tool with flexibility to simulate future inlet concept designs.

The Interactive Simulation is designed for easy manipulation of the inlet actuators and free stream conditions through Graphical User Interface (GUI) panels or from signals generated from other simulations. The simulation starts with a preset inlet geometry, free stream condition, and cold pipe exit flow open area. Based on the given geometry, a Parabolized Navier-Stokes (PNS) Solver (Ref. 18) is used to simulate the supersonic flow. Next, a curve is determined that correlates cold-pipe exit open area with the normal shock position of the inlet LSFP. This curve is dependent on the supersonic flow and the cross-sectional area of the duct. Therefore, a change in inlet geometry or free stream conditions will affect this curve and the normal shock position. The PNS Solver is capable of considering boundary layer buildup, bleeds, and off-design oblique shock structures for steady-state analysis of the supersonic flow. The ability to determine off-design oblique shock structures and downstream flow conditions is an important feature to support inlet supersonic flow analysis when the CCE Testbed splitter is no longer located at the design point. This capability is critical for simulating the inlet air flow through mode transition as the splitter rotates to close off the LSFP. The curve correlating the cold-pipe exit area with the normal shock position is for subsonic steady-state flow analysis. Volume dynamics for the subsonic flow field will be added to this simulation. Dynamic perturbations will be generated at the downstream end of the subsonic flow path that will perturb the normal shock position with a simulated bypass door. This methodology is representative of how disturbances will be generated for the CCE Testbed SysID experiments in the wind tunnel.

Controllers will be developed to dampen the disturbance from one bypass door with controlled disturbances from another bypass door.

### **LAPIN-in-the-Loop**

The principle objective for this parallel path is to make available the GRC legacy code LAPIN to work synchronously with the Aeroservo simulation. A secondary goal is to enable LAPIN to be a tool in the planned propulsion system architecture. Ideally, for both objectives, LAPIN would be run in the same common format as the Aeroservo simulation and the planned propulsion system architecture. A feasibility study on how to go about reaching these objectives considered sensitivities to maintain the published LAPIN legacy code with minimal changes and to select a methodology that can be completed within a year. Two of the difficulties that immediately come to light at the onset of this feasibility study are that the LAPIN code is designed to initiate by reading a text document in FORTRAN 77 namelist format, and its output is designed to populate another text document. Four approaches were considered: One, translate the FORTRAN code to Simulink block diagram code. This approach would yield a flexible product that would be accepted by the planned architecture. However, this approach would be time consuming. Two, use a brute force translation from FORTRAN code to another language suitable for embedding within the overall propulsion system architecture. This approach would also yield a flexible product, but not as flexible as the method mentioned in approach one above. This approach would also be time consuming and tedious. Three, use special block diagram code features that accept compiled FORTRAN code. On the surface, this approach appears to be the shortest path to our end. However, the LAPIN code is complex, making this approach difficult and time consuming. Finally, approach four; develop a Memory Map File (MMF) communication structure to exist between the LAPIN process and the overall propulsion simulation process. Memory Mapped File is an interface that facilitates data exchange between two or more programs running simultaneously. MMF does not involve disk file writes and reads. Instead, memory is used for fast operation. This last approach is appealing because it seems to meet both sensitivity issues. This section continues with a brief introduction to this fourth methodology.

The goal for LAPIN-in-the-Loop is to enable a control loop as illustrated in Figure 6. The solution involves running the control loop in MATLAB Simulink and the LAPIN simulation in a parallel process with some interface routines developed to facilitate communication and synchronization between the two processes. The illustration in Figure 7 describes the necessary modifications to the legacy LAPIN code and how the communication links between the two parallel processes are made. The interface code to facilitate communication from LAPIN to the MMF data files included FORTRAN functions with C code. The MATLAB Simulink code has available functions that can also communicate with the same MMF data banks. Based on feedback signals to LAPIN through the MMF data structure, LAPIN can make the following changes to its simulation: reconfigure the geometry of its test article, change free stream conditions, and make other boundary condition changes. Else, the MMF feedback signals to LAPIN may instruct LAPIN to exit. The MATLAB Simulink code can also read from the MMF and respond by populating its outgoing MMF. Furthermore, feedback signals read can be analyzed using tools readily available in the MATLAB environment. Essentially, the general flow of the LAPIN code has not changed. LAPIN still reads a text file formatted in FORTRAN namelist format to initiate the simulation. LAPIN will then run specified number of iterations. The significant difference is that after these iterations, LAPIN can be restarted with its current settings or with some slight modifications to its geometry or boundary conditions. Finally, LAPIN can still exit with a write to an output text file.

