CLOSED–LOOP CONTROL SIMULATION OF AN HSCT INLET

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Abstract

The use of LAPIN, an analysis technique for simulating supersonic mixed–compression inlets, to simulate the High Speed Civil Transport (HSCT) axisymmetric inlet and its control system is presented. The controllable features of the axisymmetric inlet include a translating centerbody, bypass doors, bleeds and a throat slot/vortex valve. The control system must maintain acceptable levels of total pressure distortion at the compressor face, and keep the inlet from unstarting in response to flow perturbations from either upstream (freestream) or downstream (engine). LAPIN is an acronym for "Large Amplitude Perturbation – Inlet". Sverdrup Technology, Inc., developed LAPIN on contract to NASA–Lewis Research Center. LAPIN numerically solves the quasi–one–dimensional time–dependent equations of motion for inlets, and has capabilities of modeling bleed flow, bypass flow, and centerbody movement, but does not have closed loop control capability for any of the inlet control system features. The primary emphasis in this paper is the integration and evaluation of closed–loop controls with the LAPIN inlet model. Integration of the controller with the LAPIN code is discussed. The translating centerbody and bypass door control laws are described and their performance presented.

Introduction

The objective of this effort was to identify and use simulation and analysis tools to develop a control system design for the HSCT inlet. The inlet selected for the simulation is the baseline HSCT inlet, the MCTCB (Mixed Compression Translating Centerbody) axisymmetric inlet, developed by Boeing.(1),(2)

The inlet control system objectives were to control the inlet to maintain acceptable total pressure distortion and recovery levels at the compressor face. The control system must keep the inlet from unstarting in response to upstream (freestream) or downstream (engine) flow perturbations.

The inlet control system design plan was to simulate the inlet with LAPIN, a one–dimensional nonlinear unsteady inlet code, and then develop closed–loop control subroutines for the controllable inlet features and integrate them with LAPIN.

LAPIN is an acronym for "Large Amplitude Perturbation – Inlet" and is an analysis technique for simulating supersonic mixed–compression inlets for both small signal and large flow field perturbations such as hammershock and unstart/restart transients.(3) LAPIN numerically solves the quasi–one–dimensional time–dependent equations of motion for inlets, and has capabilities of modeling bleed flow, bypass flow, and centerbody movement, but does not have closed loop control capability for any of the inlet control system features.

The first task was to model the inlet at the steady–state cruise design point condition and compare LAPIN results to predicted results. We then perturbed the steady–state LAPIN model with upstream and downstream flow perturbations and observed the inlet response. The next step was to develop closed–loop control of the centerbody and the bypass doors and to integrate these controls with LAPIN. Future work on the control system will be to develop closed–loop control of the throat slot/vortex valve.

The control system development process included using different levels of design and analysis tools in addition to LAPIN. To develop and analyze control laws, we used simple, fast linear models of the inlet and controller. We used EASY5 (Engineering Analysis System – a Boeing program which is used to model, analyze and design large, complex systems) for this level of design and analysis, and then evaluated the models and control laws by comparing time history results from the linear models to LAPIN results. We developed the controls subroutines from the EASY5 controller models and then integrated them with LAPIN.

For further control law validation, we plan to use three–dimensional time–accurate unsteady CFD (NPARC and similar codes) to compare to LAPIN and linear model results. Current time–accurate simulations for the axisymmetric inlet use two–dimensional PARC to gain understanding and expertise before starting three–dimensional time–accurate work. For the axisymmetric inlet, the three–dimensional codes can provide flow field analysis for angle of attack conditions and other nonuniform flow field conditions not accounted for by LAPIN. Three–dimensional CFD will also be necessary to analyze the two–dimensional inlet.

Figure 1 shows the MCTCB axisymmetric Inlet, which is the baseline inlet for the HSCT, and is also known as the AST (Advanced Supersonic Transport) inlet. The features available for controlling the inlet are the translating centerbody, the bypass doors, and the throat slot/vortex valve. The translating centerbody controls throat location and Mach number, and also affects normal shock location. The bypass doors control normal shock location by controlling bypass flow. Both of these features involve moving relatively large amounts of mass, and so are relatively slow to respond to a command. The throat slot / vortex valve feature can react more quickly.

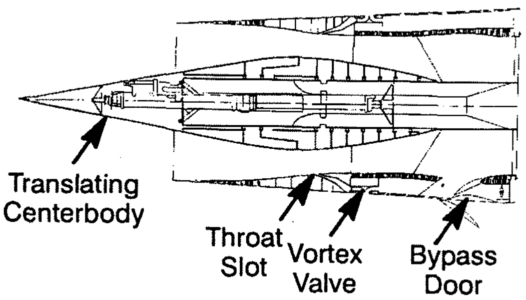


Figure 1. Mixed–Compression Translating Centerbody Inlet

Recently completed work performed at Boeing under NASA Contract NAS3–25963 defines a free-stream disturbance spectrum which contains energy over the entire frequency range, from very low to very high.(4) The controls design approach is to use the translating centerbody and bypass doors to address the low frequency portion of the disturbance spectrum, and to use vortex valves along with static margin to address the high frequency portion of the disturbance spectrum.

