Dynamic Testing of the NASA Hypersonic Project Combined Cycle Engine Testbed for Mode Transition Experiments

T.J. Stueber, R. Thomas, D.R. Vrnak, B.V. Nguyen, J.M. Nappier, J.A. Downey, E. Wong, and P. Raitano
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Abstract

NASA is interested in developing technology that leads to more routine, safe, and affordable access to space. Access to space using airbreathing propulsion systems has potential to meet these objectives based on airbreathing access to space system studies. To this end, the NASA Fundamental Aeronautics Program Hypersonic Project is conducting fundamental research on a turbine based combined cycle (TBCC) propulsion system. The TBCC being studied considers a dual flow-path inlet system. One flow-path includes variable geometry to regulate airflow to a turbine engine cycle. The turbine cycle provides propulsion from take-off to supersonic flight. The second flow-path supports a dual-mode scramjet (DMSJ) cycle which would be initiated at supersonic speed to further accelerate the vehicle to hypersonic speed. For a TBCC propulsion system to accelerate a vehicle from supersonic to hypersonic speed, a critical enabling technology is the ability to safely and effectively transition from the turbine to the DMSJ—referred to as inlet mode transition. To experimentally test inlet mode transition methods, a combined cycle engine (CCE) large-scale inlet testbed was designed with two flow paths—a low-speed flow-path (LSFP) sized for a turbine cycle and a high-speed flow-path (HSFP) designed for a DMSJ. This testbed system is identified as the CCE large-scale inlet for mode transition experiments (CCE-LIMX). The test plan for the CCE-LIMX in the NASA Glenn Research Center 10- by 10-ft Supersonic Wind Tunnel is segmented into multiple phases. The first phase is a matrix of inlet characterization (IC) tests to evaluate the inlet performance and establish the mode transition schedule. The second phase is a matrix of dynamic system identification experiments designed to support closed-loop control development at mode transition schedule operating points for the CCE-LIMX. The third phase includes a direct demonstration of controlled mode transition using a closed loop control system developed with the data obtained from the first two phases. Plans for a fourth phase include mode transition experiments with a turbine engine. This paper, focusing on the first two phases of experiments, presents developed operational and analysis tools for streamlined testing and data reduction procedures.

Nomenclature

Acronyms and Abbreviations

AAS	airbreathing access to space
A/D	analog-to-digital converter
ARMD	Aeronautics Research Mission Directorate
CAD	computer aided design
CCE	combined cycle engine
CDMs	controller design models
COTS	commercial off-the-shelf
D/A	digital-to-analog converter
DMSJ	dual-mode scramjet
FAP	Fundamental Aeronautics Program
GN&C	Guidance Navigation and Control

GRC	NASA Glenn Research Center
GUI	graphical user interface
HSFP	high-speed flow-path
IC	inlet characterization
IMX	inlet for mode transition experiments
LIMX	large-scale inlet for mode transition experiments
LSB	least significant bit
LSFP	low-speed flow-path
NASA	National Aeronautics and Space Administration
PC	personal computer
RALV	reusable airbreathing launch vehicles
RBCC	rocket based combined cycle
rms	root-mean-squared
SBC	single-board-computer
S/N	signal to noise ratio
SPDT	single-pole double throw
10x10 SWT	Supersonic Wind Tunnel
SysID	system identification
TBCC	turbine based combined cycle
TSTO	two stage to orbit
V	Volts

Symbols

A_{min}	minimum stopband attenuation
fr	corner frequency of interest (Hz)
f_i	frequency of interest
f_s	minimum sampling rate frequency
M_p	normalized peak
$p(q_e)$	probability density function
q	quantization level
q_e	quantization error
Step T	point in time when step increase in signal is applied
T	time (sec)
T_p	time to first peak (sec)
T_s	settling time (sec)
T_{si}	transient stability index
V_{fs}	full scale voltage level of A/D
Δ	small incremental change
σ	standard deviation
ξ	damping ratio

Introduction

The Hypersonic Project of the NASA Aeronautics Research Mission Directorate (ARMD) Fundamental Aeronautics Program (FAP) foundational research is towards technology development to enable the capability of future vehicles to operate across a broad range of Mach numbers, including the hypersonic flight regime (Ref. 1). One hypersonic application calls for hypersonic research on reusable airbreathing launch vehicles (RALV) to enable sustained hypersonic flight through Earth's atmosphere (Ref. 2). This will in turn enable routine, airline-type access to space. The RALV mission focuses on two stage to orbit (TSTO) (Ref. 3) systems using airbreathing combined cycle engine (CCE) (Ref. 4) propulsion technology. Two prominent airbreathing CCE propulsion schemes are the turbine based

combined cycle (TBCC) and the rocket based combined cycle (RBCC) systems (Ref. 5). This work supports investigations that consider using a TBCC propulsion system for the first stage of an RALV concept TSTO system.

