INTEGRATED TURBINE-BASED COMBINED CYCLE DYNAMIC SIMULATION MODEL

Daniel A. Haid, Eric J. Gamble

SPIRITECH Advanced Products, Inc, Tequesta, Florida

ABSTRACT

A Turbine-Based Combined Cycle (TBCC) dynamic simulation model has been developed to demonstrate all modes of operation, including mode transition, for a turbine-based combined cycle propulsion system. The High Mach Transient Engine Cycle Code (HiTECC) is a highly integrated tool comprised of modules for modeling each of the TBCC systems whose interactions and controllability affect the TBCC propulsion system thrust and operability during its modes of operation. By structuring the simulation modeling tools around the major TBCC functional modes of operation (Dry Turbojet, Afterburning Turbojet, Transition, and Dual Mode Scramjet) the TBCC mode transition and all necessary intermediate events over its entire mission may be developed, modeled, and validated. The reported work details the use of the completed model to simulate a TBCC propulsion system as it accelerates from Mach 2.5, through mode transition, to Mach 7. The completion of this model and its subsequent use to simulate TBCC mode transition significantly extends the state-of-the-art for all TBCC modes of operation by providing a numerical simulation of the systems, interactions, and transient responses affecting the ability of the propulsion system to transition from turbine-based to ramjet/scramjet-based propulsion while maintaining constant thrust.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) Aeronautics Research Mission Directorate (ARMD) Fundamental Aeronautics Program (FAP) Hypersonic Project addresses the fact that all access to earth or planetary orbit, and all entry into earth's atmosphere or any heavenly body with an atmosphere from orbit (or super orbital velocities) require flight through the hypersonic regime.[1] The hypersonic flight regime often proves to be the design driver for most of the vehicle's systems, subsystems, and components. For the United States to continue to advance its capabilities for space access, entry, and high-speed flight within any atmosphere, improved understanding of the hypersonic flight regime and development of improved technologies to withstand and/or take advantage of this environment are required.

The favored solution to the hypersonic airbreathing propulsion problem of maintaining acceptable thrust and fuel consumption over the entire flight spectrum is to unite several different propulsion systems within the same internal flowpath[2]. Airbreathing engines of this type are known as combined cycle engines and include both turbine based combined cycles (TBCC) and rocket based combined cycles (RBCC). Based on the Next Generation Launch Technology (NGLT), TBCC, Two State to Orbit (TSTO), National AeroSpace Plane (NASP), and High Speed Propulsion Assessment (HiSPA) studies, a turbofan and ramjet variable cycle engine is best suited to satisfy the access-to-space mission requirements by maximizing thrust-to-weight ratio while minimizing frontal area and maintaining high performance and operability over a wide operating range[3]. The TBCC dynamic simulation model discussed in this paper advances the state of the art for TBCC systems with simulation and controls software to model all modes of operation over a mission. The mission profile acceptable with this simulation tool includes the mode

The work was funded as a NASA NRA award under contract NNC08CA55C.

transition window when thrust production is transferred from a gas turbine to a dual-mode scramjet propulsion system.

The objective of the TBCC dynamic simulation model development effort was to develop tools and procedures that lead to numerical dynamic system simulations for TBCC systems. Using these tools, models were developed to computationally simulate a TBCC propulsion system which captures the timing and operation of the sequence of events that occur during mode transition. The integrated simulation model discussed in this report is referred to as the High Mach Transient Engine Combined Cycle (HiTECC) code.

This tool results in an integrated simulation for modeling the TBCC propulsion system and subsystems throughout the mission. This highly integrated, module based tool models each of the TBCC subsystems whose interactions and controllability affect the TBCC propulsion system thrust and operability. These five subsystems include the following: Propulsion System (afterburning turbojet and dual mode scramjet), the thermal management system, the fuel system, the hydraulic system, and the control system. Modeling tools were developed from fundamental physics and integrated into a comprehensive dynamic simulation tool that can be used to predict the transient performance. Furthermore, given actual event durations, simulation analysis can be used to properly configure the propulsion system control logic.

According to Stueber et.al.[4], five parallel paths have been taken over the past few years to meet NASA's objective to have a simulation code for the inlet that is suitable for control design and compatible with NASA's overall propulsion system architecture plans. These paths are described as follows: 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. The NRA award mentioned by Stueber is in reference to the simulation model development documented in this report. Finally, five, conduct hardware tests on an inlet model. 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. SPIRITECH is pleased to announce that its effort to make available a user-friendly propulsion system simulation tool that has led to the HiTECC tool has been completed on schedule and within budget.

The gas turbine dynamic simulation model provides engine performance data for turbojet and turbofan engines during high-speed transient studies. The model is built on a component level to provide flexibility to enable modeling a wide range of engine cycles as well as to provide internal engine performance data. In addition, the component maps include a scaling capability that was added so a single set of maps can be used for multiple cycles. The following is a current list of turbine component models included: a fan, splitter, compressor, combustor (main and afterburner), turbine, mixer, and nozzle (upstream of throat). The inlet and nozzle are modeled as separate subsystems due to their integration into the vehicle body and their interfaces with other major subsystems. These two subsystems include ports to connect with and pass data, such as total pressure, total temperature, and absolute flow inputs, to the engine face and outputs.

The Dual Mode ScramJet (DMSJ) dynamic simulation model provides real time engine performance data for ramjet and scramjet engines during high-speed transient studies. This model is also built on a component level to provide flexibility to model a wide range of engine cycles and to provide internal engine performance data.

The Thermal Management System (TMS) model is a detailed physics based computational model of the cooling system used to manage the heat load generated by the dual-mode scramjet and afterburning turbojet propulsion systems. This model has been developed assuming the fuel will be used as the coolant. The coolant flow circuit is modeled in terms of fuel heat-up and pressure loss and includes piping, or plumbing, losses, friction losses, and Rayleigh losses. Incompressible and compressible fluids can be modeled, enabling a wide variety of fuels, including both liquid and gaseous fuels.

The Hydraulics System Model (HSM) is a detailed physics based computational model of the hydraulic system used to control actuators for the propulsion system. Since this model includes the actuation of the variable geometry associated with the inlet and nozzle, it was designed to predict the aero loads and calculate the loads as they are transmitted through the kinematic system to the actuators. The HSM incorporates load calculations and rates of motion, to calculate the system pressure and flow requirements for sizing the hydraulic cylinders and pumps.

The Control System Model (CSM) includes the control laws for controlling all automated events required for the different operational phases. These events include those associated with the TMS, the inlet and nozzle actuation systems, and propulsion system (gas turbine and DMSJ). This system model is able to control operability of the integrated propulsion system throughout a mission that includes mode transition. The “Sequence of Events” defined by Snyder et. al.[5] for TBCC mode transition identifies the steps required to transition from the turbojet to the DMSJ propulsion systems. These steps have been incorporated into the integrated system model as a first step toward defining the control requirements. Furthermore, information regarding feedback loops, sensor locations and correlations, priorities, and system interactions were considered. This paper continues with an overview of the HiTECC software structure. Next, the HiTECC tool at systems level is presented.

TECHNICAL DISCUSSION

PROPULSION SYSTEM MODEL

Organization of the HiTECC TBCC Dynamic Simulator (Figure 1) includes the following four levels of software hierarchy: Simulator, System, Subsystem, and Component. The highest level is the Simulator which contains the routines to accept input, pass information between systems, and provide output. Next is the System Level which contains the Propulsion, Thermal Management, Hydraulics, and Control systems. Each System level is further segmented into Sub-Systems appropriate for supporting the System. Finally, the Sub-Systems are also segmented into Component modules.