In this effort, we designed a single loop for centerbody control and a single loop for bypass door control, and then made sure that the integrated performance was acceptable. In future studies, it may be beneficial to investigate multivariable control technology.

Procedure and Results

Steady–State Results

We modeled the MCTCB inlet with LAPIN and found a steady–state solution for the Mach 2.4 65000 ft design point cruise condition. Figure 2 shows the axial Mach number distribution as computed by LAPIN compared to predicted cowl and centerbody Mach number distributions for the AST inlet. LAPIN results predict a throat Mach number of 1.29 which is 3.2 percent higher than the design throat Mach number of 1.25 (which is a 1–D approximation). This difference may be due to the lack of an oblique shock loss model (a 2–D phenomenon) in LAPIN (a 1–D code). Normal shock Mach number as computed by LAPIN was 1.31 as compared to the AST inlet prediction of 1.30, although normal shock Mach number values cannot agree if throat Mach number does not. Inlet recovery computed by LAPIN was 0.976, which is 4.7% higher than the AST inlet prediction of 0.932. This difference may be due to not modeling subsonic diffuser losses in LAPIN.

Further work includes understanding and accounting for the differences between LAPIN results and the design predictions. The current level of agreement is adequate for developing a control system preliminary design.

Once we had a steady–state LAPIN solution at the design point, we perturbed the simulation with an upstream Mach number ramp reduction from 2.35 to 2.34. This perturbation caused the inlet to operate closer to unstart. As Figure 3 shows, the throat Mach number dropped by approximately .02 and

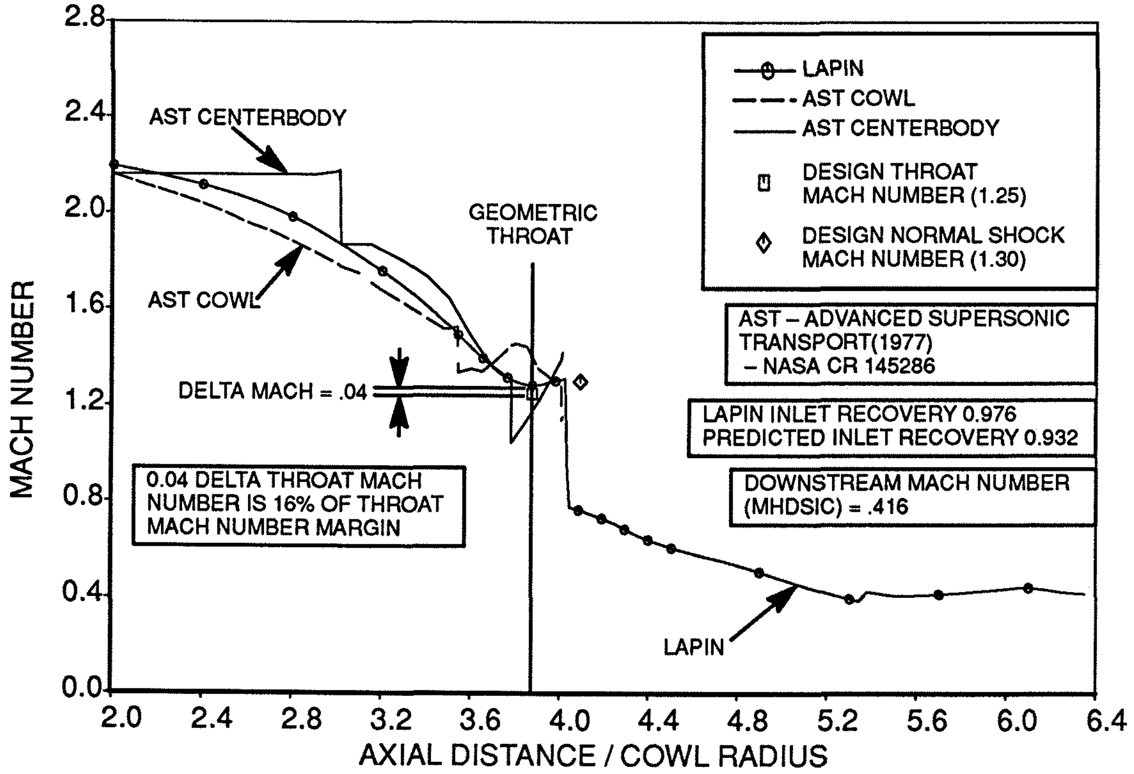


Figure 2. Steady–State LAPIN Model Mach Number Distribution

the normal shock moved forward by .08 dimensionless units. The goal was to design a centerbody controller which would hold the throat Mach number constant and a bypass door controller which could adjust the inlet exit flowrate and bring the normal shock back to its starting position.