The TBCC propulsion system for the current envisioned vehicle (Ref. 6) combines a turbine (turbojet or turbofan) engine flow-path with the flow-path of a dual-mode ramjet and scramjet (DMSJ) combustor. A schematic of such a vehicle is illustrated in Figure 1 with the DMSJ flow-path located under the turbine flow-path in an over/under configuration. For takeoff, and through the low supersonic flight regime, the turbine flow-path provides thrust to accelerate the vehicle and the DMSJ flow-path is cold-flowed (no fuel applied to the DMSJ). Continued acceleration through the supersonic regime leads to escalating temperatures that limit the operability of the turbine system. Therefore, to continue further acceleration to the hypersonic staging point, the DMSJ is started while the gas turbine is shut down and cocooned. This requires the propulsion system to transition from the turbine flow-path to the DMSJ flow-path (Ref. 7). The transition, diverting intake airflow from one flow-path to the other, is referred to as inlet mode transition (Ref. 8). Passing the inlet mode transition window is a critical event for enabling a TSTO RALV system to reach the hypersonic staging speed (Ref. 9)

A TBCC TSTO system will employ an inlet system that is conducive to enabling mode transition and performs well prior, during and after the inlet mode transition event. The inlet system is designed to provide an engine (turbine or DMSJ combustor) with air at specified levels of pressure and velocity. At flight speeds above Mach 2, an inlet having a mixture of internal and external compression allows optimal propulsion system performance by supplying the engine with airflow at a high pressure level while maintaining minimal drag and low distortion at the engine face. To meet optimal performance for this type of inlet, the terminal shock must be kept at the inlet throat. However, external airflow transients such as atmospheric turbulence and internal airflow changes such as a reduction in engine airflow demand can cause the terminal shock to move off of its design location. If the terminal shock moves forward of the throat where it is unstable, it will be expelled ahead of the inlet cowling. This shock expulsion, referred to as inlet unstart, causes a large rapid reduction in mass flow and pressure to the engine, and thus a large thrust loss along with increased drag. The closer the terminal shock is to the throat, the smaller the disturbance necessary to unstart the inlet. It is desirable for the inlet to have a sufficiently large stable margin to absorb such transients without unstarting. Increasing this margin, operating the inlet super-critical, will lower pressure and increase distortion at the inlet diffuser exit. Since any loss in inlet performance is reflected directly as a loss in propulsion-system thrust and efficiency, super-critical operation should be avoided.

An acceptable balance between system stability margin and performance can be provided through inlet design and by employing active controls. A conventional turbine engine flow-path is designed with a diffuser volume to dampen very high frequency disturbances, a passive stability bleed system to reject moderately high frequency disturbances, and an active control system to reject low frequency disturbances (Ref. 10).

Two events of concern for a DMSJ flow-path are unstart and blowout. An unstart condition for the DMSJ flow-path is one where the leading edge of the shock train is forward of the isolator. This type of inlet unstart will greatly reduce the air mass flow to the combustor, thus reducing thrust. Equally undesirable is the blowout event where the combustor loses its flame and it must be restarted.
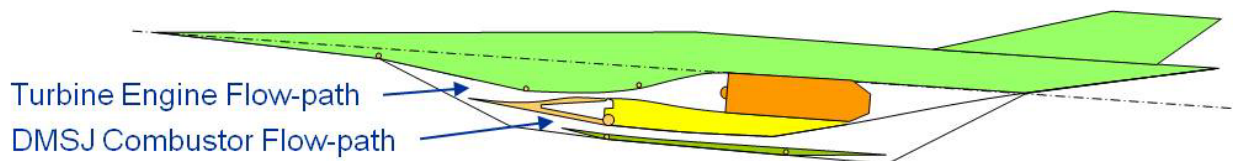

Figure 1.—Conceptual dual, over/under, flow-path propulsion system design integrated into a hypersonic vehicle.