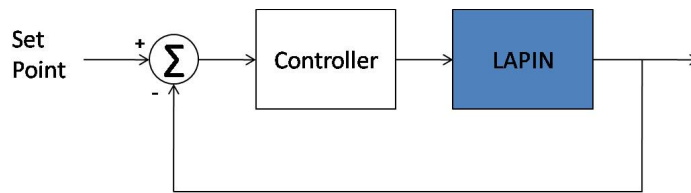


Figure 6.—Control loop with LAPIN as the process being controlled—LAPIN-in-the-Loop.

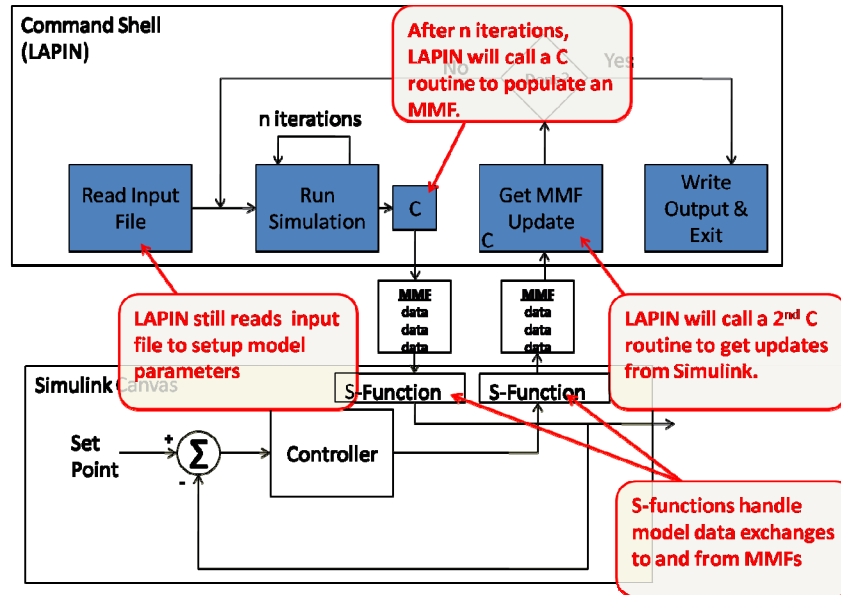


Figure 7.—Expanded view of LAPIN interface with MATLAB Simulink.

With the LAPIN-in-the-Loop approach, LAPIN has successfully run independently and synchronously with a MATLAB Simulink process. These processes are synchronized, exchange data, and are both responsive to input streams of data from the other. This technique has been demonstrated with LAPIN simulating the CCE Testbed with the Aeroservo simulation. Finally, the MMF approach can be further reproduced to accommodate multiple instances of LAPIN or other complex FORTRAN executables.

## NRA Award

SPIRITECH Advanced Products, Inc., has been awarded a NASA Research Announcement (NRA) award to develop, from fundamental physics, modeling tools for a comprehensive integrated dynamic simulation tool for a TBCC propulsion system. To date, SPIRITECH has made progress developing the High Mach Transient Engine Cycle Code (HiTECC) (Ref. 17). The HiTECC modeling elements use performance maps and fundamental conservation equations. The performance maps correlate dependent parameters to a small number of defined independent parameters using look-up tables. Implementing look-up tables helps reduce computational time over simulations that employ more detailed models. Typically, the look-up tables are used for compressor and turbine simulation applications. The models, based on conservation equations, balance the continuity, momentum, and energy equations across a component. This activity will deliver a TBCC propulsion system model suitable for computationally simulating mode transition. Furthermore, this activity will deliver a baseline controller for the HiTECC propulsion system simulation that will oversee a simulated controlled mode transition.