For this study, we selected a downstream Mach number boundary condition of 0.418, which is higher than the value of 0.416 used previously. At this condition, the inlet operates with the shock supercritical and shows changes in axial Mach number distribution more easily than at the design condition.

Centerbody Controller

We used EASY5 to design and analyze the centerbody controller to maintain throat Mach number. Figure 4 shows the EASY5 block diagram which contains the controller, compensation, centerbody actuator, inlet model and sensor dynamics. A simple linear model, developed by perturbing the nonlinear LAPIN model, simulates the inlet. EASY5 root locus analysis capabilities provided information needed to establish gains and compensation for stable controller operation. The EASY5 simulation ran essentially instantaneously on the HP/Apollo 425t workstation used. We modified the FORTRAN code generated by EASY5 to create the centerbody controller subroutines for LAPIN.

The upstream Mach number is input to the EASY5 model as a function of time. The linear inlet model converts the upstream Mach number to a throat Mach number, which the control system compares to the desired throat Mach number. The controller converts this error to centerbody actuator position, which translates the centerbody and changes throat Mach number.

We added the subroutines which simulate the centerbody controller to LAPIN. Figure 5 is a partial flowchart which shows where the subroutines interact with the original LAPIN program. The centerbody controller affects subroutines GEOM, which updates inlet geometry, and BCUPDT, which updates boundary conditions. The controller subroutines include INCTRL, which contains the control logic, and FCALC, which contains the controller time–dependent equations.

After integrating the centerbody controller subroutines with LAPIN, we perturbed both the LAPIN model and the EASY5 model with an upstream

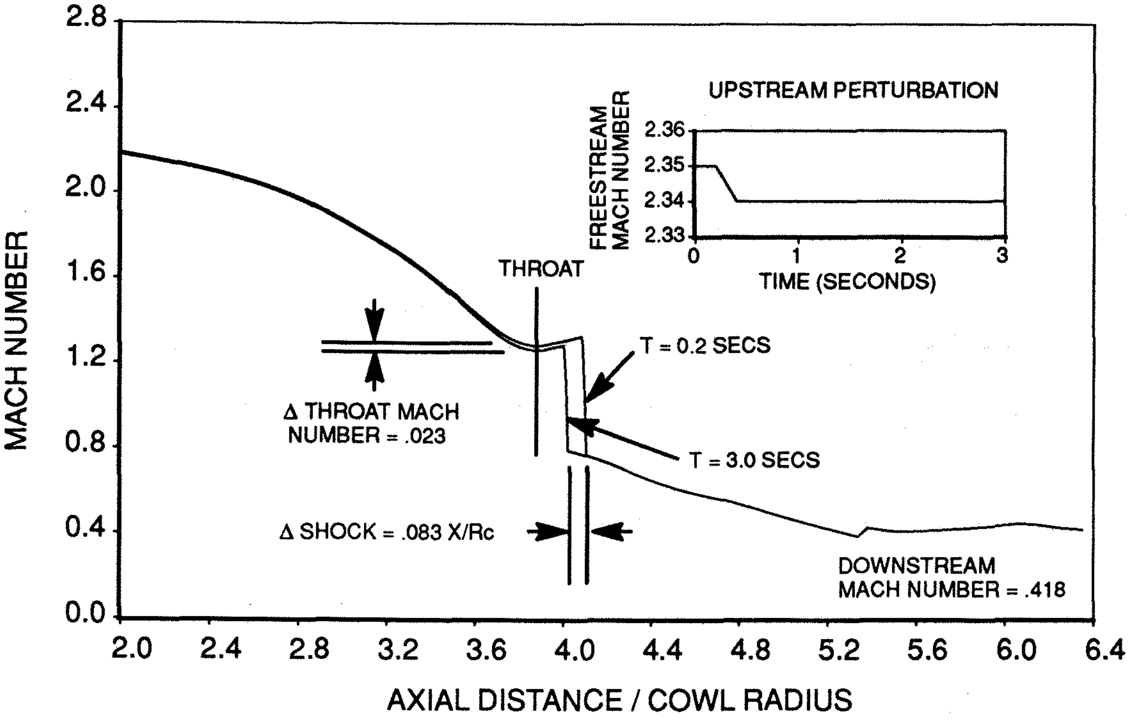


Figure 3. MCTCB Inlet Uncontrolled Response to an Upstream Mach Number Perturbation

Mach number step and compared the resulting time histories. As Figure 6 shows, both controllers have an acceptably fast and stable response. The agreement between the linear (EASY5) and the nonlinear (LAPIN) controllers showed that the LAPIN controller was implemented correctly. These results also show that for operating points near a given condition, the linear (EASY5) model could be used to approximate the nonlinear (LAPIN) model. Using the linear model for control system design is advantageous because of very fast EASY5 turnaround as compared to LAPIN turnaround. (On the HP425t workstation, three seconds of real time is nearly instantaneous for EASY5 and takes approximately 0.75 hour for LAPIN.)