A concern for a TBCC TSTO propulsion system during inlet mode transition is that a turbine flow-path unstart may unstart DMSJ flow-path or blowout the DMSJ combustor. Therefore, control research on this type of system is necessary to maintain adequate turbine flow-path performance prior and during mode transition and to minimize the probability of adversely affecting thrust production from the DMSJ combustor during and after mode transition.

To experimentally study the inlet mode transition event, a new hypersonic split-flow inlet was designed to provide flow to an over-under propulsion system with a turbine engine and a DMSJ for airbreathing propulsion from takeoff to Mach 7 (Ref. 11). A computer aided design (CAD) rendition of this inlet is illustrated in Figure 2. This inlet system has the following nine variable actuators: ramp, splitter, high-speed cowl, low-speed mass flow plug, high-speed mass flow plug and four overboard bypass gates. The low-speed flow-path (LSFP) for a turbine includes the top surface of the splitter as a variable cowl, the variable ramp, four bypass gates at the aft end of the diffuser, and a mass flow plug and cold pipe assembly to back pressure the LSFP. The high-speed flow-path (HSFP) for the DMSJ includes the variable high-speed cowl, the bottom surface of the splitter as a variable ramp, an isolator, and a mass flow plug and cold pipe assembly to back pressure the HSFP. The design of the inlet was based on a small-scale concept inlet mode transition experiment (IMX) model (Ref. 12). In comparison to the small-scale model, the CCE large scale model (CCE-LIMX) is larger and more complex to address the objectives of mode transition experiments (Ref. 13). A near term goal for the CCE-LIMX is to demonstrate that smooth inlet mode transition is possible, between the two flow-paths, with a split-flow inlet design. To meet this goal, the inlet will be rigorously tested to determine an open loop schedule for mode transition that maintains clean airflow to the turbine as it spools down (Ref. 14). These inlet mode transition schedules do not address dynamic disturbances in the LSFP that can unstart the inlet. Therefore, experiments will be conducted to enable control system studies that will focus on controller designs to reject disturbances that can unstart the inlet prior to and during mode transition. The NASA Hypersonic Guidance Navigation and Control (GN&C) discipline team will be supporting the testing of this inlet system with CCE system mode transition controls design.

To experimentally investigate and demonstrate smooth inlet mode transition with the CCE-LIMX, the following four test phases are planned to span a 3-yr period within the NASA Glenn 10- by 10-ft Supersonic Wind Tunnel (10x10 SWT) (Ref. 15) environment: Phase I) inlet performance and operability characterization (IC); Phase II) inlet dynamic system identification (SysID); Phase III) demonstration of mode transition control strategies; and Phase IV) mode transition testing and demonstrations incorporating
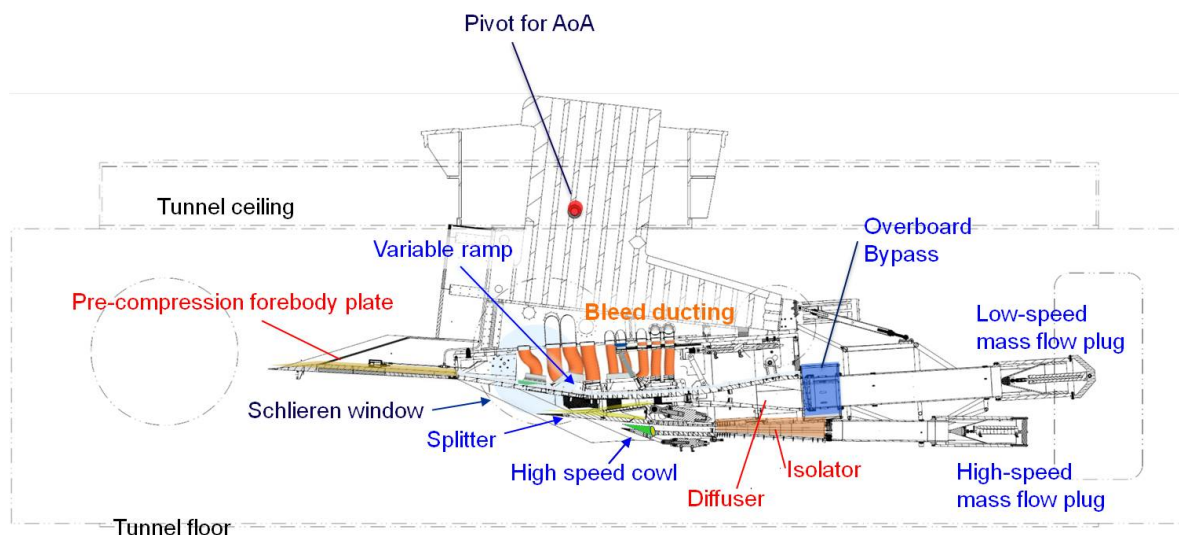