The HiTECC simulation is being developed in the MATLAB Simulink programming format. This format was chosen to permit the HiTECC elements to be readily available for being applied as baseline elements for the overall propulsion modeling and control architecture described in Figure 3.

### **Computational Modeling**

The objective for the parallel paths of computational simulation development is to make available an overall propulsion system architecture similar to the illustration in Figure 3. The overall simulation would be a useful tool for developing controllers for each component to support component hardware experiments and overall system-level controllers to support the design and flight testing of an airbreathing hypersonic vehicle propulsion system. The four parallel paths mentioned will yield computational simulations to populate the overall simulation. Three of the paths focus on the inlet system. Emphasis was placed on the inlet system component to support hardware testing of the CCE Testbed. The fourth parallel path, the NRA activity to develop HiTECC, will yield a baseline propulsion system simulation. The inlet component from the HiTECC simulation is also representative of the CCE Testbed. The hardware testing of the CCE Testbed in the GRC 10x10 SWT for dynamic mode transition will be discussed next.

The IC data does not address dynamic disturbances to the LSFP that can disgorge the normal shock and unstart the inlet. Dynamic disturbance is a concern and its rejection is important for safe operation of the inlet. The diffuser volume will dampen very high frequency disturbances, and the passive stability bleed system is designed to also effectively reject high frequency disturbances. However, an active control system is needed to reject the low frequency disturbances (Ref. 19). To aid design and development of the active control system, control design models are needed. The SysID testing is anticipated to bring about control design models suitable for designing an active disturbance rejection control system.

The SysID experiments provide the data to develop dynamic models suitable for designing controllers that will address the concern of an airflow disturbance disrupting the normal shock position while the inlet is in the started state. The SysID experiments with the CCE Testbed in the GRC 10x10 SWT are for the following three purposes: First, is to identify the inlet disturbance frequency range that is not protected with the passive bleed system. High frequency disturbances above 100 Hz will be damped with the diffuser volume dynamics. Disturbances with frequencies above 20 Hz should be rejected with the passive bleed system (Ref. 19). Low frequency disturbances, ranging from 0.0 to 0.05 Hz, could be considered, from the inlet perspective, as a change in operating boundary conditions. This low frequency type disturbance, which will impact the location of the normal shock position, can be accommodated through normal scheduled operation of the inlet actuators. This low frequency range is limited because the compressed air loading on the cowl, splitter, and ramp surfaces render these large and heavy effectors to be slow. The schedule controls for these three effectors are not designed to cancel disturbances higher than 0.05 Hz. Therefore, an active disturbance rejection feedback controller is necessary to address inlet system disturbances within the 0.05 to 20 Hz window. Since the bypass valves are capable of operating at 100 Hz, an active controller could be designed to augment the inlet schedule to reject disturbances higher than 0.05 Hz. However, the upper frequency of active bypass control effectiveness is also limited due to diffuser volume dynamics (Ref. 20). The frequency ranges identified above are approximations that will be determined from the dynamic study of the inlet.

A second objective is to identify high-speed feedback pressure sensor locations that will be suitable for supporting an active disturbance rejection controller for the bypass valves. An inlet system being considered for flight needs to be attentive to disturbances and it would not be instrumented with numerous axial pressure sensors. A flight quality inlet system would have one

or two well placed high speed pressure sensors that could be used to provide feedback to an active control system. The CCE Testbed will have high-speed pressure sensors located at many axial locations available for both the IC tests and for the SysID experiments. These pressure sensors will be responsive to disturbances that the control system is expected to reject through operation of the bypass valves. Therefore, the feedback sensor to the active bypass disturbance rejection controller will be a select high-speed pressure sensor. Selecting the best high-speed pressure sensor from the sensors available for providing feedback to the control system will need to be determined.