The TBCC Propulsion system model is divided into four subsystems. These are the Inlet, Gas Turbine, Dual Mode Scramjet (DMSJ), and Nozzle. Each of these subsystems is broken down further into components (i.e. the gas turbine contains a compressor, combustor, turbine, etc.). Figure 1 illustrates the organization of the HiTECC code that has been developed to simulate a TBCC propulsion system. The HiTECC Component Level includes models of TBCC System physical processes. These models fall into one of two categories. The first includes routines that use performance maps where a number of dependent parameters are defined as a function of a number of independent parameters, usually in the form of look-up tables. These maps are typically applied when component performance can be accurately determined from a small number of independent variables and a significant improvement in computational performance can be achieved over physics based computational models. Typical applications include compressors and turbines. The second category includes routines based on conservation models. These are physical models that balance the continuity, momentum, and energy equations across a component.

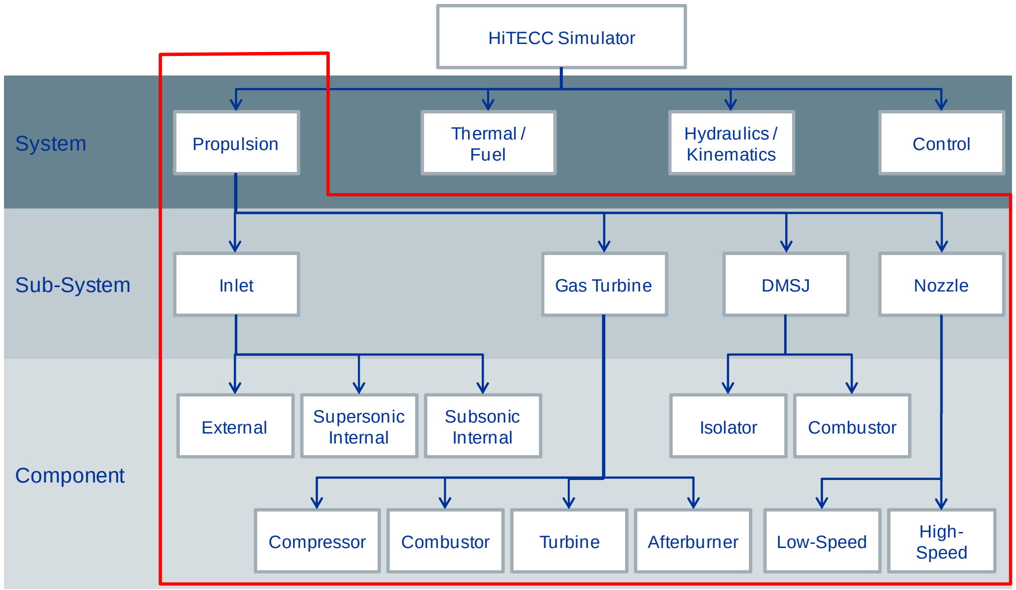

Figure 1. HiTECC Propulsion System Model.

THERMAL MANAGEMENT AND FUEL SYSTEM MODEL

The Thermal Management and Fuel System (Thermal/Fuel) model is designed to simulate fuel flow, fluid energy, and thermal energy transfer for both the low-speed and high-speed flow paths. This model couples a transient flow model with a transient thermal model and determines the fluid dynamic response of the fuel and gas path flows and corresponding thermal response of propulsion system gas path hardware (valve actuation dynamics are included in the Control System). A one-dimensional compressible flow solver allows a variety of fuels, including hydrogen, to be modeled.

This system is organized similarly to the other systems modeled in HiTECC, as shown in Figure 2. The system is broken up into three sub-systems: Flow, Power, and Storage. The Flow sub-system models the fluid and energy flow through gas path panels, valves, and other plumbing components. The Power sub-system models the flow of power to and from the battery, motor, and fuel pump components. The Storage sub-system models fuel flow to and from the storage tank and its associated plumbing components.

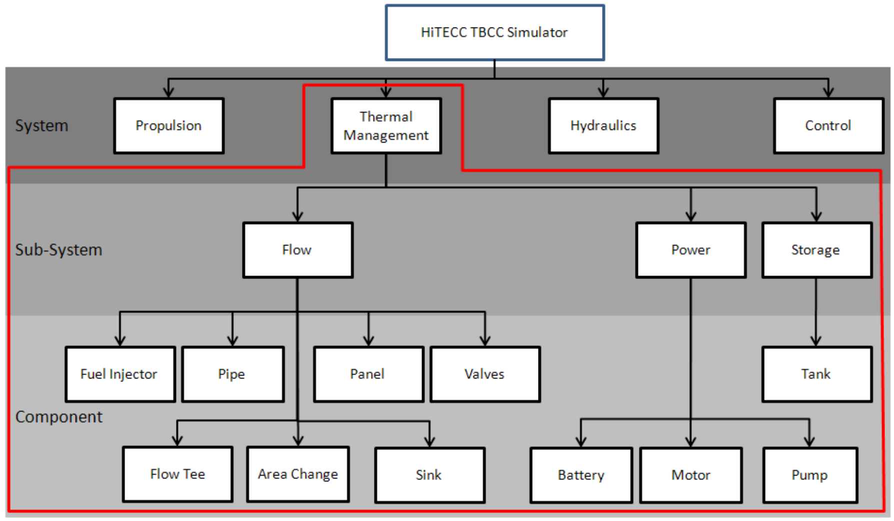

Figure 2. HiTECC Thermal Management and Fuel System Model.

HYDRAULICS AND KINEMATICS SYSTEM MODEL

The Hydraulic and Kinematics System (Hydraulics) simulates the variable geometry features of the inlet and nozzle for both the low-speed and high-speed flow paths. The system includes a flow model for determining the dynamic response of the hydraulic fluid, a kinematic model for the low-speed and high-speed inlet cowls and nozzle flaps, and models for the power storage and generation for pumping the hydraulic fluid.

The organization of this system is illustrated in Figure 3 with four sub-systems. The first, the Flow sub-system, models the fluid and energy flow through actuators, valves, and other hydraulic components. The second, the Kinematics subsystem, models the loads and energy transfer through body (links) and joint components. The third, the Power sub-system, models the flow of power from the battery, motor, and pump components. Finally, the Storage sub-system models fluid flow to and from the storage tank and other plumbing components associated with it.

The Hydraulic and Kinematic System is required for simulating fluid flow throughout the hydraulic system and mechanical loads, and it addresses energy transfer through the kinematics system. The flow subsystem is modeled with a one-dimensional incompressible flow solver. The Kinematics model components use a dynamic rigid body model. This system requires the user to input the arrangement of the components, their specifications, and the hydraulic fluid type. Output from the system includes data from the individual components that can be used to adjust the system sizing.

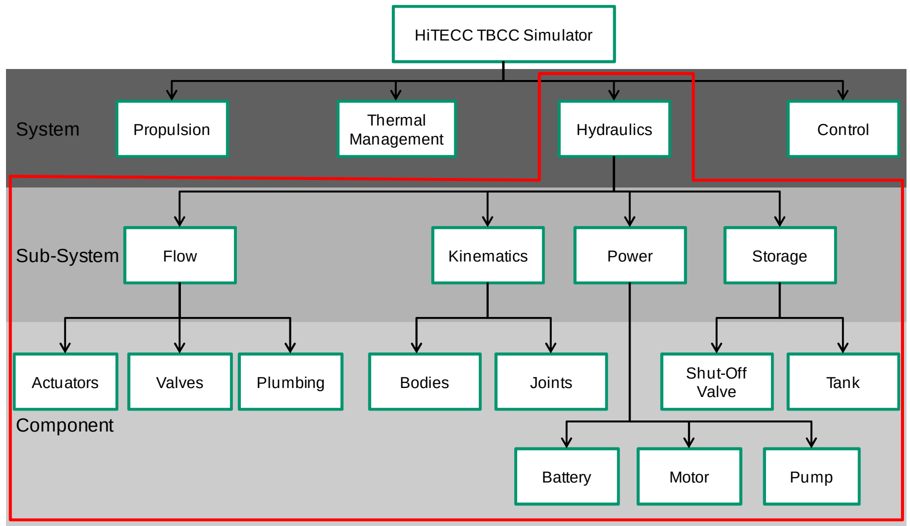

Figure 3. HiTECC Hydraulics and Kinematics System Model.