Figure 2.—A computer automated design rendition of the combined cycle engine large scale inlet for mode transition experiments. The facility labels are black, stationary features of the inlet have red labels, variable inlet features have blue labels, and the bleed ducting is orange.

the WJ38 turbine engine and integrated turbine nozzle (Ref. 14). Phase I testing will conclude with a demonstration of steady-state scheduled mode transition and the results passed on to the GN&C team from Phase I will be the mode transition schedule (Ref. 16). Phase II will provide the GN&C team a database suitable for designing control design models for this inlet system (Ref. 16). Phases III and IV will be opportunities for the GN&C team to test and demonstrate inlet mode transition controller designs. This paper focuses on activities the GN&C discipline team is engaged in to support the first two phases of experiments.

The GN&C team activities have led to the buildup and development of hardware and software tools that streamline experimental processes, data acquisition, and documentation. These tools are necessary to minimize downtime between tests while the wind tunnel air is flowing, reduce the risk of operator error, automate mode transition schedules, and insure that experimental data is appropriately documented. The hardware and software tools have been collected and assembled into a single unit identified as the SysID Rack. The SysID Rack hardware and software development activities are presented in this paper.

This paper continues with descriptions of the Phase I and Phase II experiments from the perspective of the GN&C team with an interest in demonstrating scheduled mode transition and designing disturbance rejecting controls. Next, an overview of the hardware and software tools developed to support the GN&C activities are presented. Next, software tools developed to reduce the Phase II data are presented. To explain sampling rate decisions, an appendix has been attached to the end of this document that describes the selection process for the anti-aliasing filters and the sampling rate.

Discussion

Phase I Experiments

The primary Phase I experiment objective is the determination of a mode transition schedule. A mode transition schedule is an equation set used to determine positions for all actuators based on the position of a select lead actuator. Any of the nine CCE-LIMX actuators can be selected as the lead actuator, although only one at a time. The remaining eight actuators are deemed followers. Therefore, a mode transition schedule will consist of a set of eight unique actuator follower equations that express the positions of their respective actuators as functions of the lead actuator position. The actuator follower equations can be a constant, a linear, or an nth order polynomial function of the lead actuator position. To satisfactorily demonstrate inlet mode transition, all follower actuators must move in concert with the lead actuator as defined by the inlet mode transition equations. Because of the splitter, high-speed cowl, and ramp ranges of motion, a potential for actuator travel paths to intersect exists. Therefore, care must be taken to prevent collisions while demonstrating inlet mode transition.

Phase I test results will reveal distinct positions for each actuator at select positions of a lead actuator. The collection of these positions represents the inlet mode transition operating points. The inlet mode transition equations are then determined with curve fits through the operating points of each follower actuator with respect to the position of a lead actuator. Therefore, each inlet mode transition schedule will reveal (9 potential lead actuators) * (8 follower actuators) = 72 curve fit equations. The coefficients of these curve fit equations will be recorded. Potentially, the Phase I data analysis activity may reveal multiple candidate inlet mode transition schedules—multiple sets of coefficients for the 72 equations.

Once candidate inlet mode transition schedules have been determined, the curve fit process completed, and curve fit equation coefficients logged, a scheduled inlet mode transition can be demonstrated with the following five steps:

1. Select a candidate inlet mode transition schedule to be demonstrated.
2. Select an actuator to serve as the lead actuator.
3. Select a new position for the lead actuator.
4. Check movement paths of all actuators for potential collision scenarios.
5. Instruct the lead actuator to commence movement and the other actuators to synchronously follow the movement of the lead actuator.

Upon completion of a movement, another movement can be initiated, a new lead actuator can be selected, or another logged mode transition schedule can be tested. Multiple movements with the same schedule and lead actuator can be conducted by repeatedly performing the third through fifth steps. A new lead actuator may be selected by repeating the process starting at the second step. To test another one of the logged candidate inlet mode transition schedules, the five steps listed above are repeated.