The third objective is to create empirical CDMs suitable for supporting control research. The CDMs are to be linear about desired operating points of the inlet and must include all important dynamical elements. The CDMs may be coupled to create a piece-wise linear simulation for the mode transition study. The resulting CDMs will be applicable to propulsion control studies, and they will be used to enable development of control algorithms to promote the propulsion system mode transition.

The SysID procedure will be to apply various perturbation signals to the CCE Testbed bypass valve actuators while operating the inlet at select operating conditions, as determined from the IC testing, and measure the LSFP pressure sensitivity to these disturbances. Since the only control actuators being considered are the AIP bypass doors, these actuators are the control variables that will receive system identification perturbation signals. Ultimately, the terminal shock position is to be controlled; however, no terminal shock position sensor is employed. The terminal shock position will be inferred from the dynamic pressure sensors; therefore, the feedback signals to be recorded are the high-speed pressure sensors in the throat area of the LSFP. The goal of the system identification experiment will be continuous linear transfer functions correlating AIP bypass door dynamics to each of the high-speed pressure sensor dynamics.

Four types of perturbation signals will be applied to the bypass doors: single pulse sine wave as illustrated in Figure 8(a), step as illustrated in Figure 8(b), staircase as illustrated in Figure 8(c), and sinusoidal frequency sweep as illustrated in Figure 8(d). The single pulse sine wave, with variable amplitude and frequency, will be used to determine the ability of the inlet passive stability bleed system to absorb internal airflow transients. The step data will be used to design the staircase and sinusoidal frequency sweep signals. The staircase test data will be used to check for linear range and hysteresis, and the data will be compared with resultant linear models. Sinusoidal frequency sweep disturbance signals can be applied to the bypass valve actuators as perturbations about the trim condition. The sinusoidal perturbations are excitations that start from the trim value. The amplitudes are selected so that the operating conditions remain essentially unchanged and can therefore be considered constant. The sinusoidal frequency sweep input signals will cover a 0.0 to 100 Hz frequency band and are expected to result in models with very good prediction capability (Ref. 21). This section continues with a description of each stimulating signal that will be applied to the CCE Testbed. Next, the system identification experiment procedure is presented. Following the experiment procedure description, the method for reducing the system identification raw data to control design models is explained.

The single pulse sine wave test consists of applying a single sine wave perturbation pulse to one of the four AIP bypass control signals. Only one bypass door needs to be perturbed under the assumption that moving multiple bypass doors is linearly related to moving only one—assuming a linear system. This assumption will be verified in the course of the staircase testing. This procedure will be conducted by moving the bypass door towards the closed position, with a pulse as described in Figure 8(a), at frequencies ranging from 0.05 to 100 Hz and variable amplitudes to determine the maximum door amplitude or perturbation that the inlet, with only a passive bleed system employed to prevent unstart, will tolerate without unstating. At the onset of the single pulse sine wave response test, the following signals will be sampled and saved: all