Using a freestream Mach number ramp, we perturbed the LAPIN model with the integrated centerbody controller and compared the resulting axial Mach number distribution to one obtained without the centerbody controller. Figure 7 shows that the centerbody controller catches the throat Mach number and brings it up to its desired (initial) level. However, the normal shock moves forward, and the inlet operates closer to unstart. The next step in the control system design is to develop the bypass door controller to control the bypass flow and bring the normal shock back to its initial condition.

Bypass Door Controller

The bypass door controller design followed the same procedure as the centerbody controller design. We first developed an EASY5 model which has basically the same components as the centerbody controller has. The EASY5 block diagram shown in Figure 8 contains the controller, compensation, a bypass door actuator model and a simple inlet model. The EASY5 inlet model, developed in part by perturbing the nonlinear LAPIN model, contains a Pade approximation. The bypass door controller senses normal shock position, computes the error between that and desired shock position, and controls the bypass door actuator to give the appropriate flow change to obtain the desired normal shock position. The simple inlet model is valid only near a specified operating point. The gains and compensation in the controller were adjusted, guided by root locus analysis, to give a stable and timely response. We modified the EASY5 FOR-

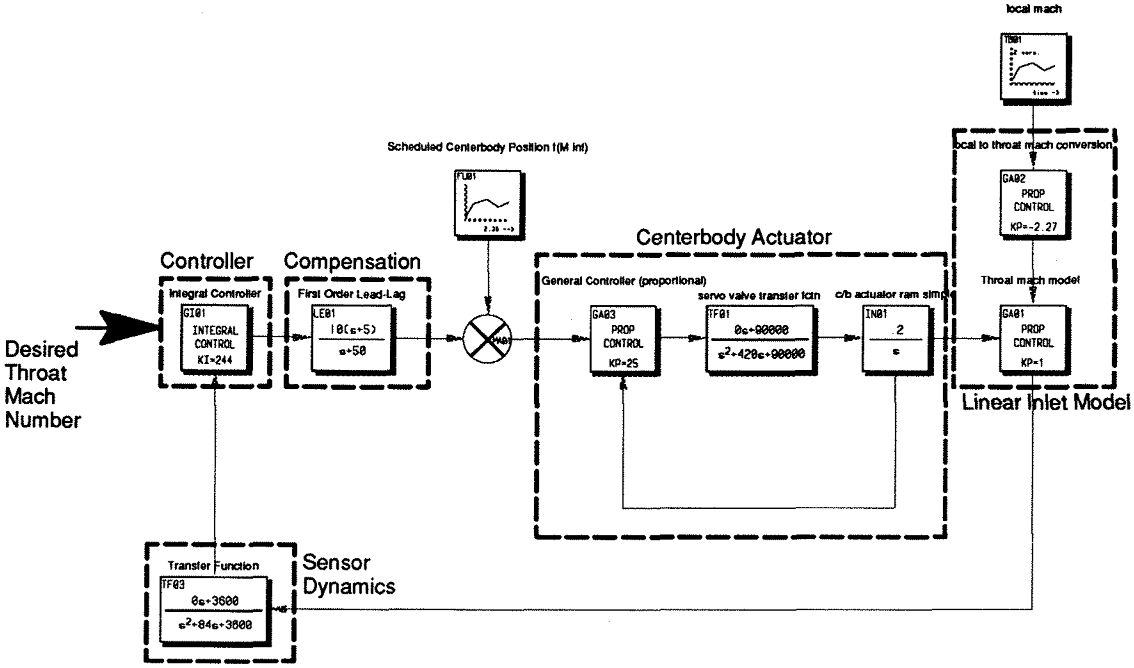
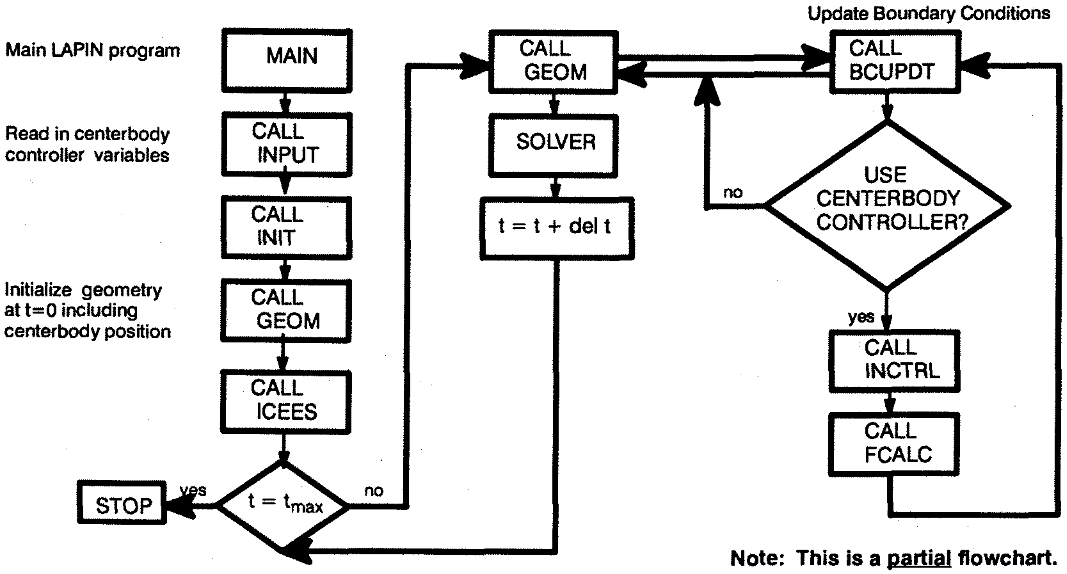