For Phase I experiments, the GN&C discipline team has the following three objectives to prepare for Phase II experiments and to support the primary Phase I objective: First, to obtain sufficient data to determine signal noise levels under experimental conditions. This information will be useful for setting up Phase II experiments. Second, identify discrete operating points that can be sequenced to provide a piecewise continuous inlet mode transition schedule. Third, to provide the CCE-LIMX research team a tool that will implement inlet mode transition schedules designed for the CCE-LIMX hardware in the 10x10 SWT. To meet the first objective, select sensor signals need to be monitored and recorded with hardware that includes analog-to-digital (A/D) converters. All signals applied to the A/D converters are measured and saved for post processing data reduction with noise analysis software. Objectives two and three will lead to inlet mode transition demonstrations, which is the primary objective for this program. The second objective identifies the discrete operating points to which SysID experiments will be conducted in Phase II. The third objective requires the capability of the SysID Rack to select and perform the five steps for demonstrating the scheduled inlet mode transition. To add flexibility to the experiment process, the SysID Rack also included the following four user friendly capabilities: readily make changes to the inlet mode transition schedules, easily switch to and execute a different inlet mode transition schedule, easily select or change a lead actuator, and graphically illustrate simulated actuator movements as a check for potential collision scenarios. Providing a resource to meet the requirements for this third objective is a challenging GN&C team deliverable. Hardware and software development activities to meet GN&C Phase I objectives are included below.

Phase II Experiments

For Phase II experiments, the GN&C discipline team has the following three objectives: First, is to identify the inlet disturbance frequency range that is not protected by either the diffuser volume or the passive stability bleed system. Second, is to identify high-speed feedback pressure sensor locations that will be suitable for supporting an active disturbance rejection controller. Third, is to create empirical controller design models (CDMs) suitable for supporting control research.

The inlet mode transition schedules, revealed from Phase I IC experiments, are collections of steady-state operating points. These operating points are configurations, which are experimentally proven to be safe and acceptable, where the inlet can slowly transition to and hold. A safe and acceptable operating point is a selected configuration where the inlet is started, has acceptable performance, and has acceptably clean airflow at the turbine aerodynamic interface plane.

The Phase II experiments are designed to apply stimulating signals and acquire data for populating a database suitable for developing dynamic CDMs (Ref. 16). The following four types of stimulating signals will be used (Ref. 16): step, single sine pulse, staircase, and sinusoidal sweep. Step response data will determine signal-to-noise ratio (S/N) and the data will be used to select CDMs. Single sine pulse data will reveal the disturbance frequency range that needs to be addressed by an active control (Ref. 10). Staircase response data will be used to check for hysteresis. Sinusoidal sweep data will be reduced to CDMs (Ref. 17). The CDMs will then be used to aid designing an active disturbance rejection control system using bypass gate valve actuators and high-speed pressure sensor feedback. The control actuators will be four bypass gate valves positioned 90° apart at the aft end of the diffuser. A select group of high-speed pressure sensors will provide LSFP diffuser feedback to the control system. The Phase II experiments will primarily consist of SysID tests where various perturbation signals will be applied to the CCE-LIMX bypass gate valve actuators. These experiments will be conducted while operating the inlet at the select inlet mode transition operating points identified from the Phase I tests. Another outcome of the

Phase II experiments will be the identification of the optimal high-speed pressure sensor locations that will provide feedback to the controller.

The SysID Rack requirements, for performing the Phase II experiments, include the capability to do the following:

- Position the CCE-LIMX hardware to any of the operating positions identified from the Phase I IC tests.
- Apply step, staircase, sine-pulse, and sine-sweep signals to the bypass gates.
- Sense and log signals from high-speed pressure sensors.
- Sense and log actuator control and position feedback signals.

Providing a resource to meet the challenging Phase II experiment objectives are a focus for the hardware and software activities described below.

SysID Rack Overview

The SysID Rack hardware and software is designed to be a tool that performs the procedures required for demonstrating scheduled mode transitions in Phase I and conducting SysID experiments with the CCE-LIMX in Phase II. To use this tool to perform these experiments entails hardware buildup and software development. The hardware applies and senses signals on digital to analog (D/A) and A/D channels that interface the SysID Rack with CCE-LIMX actuator, actuator feedback signals, and high-speed pressure sensors. The software controls the signals applied to the D/A channels based on operator input and feedback signals. The software also supports experiment documentation.