INTEGRATED MODEL

The Propulsion, Thermal Management/Fuel System, and Hydraulics/Kinematics models were integrated into a common format suitable for running simulations with Simulink® software. The illustration in Figure 4 is the HiTECC System level perspective as it appears using the Simulink software. In addition, a Control system was developed and incorporated within the integrated model.

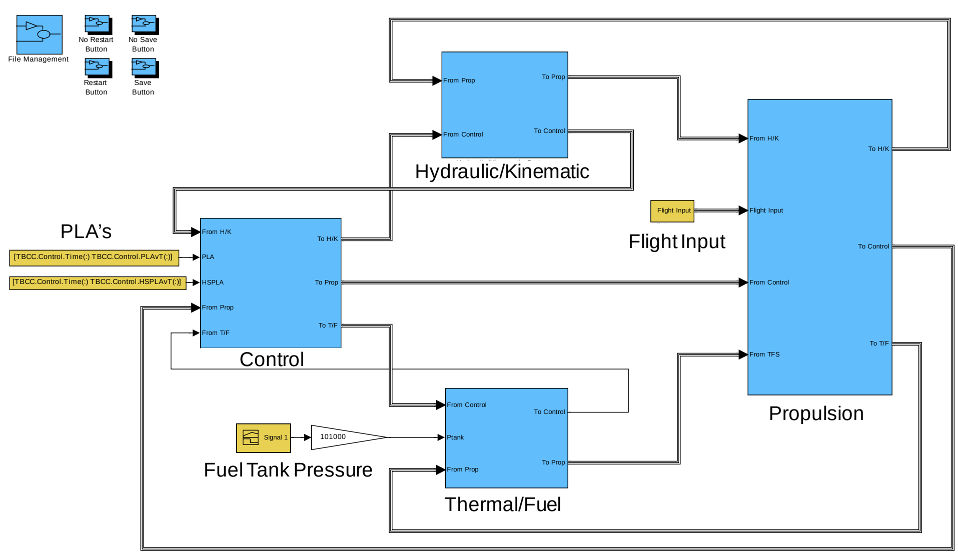

Figure 4. Integrated HiTECC Model Illustrated using Simulink® Software

The NASA Combined Cycle Engine Large Scale Inlet for Mode Transition studies (CCE-L-IMX) shown in Figure 5, is built using components from the Propulsion and Hydraulics/Kinematics Systems. The geometry is defined in the Kinematics sub-system of the Hydraulics/Kinematic System. Relevant geometry is communicated to the Propulsion System. The Propulsion System returns the aerodynamic loads to the Hydraulics/Kinematics System where the dynamic response of the bodies and hydraulic actuators are calculated.

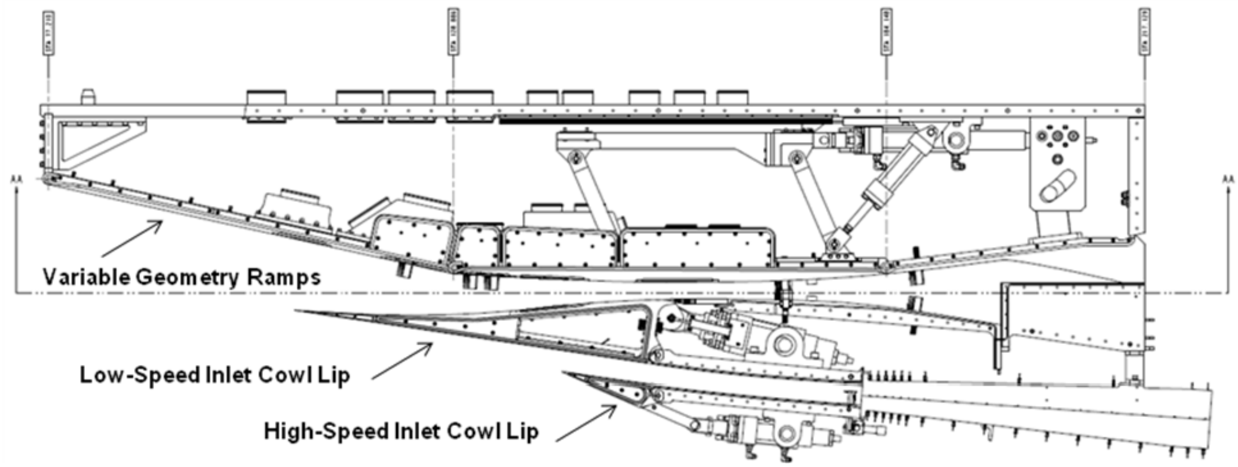

Figure 5. Inlet Components with Actuators: Variable Geometry Ramp, Low-Speed Inlet Cowl Lip, and the High-Speed Inlet Cowl Lip [6]

High and low-speed cowl lips (flaps) rotate about their respective body connection points, identified as rotation points in Figure 6, with the flap structures directly connected to the driving hydraulic actuators. These actuators are positioned in the cavities aft of the flaps and are supported by rotational joints grounded to the aircraft.

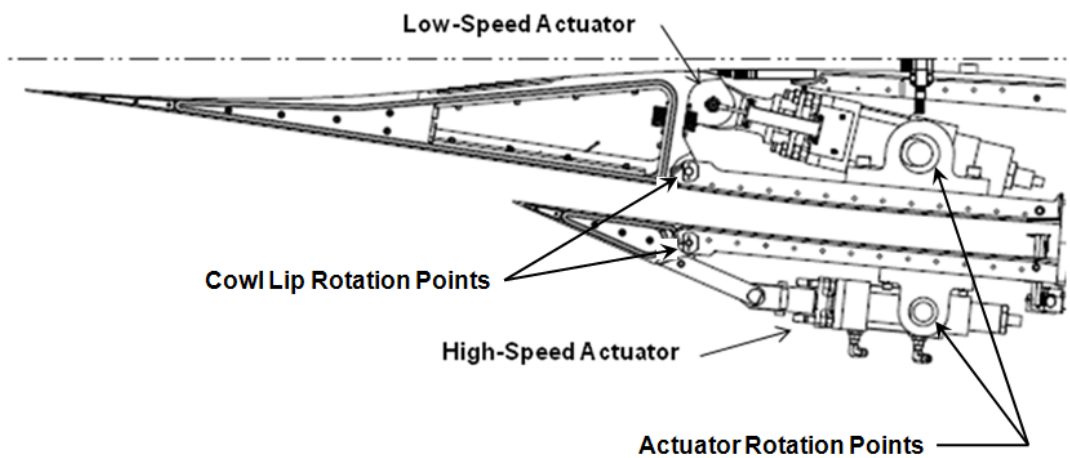

Figure 6. Low and High Speed Cowl Lip (Flap) Actuators, Flap Rotational Points, and Actuator Rotational Points [6]

The configuration for the Thermal Management and Fuel System adopted for this presentation is shown in Figure 7. The Thermal Management and Fuel System uses fuel to cool the turbojet afterburner liner and the DMSJ liner. The fuel is circulated through the liners and vehicle fuel tanks continuously with a variable speed pump driven by an electric motor. A controller regulates the pump speed to maintain a set pressure in the fuel system as flow demand varies. Three control valves divert a portion of the fuel flow into the turbojet main burner, turbojet afterburner, and the DMSJ. A fourth control valve varies the flow returning to the tank. This fourth valve is adjusted to maintain fuel tank temperature below 550K at high power conditions and a minimum flow rate at low power conditions. This approach was chosen for its simplicity, but allows for verification of all the physical processes that occur in more complex systems.