Figure 4. Centerbody Controller EASY5 Block Diagram



Centerbody Controller FORTRAN Code

Subroutine INCTRL: contains centerbody controller logic and calculations

Subroutine FCALC: contains centerbody controller time–dependent equations

COMMON/INLCON/: contains centerbody controller variables. This common is in the main LAPIN program and subroutines BCUPDT, GEOM, INPUT, and INCTRL

Figure 5. Flowchart of LAPIN Centerbody Controller

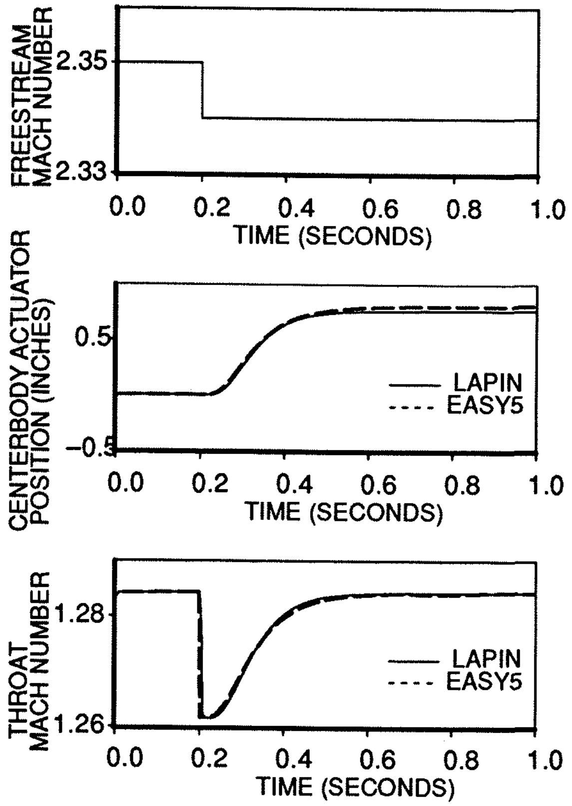


Figure 6. Comparison of LAPIN and EASY5 Centerbody Controllers

TRAN code to create bypass door controller subroutines for integration with LAPIN.

The flowchart in Figure 9 shows the bypass controller subroutines integrated with the LAPIN code. The bypass door controller interacts with Subroutine USS, which updates source terms, including bypass mass flow. The bypass door controller subroutines are BYDOOR, which contains the controller logic and calculations, and FBCALC, which contains the bypass door controller time–dependent equations.

Combined Controller

After the centerbody and bypass door controllers were integrated with LAPIN, we perturbed the LAPIN model with a freestream Mach number ramp from Mach 2.35 to 2.34. The controller brings the throat Mach number and the normal shock position back to their initial values in a stable and timely manner as Figure 10 shows.

The bypass door and centerbody controllers are Type 1 controllers, which result in significant tran-