The SysID Rack controls and positions the CCE-LIMX actuators by applying signals to setpoint input ports of proportional controllers for hydraulic cylinders. The setpoint signals represent desired hydraulic cylinder positions. The signals applied to the proportional controller feedback nodes, representing a cylinder piston position, corresponds to the current CCE-LIMX actuator position. Therefore, repositioning the CCE-LIMX actuators involves adjusting the setpoint values applied to the cylinder's controller units with the SysID Rack D/A channels.

Precautions were taken to prepare for the event of a SysID Rack system lockup or failure. The concern is that if this event happens, errant commands from the SysID Rack may be transmitted to the CCE-LIMX actuator controllers that will reposition the actuators to an unsafe configuration while the wind tunnel air is flowing. To relieve this risk scenario, a Dspace (dSPACE GmbH) system is employed to receive and pass the nine control signals from the SysID Rack to the actuator controllers. In addition to these nine signals, a tenth "status" analog signal from the SysID Rack that is programmed to maintain 5 V is also monitored by the Dspace system. In the event of a SysID Rack lockup or failure, the status signal will drop to 0 V. Upon detection of the step change from 5 to 0 V on the status signal, the Dspace system will respond by maintaining previous output signals on its D/A channels. This course of events will cease movement of the CCE-LIMX actuators, as opposed to leading to potential unsafe step changes in the inlet geometry.

SysID Rack Hardware

The SysID Rack includes the following components: real-time operating system Target Computer, A/D boards, D/A boards, user interface Host Laptop, Target Computer to Host Laptop communication, and a real-time Dspace system. Not included within the SysID Rack is also an 8th order anti-aliasing Bessel function filter. Determining the Bessel function parameters and the sampling rate used for these experiments is reviewed in the Appendix.

The Target Computer periodically, 2.5 kHz, applies signals to the D/A channels based on instructions received from the Host Laptop and reads signals from the A/D channels. To meet the Target Computer requirements, a rack-mount computer was procured. The Target Computer is a rugged 4U personal

computer (PC) compatible enclosure that includes the following: An Intel Core (Intel Corporation) dual-core Xeon (Intel Corporation) Processor based single-board-computer (SBC); an A/D card with 64 channels, 16-bit, 500k samples/Sec; and two D/A cards with 8 channels each, 16-bit, 750K samples/sec. The Target Computer employs an xPC TargetBox (The MathWorks, Inc.) configuration to run the MATLAB (The MathWorks, Inc.) real-time xPC Target (The MathWorks, Inc.) operating system. The xPC Target system enables code written with MATLAB and Simulink (The MathWorks, Inc.) software to run as executable applications on the Target Computer. The A/D board is wired to receive signals from 20 high-speed pressure sensors, nine actuator position feedback signals, nine actuator output control signals from the Dspace system, and nine actuator output control signals applied to the D/A board. The D/A board channels apply nine actuator control signals to the Dspace system. Additionally, the signal from a tenth D/A channel is transmitted to the Dspace system as a SysID Rack status line. The Dspace system employed for these experiments can receive and transmit signals within either the ± 5 or ± 10 V range.

The Host Laptop is used to develop a Target Model that can be downloaded to the real-time xPC Target system, develop a Host Model that can serve as a user interface to the Target Model, and serve as a user interface point for an operator to set control parameters and receive feedback. To serve these purposes, a Host Laptop computer system was procured. The Host Laptop is a dual-core Intel Xeon Processor, 2.33 GHz system that runs the Windows Vista Ultimate (Microsoft Corporation) operating system. Other commercial off-the-shelf (COTS) software loaded onto the Host Laptop to support this project include: Microsoft Excel (Microsoft Corporation), MATLAB, Simulink, Real-Time Workshop (The MathWorks, Inc.), xPC Target, and a C compiler. The Host Laptop communicates with the Target Computer via an Ethernet crossover cable.

The Host Model and Target Model are described in the following section.

SysID Rack Software

The SysID Rack software was designed to enhance research capabilities by automating the experiment process without constricting research flexibility. Automating the experiment process streamlines experiment procedures and data acquisition while minimizing the probability of operator error. The SysID Rack software operating in conjunction with the SysID Rack hardware, functions as a tool that supports the performance of select CCE-LIMX experiments by providing the operator with the capability to perform the following four tasks:

1. Configure the experiments with-
    a. CCE-LIMX geometry specifications.
    b. Experiment type.
    c. Experiment parameters.
2. Start or stop experiments—automated or manual.
3. Perform general housekeeping functions, such as-
    a. Guiding the operator through task sequences.
    b. Checking experiment parameter information for proper entry.
    c. Providing operator warnings for potential hardware crash scenarios.
    d. Delivering status feedback for the CCE-LIMX.
4. Perform data transfer and save operations.