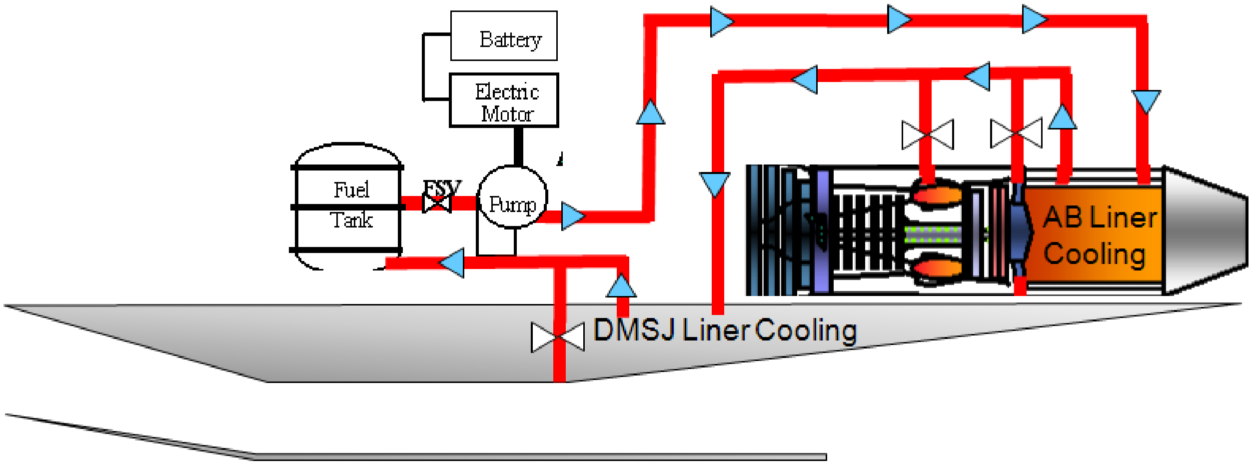

Figure 7. Thermal Management and Fuel System

The list of control effectors in the HiTECC simulation is shown in Table 1. All control effectors represent either a motor or a servo (valve), and all sensed parameters are accessible within the HiTECC simulation. These motors, servos, and sensors have all been integrated into the physical model along with their corresponding control logic.

Table 1. Initial HiTECC Control Effectors

Control Effectors	Control Variable	Control Loop	Sensed Parameters	Regulated Variable
TJ Main Fuel Flow	Valve Position	Closed	PLA, N_L, T_{T2L}, P_{T2L}	N_L
Fuel Pump	Speed	Closed	P_{fuel}	P_{fuel}
TJ AB Fuel Flow	Valve Position	Open	PLA, P_{T5L}	
TJ Bypass Valve	Valve Position	Closed	x_{shockL},M_0	x_{shockL}
Inlet LS Bleed	Valve Position	Closed	M_t	M_t
Hydraulic Pump	Speed	Open	P_{hyd}	
Inlet Ramp Angle	Valve Position	Closed	s_2,M_0	s_2
Inlet LS Cowl Angle	Valve Position	Closed	s_3,M_0	s_3
Inlet HS Cowl Angle	Valve Position	Closed	s_4,M_0	s_4
Nozzle LS Conv. Flap Angle	Valve Position	Closed	N_L, T_{T2L}, P_{T2L}, T_{t5L}	T_{t5L}
Nozzle LS Div. Flap Angle	Valve Position	Closed	s_{DL}, s_{CL}, P_{atm}, P_{t6L}	s_{DL}
Nozzle HS Conv. Flap Angle	Valve Position	Closed	s_5, M_0	s_5
Nozzle HS Cowl Angle	Valve Position	Closed	s_6, M_0	s_6
DMSJ Fuel Flow	Valve Position	Closed	PLA, x_{shockH}, M_0	x_{shockH}

The Closed Control Loops employ proportional and integrating (PI) control algorithms. Controller tuning for each of the PIs was accomplished using a manual approach, with Ziegler-Nichols[7] techniques employed in some instances. Initially, the PI component gains were set manually. These gains were adjusted while running the models using trial-and-error until the system performed with stable results.

The challenge of integrating the inlet with the gas-turbine is to balance the mass flow captured by the inlet with the flow demanded by the engine. A well balanced system is one in which a stable normal shock structure resides in the low-speed flow-path. Ideally, to maximize inlet performance, the normal shock would be located at the throat of the air-flow path. However, such a configuration would be risky, because the inlet system would be prone to unstart. To decrease the probability of an inlet unstart, the normal shock is selected to reside downstream from the throat at an acceptable cost to inlet performance. A normal shock that resides too far downstream from the throat will result in poor inlet performance. Let the term that identifies the shock position, shock margin, be defined as the ratio of the distance between the throat and the shock position to the length of the diffuser duct. A stable shock margin will have a value ranging from 0 to 1 where 0 (ideal) is located at the inlet throat, and 1 (supercritical) is located at the engine face. The simulations considered in this paper were controlled to maintain a shock margin of 0.35. The three actuators that define the inlet geometry are set based on Mach number to maintain the desired shock margin. To balance the flow between the inlet and the engine and to keep the desired shock margin, a bypass was installed. The bypass can be moved towards close-off to decrease the shock margin or it can be moved towards more open, which currently dumps the flow overboard, to increase shock margin. In addition to the bypass flow, bleed flow on the ramp surface is included to remove low-energy flow from the boundary layer. This flow is also actively controlled to maintain a Mach number at the throat of 1.3.

The control system is capable of preventing the inlet from unstarting or operating supercritical, although there is significant variation in shock margin from the design point. This could be relieved with some additional tuning. On the other hand, the throat Mach number is maintained very close to 1.3 over the operating range until close to shutdown, where the geometry prohibits that low of a Mach number.

Shaft speed (N) and turbine exit temperature (T_{t5}) are the regulated parameters used to control the gas turbine. For simplicity during partial power, the exhaust nozzle is controlled to an area schedule based on Power Lever Angle (PLA).

RESULTS: TBCC SYSTEM SIMULATION

Two simulations were conducted to demonstrate the capability of the HiTECC tool to develop simulations for TBCC propulsion systems. The first, Flight Range Demonstration, demonstrated the ability to operate over the flight range of Mach 2.5 through 7.0. This included turbojet-only operation, mode transition, and DMSJ-only operation. The second, Mode Transition Sequence of Events, demonstrated the model’s ability to simulate mode transition with sufficient time resolution for evaluating the sequence and timing of events during this complex and critical period.

FLIGHT RANGE DEMONSTRATION

A simulation was developed using the HiTECC tool to simulate a propulsion system as its vehicle spans the Flight Mach numbers and operating modes shown in Figure 8. This flight trajectory is one with a vehicle accelerating from Mach 2.5 to 7.0 and includes the critical mode transition period at Mach 3.75. The periods of turbine-only, transition, and DMSJ-only operation are also illustrated. The schedules for the PLAs for both low-speed and high-speed flow paths, are shown in Figure 9. The assumed equivalence ratio, or phi, for the DMSJ is also shown. Equivalence ratio is the ratio of fuel flow divided by the stoichiometric fuel flow.