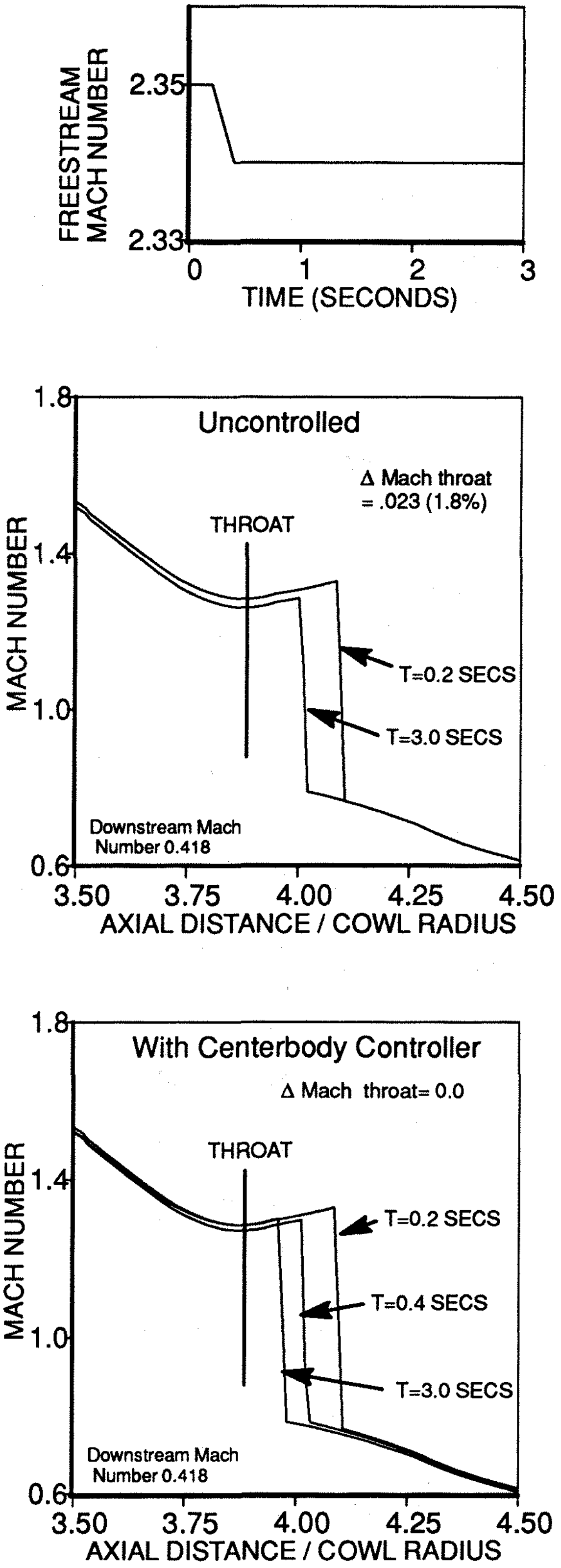


Figure 7. Centerbody Controller Throat Mach Number Response

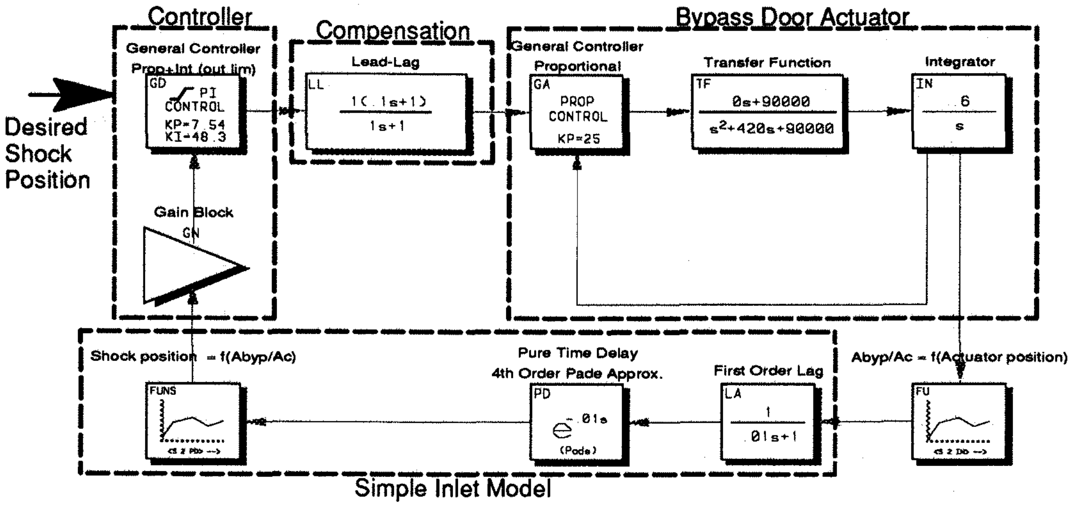
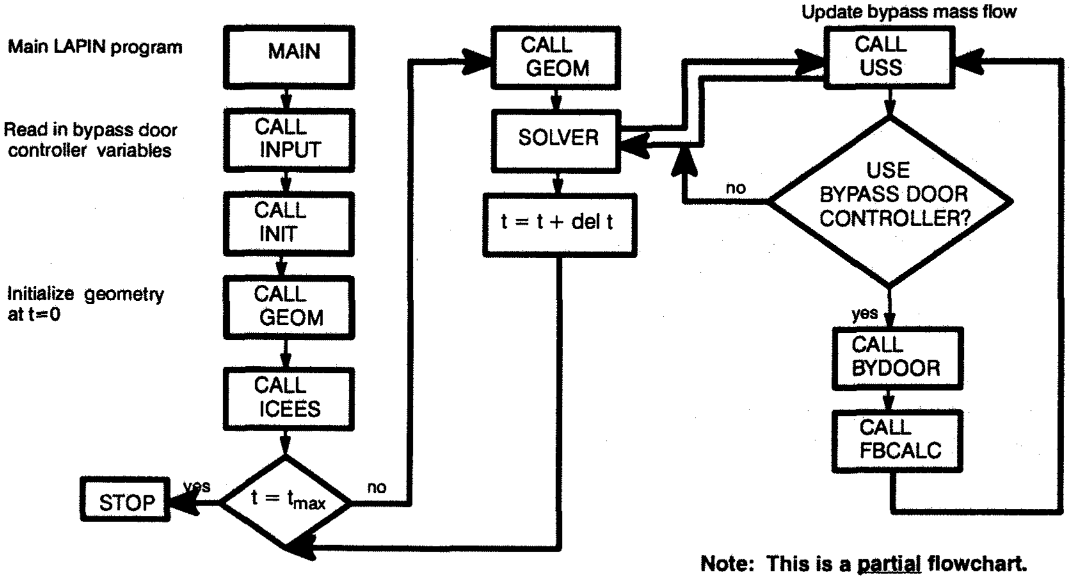