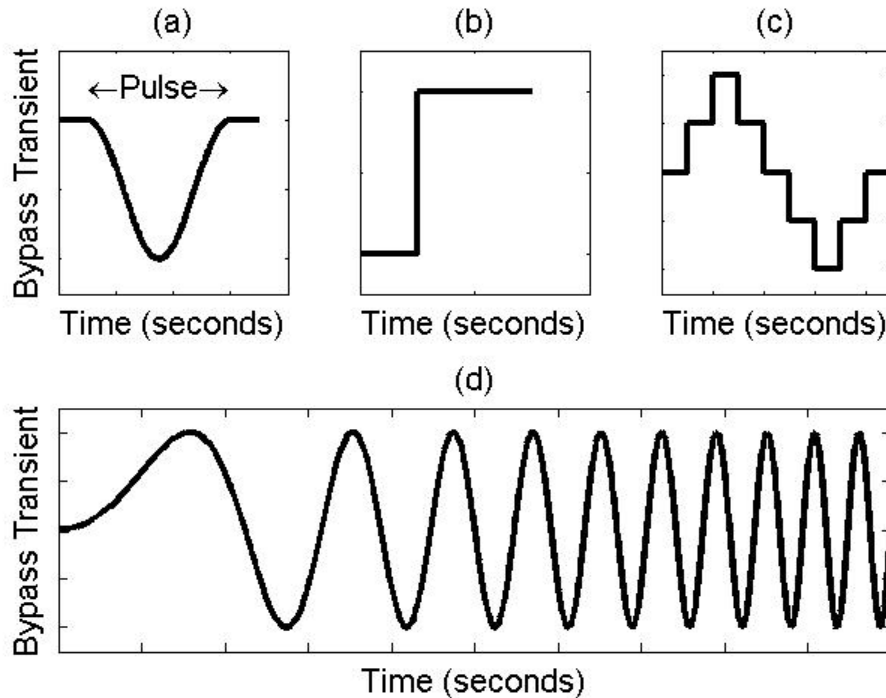


Figure 8.—System Identification experiment perturbation signals to be applied to the inlet bypass doors: a, single sine pulse; b, step; c, staircase; and d, linear sinusoidal sweep.

dynamic pressure sensors, the bypass valve actuator position feedback sensor, and the bypass valve set-point. The single pulse sine wave is used to map the maximum disturbance amplitude, at various frequencies, that will not cause the inlet to unstart.

The step perturbation response test consists of applying a single step perturbation to the operating point AIP bypass control signal as described in Figure 8(b). This procedure will be conducted by perturbing only one of the four bypass valves. At the onset of the step response test, the following signals will be sampled and saved: all dynamic pressure sensors, the bypass valve actuator position feedback sensor, and the bypass valve set-point. The step response data will be used to determine: signal to noise ratio, system settling time, and the system fundamental frequency.

The staircase response tests consist of applying a staircase perturbation pattern of discrete step changes to the operating point AIP bypass control signal as described in Figure 8(c). The value of the incremental movement will be determined based on the step response analysis. The select incremental movement value will be sufficient to promote at least a 10:1 signal-to-noise ratio. The wait time prior to the next step change in amplitude will be set to 200 percent of the calculated settling time determined from the step test—long enough for the system to settle at a new steady-state condition. As illustrated in Figure 8(c), the bypass valve position will take two incremental steps to further open the valve, followed by four incremental steps to close the bypass valve, and then two more incremental steps to return the bypass valve to their original position. At the staircase test onset and through all step changes until completion, the following signals will be sampled and saved: all dynamic pressure sensors, the bypass valve actuator position feedback sensor, and the bypass valve set-point. The duration of the staircase test and the amount of data sampled and saved will be dependent on the system settling time. The staircase data will be used to confirm linearity and check for inherent nonlinear system hysteresis.

The sinusoidal frequency sweep perturbation tests consist of applying sinusoidal perturbation signals, at frequencies that vary linearly with respect to time, to the operating point AIP bypass control signal. A typical linearly varying sinusoidal sweep pattern is illustrated in Figure 8(d). The sinusoidal frequency sweep pattern that will be applied to the AIP bypass doors will span 100 sec, a 0.0 to 100 Hz frequency range, and an amplitude equal to the value used in the staircase tests. For the duration of the sinusoidal frequency sweep tests, the following signals will be sampled and saved: all dynamic pressure sensors, the bypass valve actuator position feedback sensor, and the bypass valve set-point. The sinusoidal frequency sweep experimental data will be reduced to linear control design models at each operating point.

Data from the logged dynamic sensors and stimulating bypass control signals from the frequency sweep perturbation tests will be reduced to linear single-input-single-output rational transfer function models. The parameter identification method from experimental data will use the method of least-squares (Ref. 22). Step responses to the resultant rational transfer function models will be compared against data logged from the staircase tests.

For these experiments, all data analysis is post-processed offline. Therefore, if the data reduction procedure is inadequate, another system identification function or method can be employed with the same data set to determine a CDM. The model quality will be determined by comparing the step response of the model to the data obtained while performing the staircase experiments.