The SysID Rack software graphical user interfaces (GUIs) were designed to facilitate operator communication with the Target Model. The capabilities of the GUIs are as follows:

- Receive operator instructions to reconfigure an experiment.
- Initiate data acquisition.
- Start an experiment.
- Stop an experiment.

- Stop data acquisition.
- Coordinate data transfer.
- Display general housekeeping status.

Code design and development employs the following convention:

- The operator enters and reads data in engineering units.
- D/A boards accept signals in units of volts.
- A/D boards read signals in volt units.
- Database includes all data saved in the same units that they enter or leave the SysID Rack-
  - Setup variables have engineering units.
  - Input and output variables have voltage units.

Therefore, calibration coefficients are needed to translate between the engineering units and voltage values. The calibration coefficients define polynomials for translating engineering units to voltage or voltage units to engineering units. The coefficients for these calibration polynomials are defined pretest by exercising the CCE-LIMX hardware, recording comparisons between measured actuator positions against D/A setpoint voltages (engineering units to volts curve), and recording measured actuator positions against A/D feedback measured voltages (volts to engineering units curve). The product of the calibration exercises are setpoint and feedback calibration coefficients for each actuator. Similarly, calibration coefficients are also saved for translating the high-speed feedback pressure sensor signal millivolt units to pressure. The calibrations coefficients are conveniently saved in a customized document that is populated using Microsoft Excel spreadsheet software.

Customized SysID Rack software code has been composed, to work with the SysID Rack Hardware, to meet the Phase I and Phase II objectives. Further software development will be needed to meet Phase III and IV objectives. Code for SysID Rack software is grouped into two pairs of Host Models and Target Models. One model pair is designed to support the Phase I scheduled inlet mode transition demonstration. The other pair is designed to support the Phase II SysID dynamic experiments. Both pairs include code to enable sampling and recording all signals applied to the A/D boards in real time within each sampling period. The recorded data becomes the database for identifying CDMs. Both pairs also employ GUIs to guide the operator through multi-step procedures by employing color changing and button enabling or disabling graphic enhancements.

The Host Models are programmed using MATLAB Simulink software and run within a MATLAB environment on the Host Laptop. These models are designed to run on a PC with the Microsoft Vista operating system to perform the following tasks:

- Receive experiment setup and control information via GUIs from an operator.
- Transmit experimental configuration and control information to the Target Model.
- Translate user input values to the GUI from engineering units to Target Model required voltage values.
- Translate all Target Model feedback voltage values to engineering units.
- Periodically display signals from the Target Model.
- Check for potential hardware collisions.
- Streamline testing procedures.

The Target Models are also programmed using MATLAB Simulink software; however, these models are uploaded to the Target Computer from the Host Laptop. These Target Models are designed to run in real-time on the xPC Target computer and continuously perform the following tasks:

- Read experiment configuration information from the Host.

- Calculate values to be applied to D/A channels.
- Update all D/A channels.
- Read and log all A/D channels.
- Download information to the Host.

Target Model experiment configuration information received from the Host includes calibration information, start or stop logging feedback A/D signals flag, and initiate or stop an experiment sequence flag. Since the Target Model is running on the Target Computer, all acquired data must be transferred from the Target Computer to the Host Laptop for post processing. Therefore, a flag to initiate this data transfer is included in the experiment configuration information.

The subsequent sections will present details about the Target Model software and the Host Model software, respectively, that will support both Phase I and Phase II experiments.