Figure 8. Bypass Door Controller EASY5 Block Diagram



Note: This is a partial flowchart.

Bypass Door Controller FORTRAN Code

Subroutine BYDOOR: contains bypass door controller logic and calculations

Subroutine FBCALC: contains bypass door controller time–dependent equations

COMMON/INLCON/: contains bypass door controller variables. This common is in the main LAPIN program and subroutines BCUPDT, GEOM, INPUT, USS, INCTRL, and BYDOOR

Figure 9. Flowchart of LAPIN with Bypass Door Controller

sient errors. This type of controller is acceptable for the initial control system design to demonstrate the design method and tools. A more sophisticated Type 2 controller would probably be used in a final control system design.(5)

Final control system design will account for input disturbance definitions (from Task 12, NAS3–25963, see Reference 4), various nonlinearities (e.g., effector nonlinearities, effector selection logic and inlet aerodynamics) and closed–loop control of the throat slot.

Figure 11 shows the inlet axial Mach number distributions, with and without the inlet controller, in response to a freestream ramp perturbation. The throat Mach number stays at the desired initial level. The normal shock comes forward in response to the perturbation and then the bypass door controller brings the shock back to the desired initial level. For the design point cruise case, at zero degree angle of attack, the inlet controller successfully performs closed–loop control on the centerbody and bypass doors.