## **Summary and Conclusion**

This paper presented the NASA Fundamental Aeronautics Program (FAP) Hypersonic activity to develop modeling and control design architecture for a Turbine Based Combined Cycle (TBCC) airbreathing hypersonic vehicle propulsion system. The presented architecture will make available a reconfigurable propulsion system simulation with elements that can be removed, modified, or replaced. Furthermore, the element models can function independently to support designing element controllers. An overall control system will then wrap around the element controllers to complete the baseline TBCC propulsion control system. The use for these tools will be to analyze propulsion concept designs for controllability prior to buildup. The first element being developed in this system is the TBCC inlet system. Specifically, the target design for the inlet computational model is the Combined-Cycle Engine (CCE) Testbed. A desire to leverage the Large Perturbation Inlet Model (LAPIN) legacy software to support this task has led to an innovative methodology to enable LAPIN FORTRAN code to synchronously run and interface with code written in another format. This methodology, referred to as LAPIN-in-the-Loop, enables LAPIN to receive and respond to signals from the overall control system model and vice versa. To enhance the capabilities of the LAPIN simulation, an Aeroservo Simulation is also being developed. The Aeroservo Simulation will communicate and exchange data and instructions with LAPIN to enable considering dynamic interactions between the inlet air flow and the inlet mechanical actuators. The mechanical actuator dynamics being addressed include hydraulic actuator dynamics, seal friction, and couplings between air flow and actuator dynamics. Also to address inlet computational modeling, an interactive inlet simulation is being developed. This interactive simulation is user friendly, designed to be flexible to accommodate changes to the inlet design, and it is being written in the same format as the overall propulsion system simulation. A NASA Research Announcement (NRA) award to develop a High Mach Transient Engine Cycle Code (HiTECC) will yield the baseline airbreathing hypersonic propulsion system simulation. The HiTECC simulation will include component simulations, in a modular format, of each element in the overall propulsion system architecture. Finally, experiments planned for the CCE Testbed inlet designed to facilitate mode transition studies was presented that included an Inlet Characterization (IC) test and System Identification (SysID) experiments.

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<b>14. ABSTRACT</b> <p>Control research for a Turbine Based Combined Cycle (TBCC) propulsion system is the current focus of the Hypersonic Guidance, Navigation, and Control (GN&amp;C) discipline team. The ongoing work at the NASA Glenn Research Center (GRC) supports the Hypersonic GN&amp;C effort in developing tools to aid the design of control algorithms to manage a TBCC airbreathing propulsion system during a critical operating period. The critical operating period being addressed in this paper is the span when the propulsion system transitions from one cycle to another, referred to as mode transition. One such tool, that is a basic need for control system design activities, is computational models (hereto forth referred to as models) of the propulsion system. The models of interest for designing and testing controllers are Control Development Models (CDMs) and Control Validation Models (CVMs). CDMs and CVMs are needed for each of the following propulsion system elements: inlet, turbine engine, ram/scram dual-mode combustor, and nozzle. This paper presents an overall architecture for a TBCC propulsion system model that includes all of the propulsion system elements. Efforts are under way, focusing on one of the propulsion system elements, to develop CDMs and CVMs for a TBCC propulsion system inlet. The TBCC inlet aerodynamic design being modeled is that of the Combined-Cycle Engine (CCE) Testbed. The CCE Testbed is a large-scale model of an aerodynamic design that was verified in a small-scale screening experiment. The modeling approach includes employing existing state-of-the-art simulation codes, developing new dynamic simulations, and performing system identification experiments on the hardware in the NASA GRC 10 by 10-Foot Supersonic Wind Tunnel. The developed CDMs and CVMs will be available for control studies prior to hardware buildup. The system identification experiments on the CCE Testbed will characterize the necessary dynamics to be represented in CDMs for control design. These system identification models will also be the reference models to validate the CDM and CVM models. Validated models will give value to the tools used to develop the models.</p>				
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