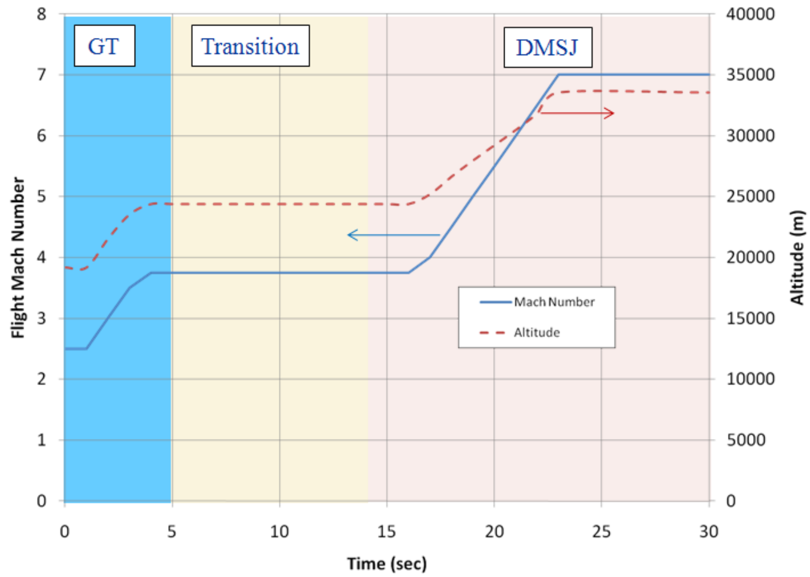

Figure 8. Flight Mach Numbers and Operating Conditions

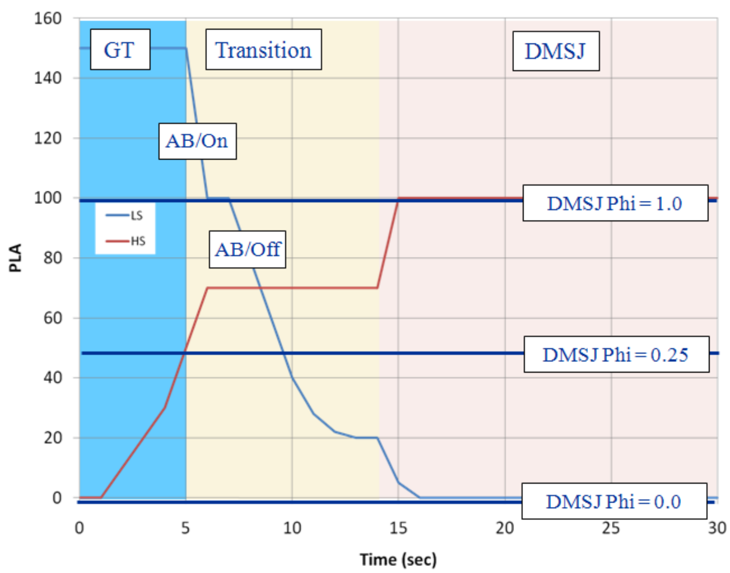

Figure 9. Power Lever Angle Schedules

Simulation results indicating liner surface temperatures and fuel temperatures entering the turbojet and DMSJ are shown in Figure 10 and Figure 11, respectively. At time t=0, during turbojet only operation, the temperature in the afterburner is significantly higher than the temperature in the DMSJ gas path, as reflected in the liner temperatures. However, the fuel entering the turbojet is cooler than the fuel at the DMSJ fuel injector since it has only passed through the afterburner liner. As the vehicle accelerates during turbojet-only operation, the gas path temperatures of the two streams rise as Mach number increases due to the increase in the total temperature of the air, as indicated by liner temperatures. The afterburner gas path temperature does not rise as rapidly, though, as the control system reduces fuel flow in the main burner to maintain the maximum allowable turbine inlet temperature.

At approximately five seconds, the total temperature of the fuel entering the DMSJ exceeds the maximum allowable fuel temperature of 550K. The controller adjusts the control valve to increase recirculation fuel flow to maintain that temperature. The fuel recirculation valve controller continues to make adjustments as temperatures continue to increase in the DMSJ due to acceleration and increased gas path equivalence ratio.

The trends in fuel and liner temperature as gas path temperatures changed due to changes in flight conditions and mode of operation were as expected. Although the fuel temperature exceeding the maximum limit is not desirable from an operational standpoint, it does demonstrate the ability of the tool to assess the design of the thermal management and fuel system as well as the control system design.

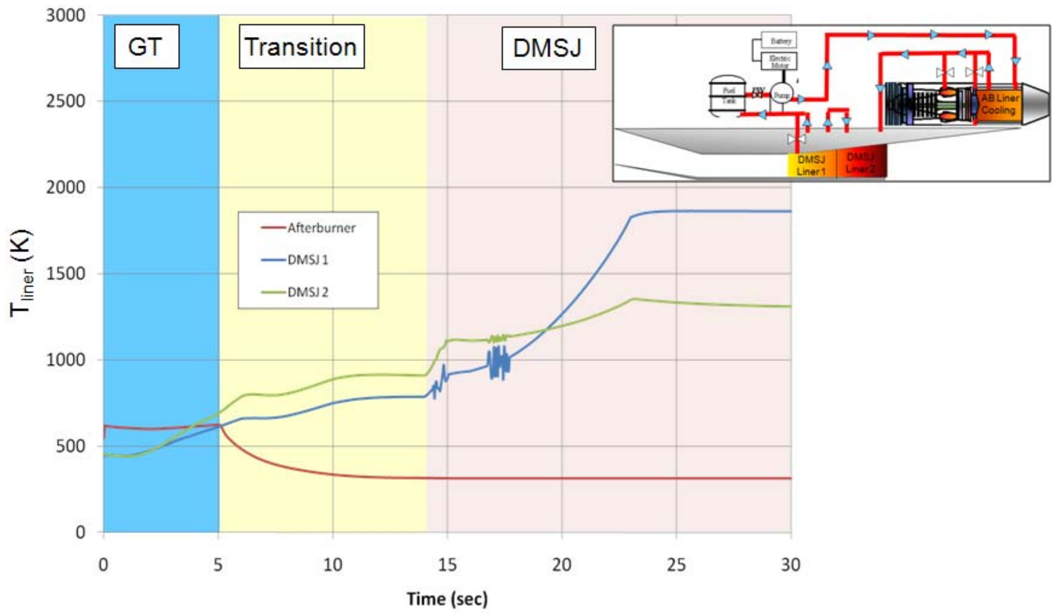

Figure 10. Liner Surface Temperatures versus Simulation Time

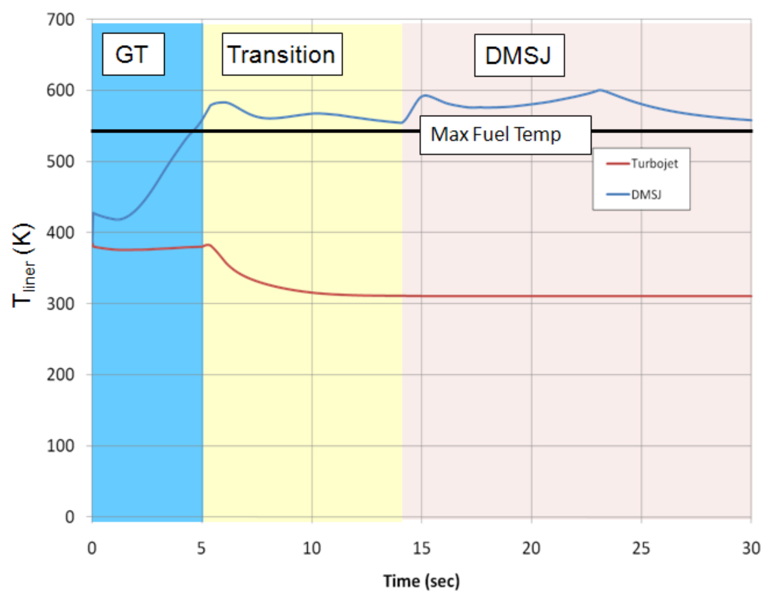

Figure 11. Fuel Temperature Response to Acceleration

The simulation also provided the response of the low speed and high speed exhaust systems. The low-speed convergent flap controls the throat area of the low-speed nozzle and is used to regulate the turbojet exhaust gas temperature at military rated power (100% shaft speed) up to maximum rated power (full augmentation) and follows an area schedule at partial power. The convergent flap position is often monitored with its actuator stroke, which is shown in Figure 12 over the range of flight conditions and operating modes. As the vehicle accelerates during turbojet-only operation at maximum power, the flap moves to gradually reduce flow area. From *t*=5 to *t*=6 seconds, when the transition from turbojet to DMSJ begins, the flap rotates rapidly to decrease the exhaust area as the afterburner is shut down. Finally, the flap gradually rotates to its final position at *t*=14 seconds when the turbojet shuts down. The throat area does not fully close since the divergent flap is used to close off the flow path.