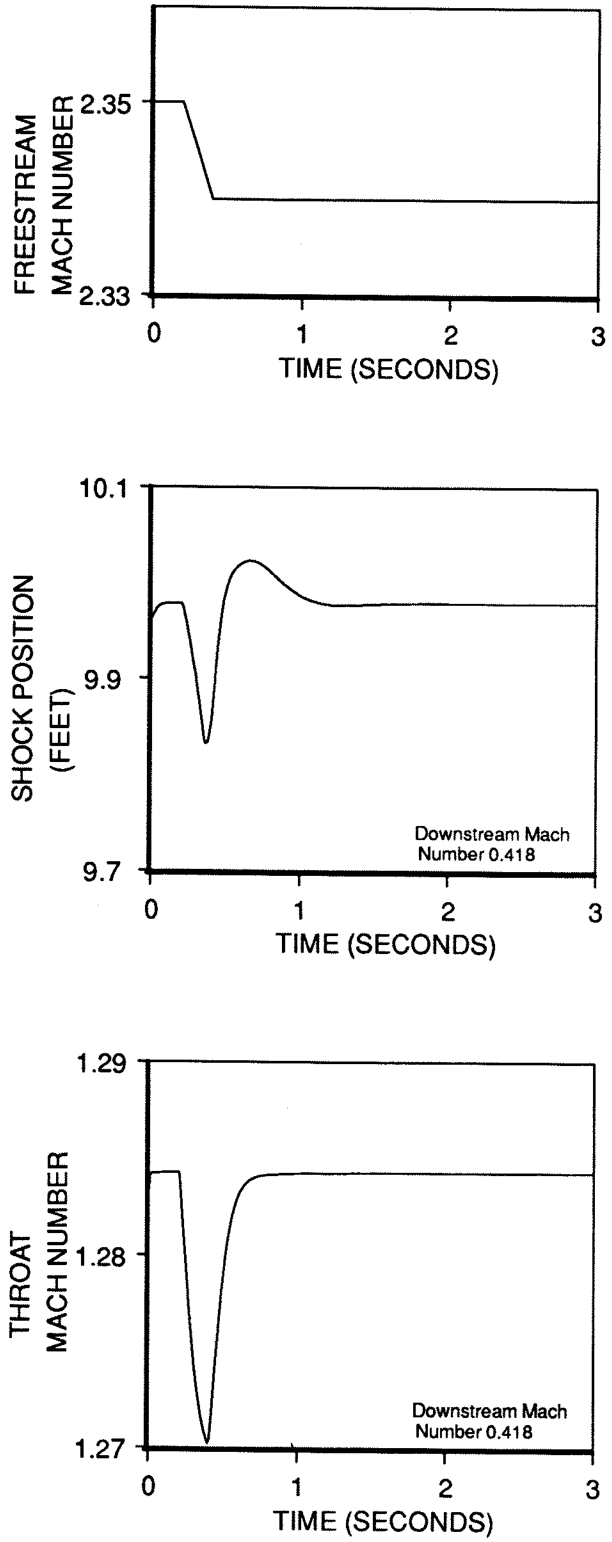


Figure 10. Time Histories from Closed–Loop Centerbody and Bypass Door Control

Conclusions and Recommendations

Closed–loop control of the translating centerbody and bypass doors for the design point cruise condition works and is integrated with LAPIN. Simulation and analysis tools are in place to develop a control system design for the HSCT inlet. LAPIN is a good time domain simulation tool for one–dimensional inlet flow, and has positive value as a control system development tool. Although this capability was not demonstrated in this particular exercise, LAPIN can model inlet unstart and restart. When used with an appropriate workstation, LAPIN gives marginally acceptable turnaround.

Recommendations for further control system development for the design condition include evaluating bleed and throat slot modeling within LAPIN and designing and implementing a closed–loop control on the throat slot / vortex valve. We also need to evaluate the LOSS model within LAPIN to better model oblique shock losses and the subsonic diffuser. Another recommendation is to improve LAPIN aerodynamic modeling to correct and/or understand discrepancies between LAPIN results and design predictions. It would also be useful to compare LAPIN and time–accurate two–dimensional and three–dimensional CFD results.

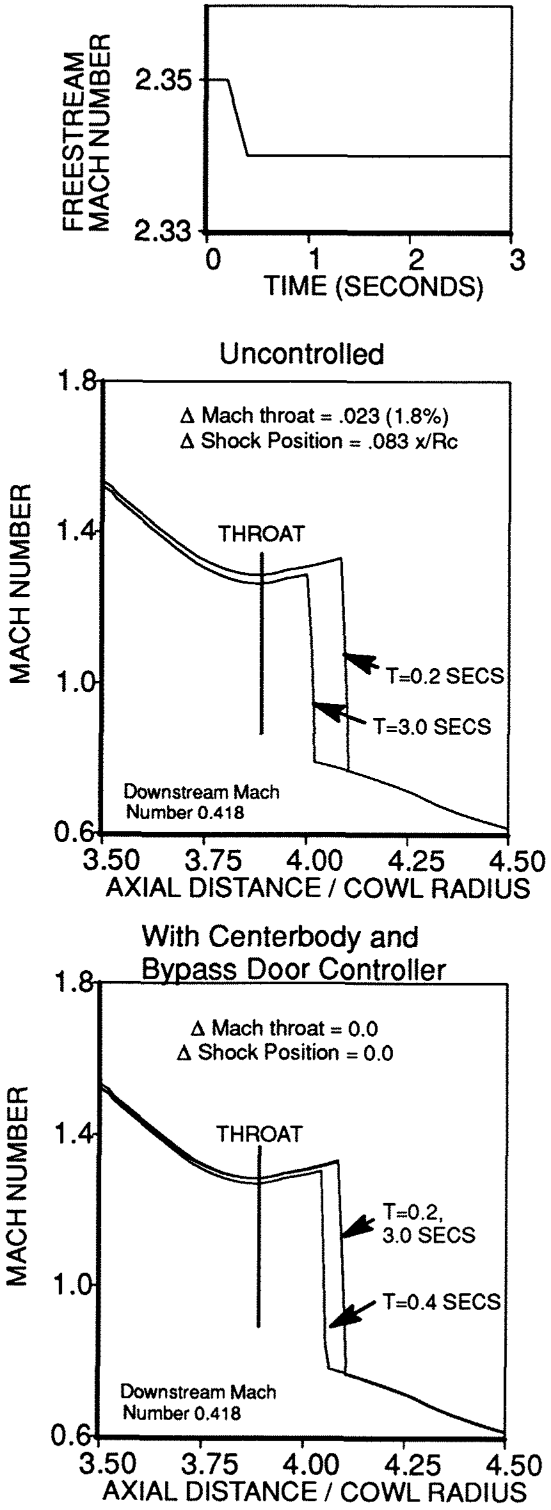


Figure 11. Controlled Throat Mach Number and Shock Position Response

Further work includes developing a method of modeling off design cases such as angle–of–attack and sideslip with LAPIN, as well as designing a control system to handle these cases.

Additional tasks include applying LAPIN to a two–dimensional inlet and evaluating that application.

To improve turnaround, we should investigate methods of accelerating LAPIN through code refinements and possibly parallelization.

Acknowledgements

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