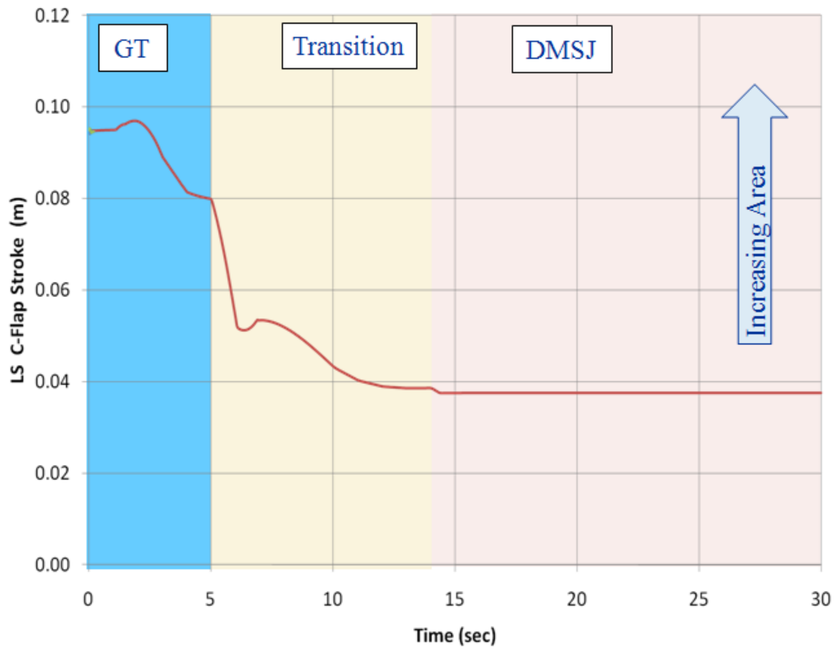

Figure 12. Low-Speed Convergent Flap Position

The low-speed nozzle total pressure and aerodynamic loads on the low-speed convergent flap over the range of flight conditions and operating modes are shown in Figure 13 and Figure 14, respectively. During turbojet only operation, the nozzle pressure ratio rises as the vehicle accelerates, leading to an increase in the magnitude of the aerodynamic loads. At the beginning of transition, the nozzle pressure ratio fluctuates as the low-speed flap is regulated to maintain the proper exhaust gas temperature while the afterburner shuts down. As transition continues until complete turbojet shut-down, the pressure and load steadily drop.

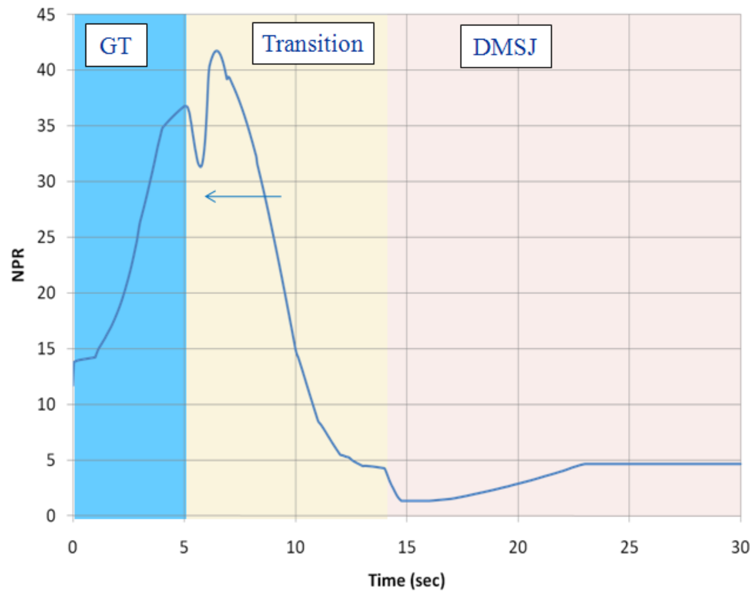

Figure 13. Low-Speed Nozzle Total Pressure

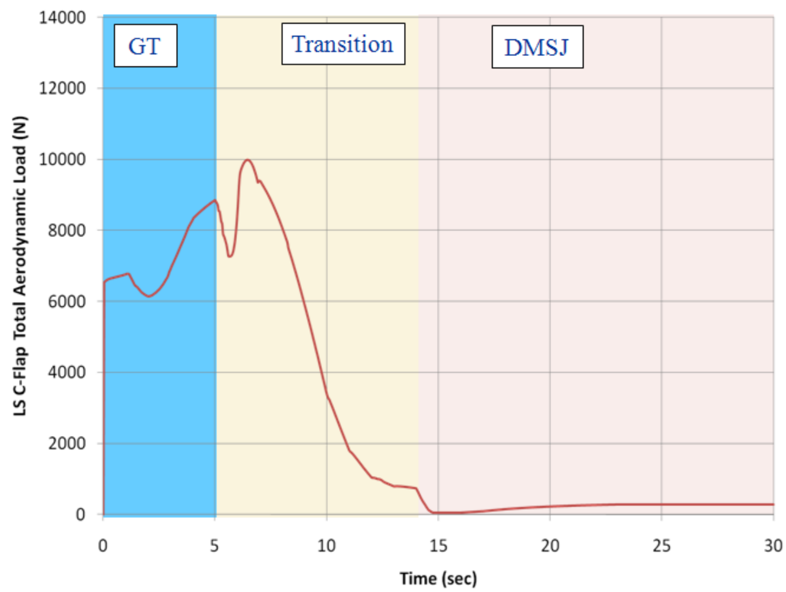

Figure 14. Low-Speed Convergent Flap Aerodynamic Loads

The response of the convergent flap actuator through this mission profile is shown Figure 15. The reaction load does not exactly mimic that of the aerodynamic load as the distribution of the load between the actuator and ground is affected by the angle of the flap. This is best seen between *t*=5 and *t*=6 seconds when the afterburner shuts down. The aerodynamic load peaks closer to six seconds while the actuator load peaks at five seconds.

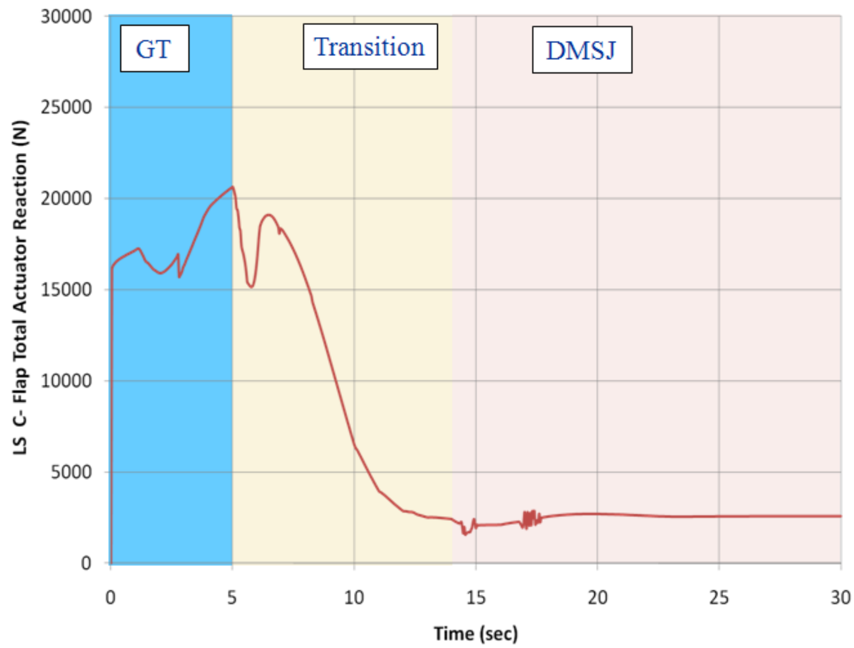

Figure 15. Low-Speed Convergent Flap Actuator Reaction Loads

MODE TRANSITION SEQUENCE OF EVENTS DEMONSTRATION

A more detailed investigation of the sequence of events that occur as the propulsion system transitions from the low speed (turbojet) to the high speed (DMSJ) system was performed. The sequence of events defined by Snyder et. al.[5] for a transition Mach number of 4.0 was used as a starting point for the investigation. The major phases within the sequence of events include:

- DMSJ start sequence
- Turbojet afterburner staged shutdown / DMSJ throttle up
- Turbojet shutdown/ DMSJ throttle up
- Turbojet windmilling / cool down
- Transition complete

In the absence of a vehicle model, the criteria for operation during transition was to maintain constant gross thrust as the propulsion system transitioned from the low-speed turbojet to the high-speed DMSJ. During the simulation, the low-speed power lever angle (PLA), was decreased and the high-speed power lever angle (HSPLA) was increased through user inputs. This was performed in a stepwise fashion with angle changes occurring over a 0.1 second period, as shown in Figure 16, so as not to limit the response of the propulsion system components. This allowed the limiting control effector during each phase to be identified.

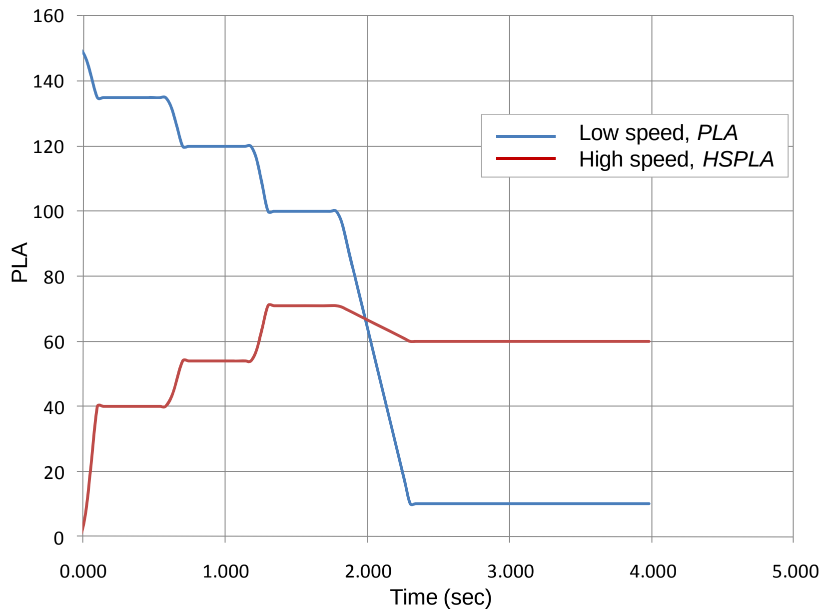

Figure 16. PLA Input Schedule During Transition Sequence of Events Demonstration

A timeline showing the operation of the control effectors during a HiTECC simulation of transition is shown in Figure 17. The turbojet subsystem currently does not have a windmilling model; therefore, the turbojet windmilling/cool down phase is not included. Yellow indicates when the response of a control effector is causing the propulsion system to approach a limit; red indicates that a control effector has caused a limit to be exceeded.

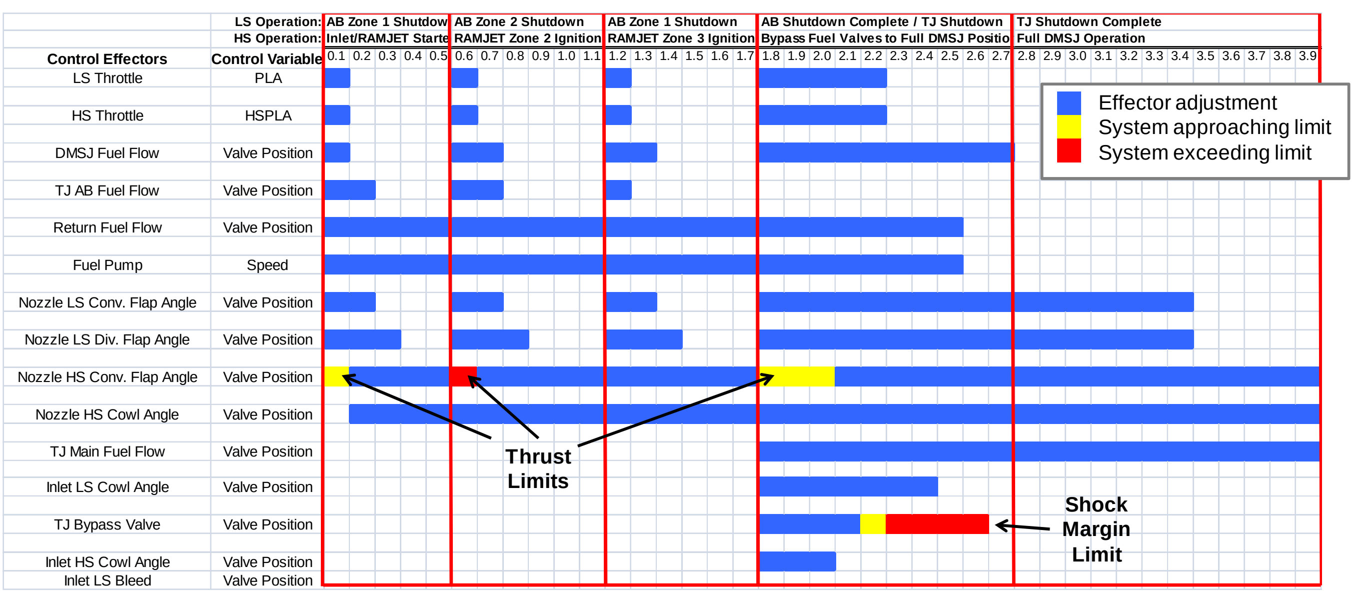

Figure 17. Control Effector Timeline During Sequence of Events Demonstration

A summary of the limits that were monitored during the simulation is included in Figure 18. Note that the thrust limit of *Fg*=10,100 ±5% and the shock margin limit of 0.25<X_{shock}<0.45 were exceeded in the simulation. Shock margin, X_{shock}, of 0 indicates inlet unstart while 1 indicates that the terminal shock is located at the engine face. The shock margin limits were selected at 0.25 and 0.45 to provide adequate margin at all times to ensure that the inlet does not unstart and that the shock does not move to the engine face.

1. Total Vehicle Thrust: F_g = 10,100 N 5%
2. Shock Margin: 0.25 < X_{shock} < 0.45

Limits Exceeded

Limits Not Exceeded

3. Fuel Temperature: T_{fuel} < 638 K
4. Liner Temperature: T_{liner} < 1100 K

Figure 18. Limits Monitored During Sequence of Events Demonstration

During afterburner shutdown, the thrust limit was nearly exceeded at the start of transition and at the start of turbojet shutdown and was exceeded at t=0.5 seconds, as shown in Figure 19. ("Red" lines indicate the thrust limit of *Fg*=10,100 ±5%. "Yellow" lines were added at *Fg*=10,100 ±3% to indicate when the system was approaching the limit.) Further investigation showed that the high-speed exhaust nozzle convergent flap was slow to move into position for optimal expansion, thereby limiting the thrust from the high-speed side. Better response out of the high-speed convergent flap could be expected if the actuators and controls are optimized. Control optimization was not part of this study.

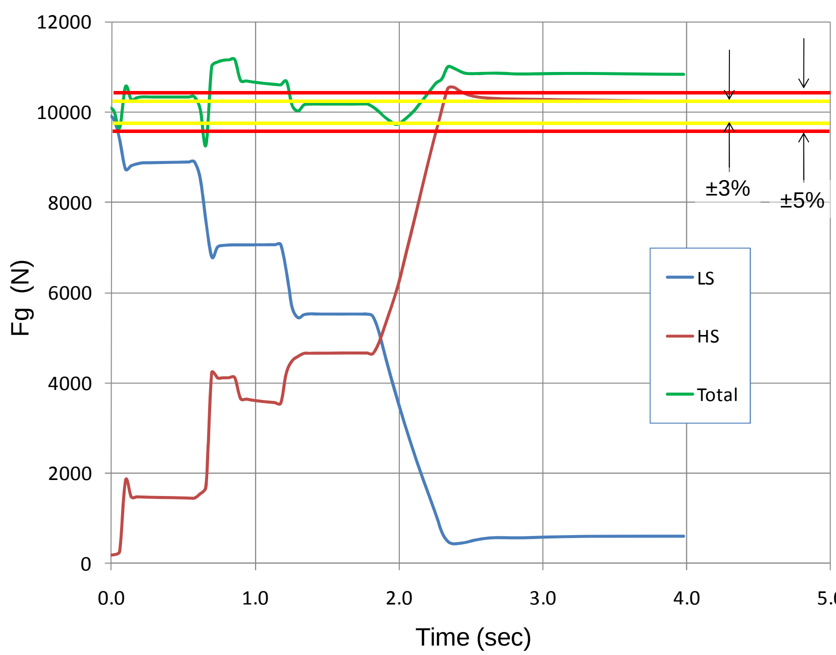

Figure 19. Gross Thrust During Sequence of Events Demonstration

The shock margin limit was also exceeded during turbojet shutdown. This eventually led to a low-speed inlet unstart as shown in Figure 20. Further investigation indicated that the turbojet bypass valve was not responding quickly enough to increase air flow and balance out the drop in flow into the engine as the turbojet shut down. This poor response was due to gains being set at a different flight point. Once again, a better response could be expected through control optimization.

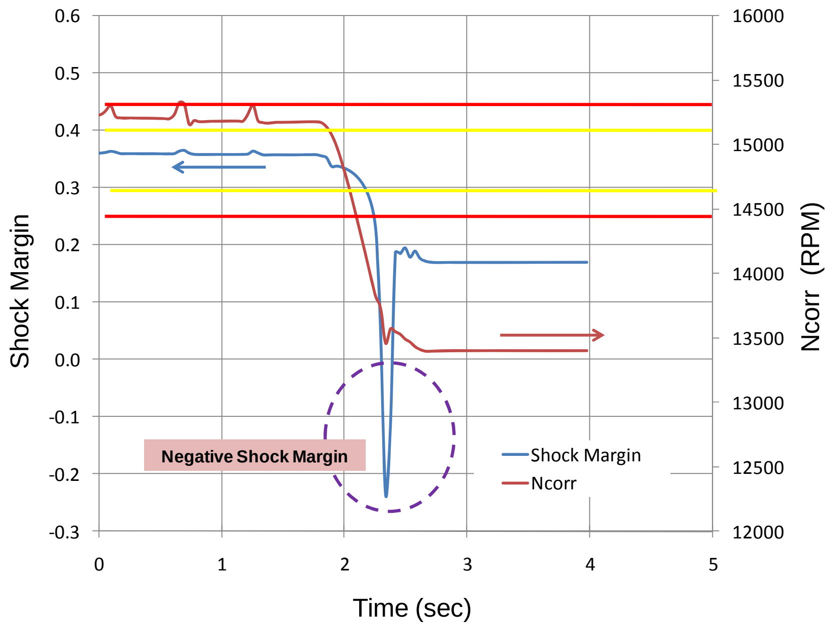

Figure 20. Shock Margin During Sequence of Events Demonstration

CONCLUSION

Tools and procedures have been developed for numerical dynamic system modeling of the Turbine Based Combined Cycle (TBCC) propulsion systems, including both the gas turbine and dual mode scramjet engines. These tools have been incorporated within the High Mach Transient Engine Combined Cycle (HiTECC) code to computationally simulate a TBCC propulsion system. HiTECC is a dynamic turbine engine model formatted to run using Simulink® software to provide engine performance predictions during high-speed transient studies. The model is built down to the component level to provide flexibility to model a wide range of engine cycles and to provide internal engine performance data. The tool is structured to simulate the following systems: Propulsion, Thermal/Fuel, Hydraulics/Kinematics, and Control. Each System is further segmented into Sub-Systems. For the Propulsion system, the sub-systems are the Inlet, Gas Turbine, Dual-Mode ScramJet (DMSJ) and the Nozzle. Each of these subsystems includes a collection of component models.

A system study was demonstrated for a mission that accelerated from Mach 2.5, transitioned at Mach 3.8, and terminated at Mach 7. This simulation demonstrated the HiTECC TBCC Dynamic Simulator's ability to integrate all the subsystems and predict the performance of a TBCC engine within the design requirements. In addition, a detailed investigation was performed of the TBCC mode transition at a Mach 4 flight condition. This simulation added fidelity to the "Sequence of Events" for TBCC mode transition and provided insight into the control effectors and system limits that drive the overall time requirements for transitioning from the low speed to the high speed propulsion systems.

The development of the TBCC propulsion system dynamic model significantly extends the state-of-the-art for TBCC vehicles by providing the capability for numerical simulation of the propulsion systems for use in future control system development. The HiTECC simulator provides definition of transient response rates and system interactions that will define the control laws required for mode transition.

ACKNOWLEDGMENT

The work documented in this paper is the product of a NASA NRA award under contract NNC08CA55C. The authors would like to thank Dr. Thomas J. Stueber of NASA Glenn Research Center for his guidance and support throughout this effort.

REFERENCES

[1] Auslender, A.H., Suder, K.L., and Thomas. S.R., ***An Overview Of The NASA FAP Hypersonic Project Airbreathing Propulsion Research***, AIAA 2009-7277, 16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference, Bremen, Germany (Oct 2009).

[2] Heiser, W.H., Pratt, D.T., ***Hypersonic Airbreathing Propulsion***, pg. 456, AIAA Education Series, AIAA Washington DC (1994).

[3] Pittman, J., Bartolotta, P.A., Mansour, N.N., ***Fundamental Aeronautics Hypersonics Project Reference Document*** (May 2006).

[4] Stueber, T.J., Vrnak, D.R., Le, D.K., and Ouzts, P.J., ***Control Activity in Support of NASA Turbine Based Combined Cycle (TBCC) Research***, NASA/TM—2010-216109, (March 2010)

[5] Snyder, L.E., Escher, D.W., DeFrancesco, R.L., Gutierrez, J.L., and Buckwalter, D.L., ***Turbine Based Combination Cycle (TBCC) Propulsion Subsystem Integration***, AIAA 2004-3649, (July 2004).

[6] S. Morales, “ATK Instrumentation Layout,” Drawing CCE-47502, June 2009

[7] Ziegler, J.G and Nichols, N. B. (1942). ***Optimum Settings for Automatic Controllers***, Transactions of the ASME. **64**. pp. 759–768.