SysID Rack Target Model Software

The Target Model code to support Phase I scheduled mode transition demonstrations and Phase II SysID experiments are very similar. Both Target Models receive instruction from the Host Model pertaining to D/A signal generation. Both also sense and log all A/D channels using MATLAB software filescopes. The filescopes are data storage devices with memory allocated in the xPC Target when the model is compiled. During data saving operations, if incoming information exceeds allocated memory, then the oldest data gets written over. Both Target Models receive instruction words from the Host Model indicating that it is time to apply new signals to the D/A channels, start or stop saving A/D channels, and to transfer saved data logged on the Target Computer to the Host Laptop memory. The significant difference between the two Target Models is the amount of information that each receives from the Host Model. For Phase I mode transition demonstrations, the Target Model receives the next setpoint values to be applied to the hydraulic cylinder controllers. Whereas, the Phase II Target Model receives an instruction packet that includes information for applying step, staircase, sine-pulse, or sine-sweep signal traces to the D/A channels. The reason for having two separate Target Models is to insure real-time capability by minimizing the size of the Target Model length of code—Phase I does not need SysID signal generation capability and Phase II does not need scheduled mode transition demonstration capability.

The Target Model for Phase I will receive a signal from the Host Model to start saving A/D channel signals into filescopes. Next, the Target Model will receive a new set of nine signals to apply to the D/A channels. Upon receipt of an instruction to update all D/A channels, new hydraulic cylinder controller setpoint signals will be applied to the D/A channels. These setpoint signals are applied with a rate limiting ramp movement profile. The actuator feedback signals are monitored and periodically transmitted to the Host Model for display on the GUI. Upon receipt of an instruction to stop recording A/D signals, the filescopes will stop accepting new data. Finally, the Target Model will transfer all filescope data to the Host Model upon receipt of the instruction to do so.

The Target Model for Phase II will receive an experiment information packet from the Host model that describes the following parameters for a specific SysID experiment: actuator(s) selection, signal type, amplitude, frequency, and number of cycles. Next, the Target Model will receive a signal from the Host Model to start saving A/D channel signals into the filescopes. Upon receipt of an instruction to initiate an experiment, the Target Model will apply scheduled signals to the D/A channels based on the experiment information packet. After all scheduled signals for an experiment have been applied; the last signal is maintained on the D/A channel. An interrupt signal from the Host Model will cut short the predetermined schedule of signals for the SysID experiments. Upon receipt of an instruction to stop recording A/D signals, the filescopes will stop accepting new data. Finally, the Target Model will transfer all filescope data to the Host Model upon receipt of the instruction to do so.

Besides the four fundamental SysID experiment types for Phase II, the experiment information packet may contain instructions to move all or some of the hardware actuators, that is, to reconfigure the CCE-

LIMX. The filescopes can be employed while the CCE-LIMX is reconfigured by having the Target Model start them prior to having the Host transmit the instruction to initiate an experiment. For this last experiment instruction case, the D/A channels are rate limited to maintain a ramp movement type of profile.

SysID Rack Host Model Software

The Host Model for Phase I, including its accompanying GUI, was developed specifically to support mode transition schedule following experiments. Similarly, the Host Model for Phase II, including its accompanying GUI, was developed to support the SysID experiments. In order for either Host Model to satisfactorily perform their respective tasks, they must be initialized with calibration coefficients, actuator range-of-motion limits, and maximum acceptable ramp rates-of-motion for each actuator while reconfiguring the inlet geometry. This information is saved in a document, which is populated using Microsoft Excel software, and automatically accessed upon initial startup of the Host Models and their respective GUIs.

The custom designed Mode Transition GUI, illustrated in Figure 3, allows an operator to interact with the Phase I Host Model, which in turn provides the ability to configure and direct the operation of the associated Target Model. In this manner, Phase I Mode Transition tests can be fully managed and controlled. By operating the GUI's input fields, selection elements and control buttons, an operator can select a mode transition schedule, select a lead actuator, specify a new position to which the lead actuator will move, and initiate moving all actuators in concert with the lead actuator. Upon initial startup of the Phase I Host Model, the configuration information is read and the state of the Mode Transition GUI is as illustrated in Figure 3. The elements of the GUI are grouped according to function. The left half of the GUI window is comprised of groups of input and selection components and the right half is dedicated to groups of data monitoring and data collecting components. The typical sequence of operation for the Mode Transition GUI is as follows:

1. Use the file selection tool in the "Actuator Transition Profiles" group to select a desired mode transition schedule.
2. Identify the lead actuator by manipulating the radio buttons within the "Select Lead Actuator" group.
3. Check for hardware collision scenarios.
4. Move the selected lead actuator to a new position using the fields within the "Set Desired Setpoint for Actuator" group.

Since multiple schedules may be available, a specific schedule is selected by identifying a document, by filename, which includes the desired mode transition polynomial coefficients. The Mode Transition GUI will not allow the operator to further operate this GUI until a specific mode transition schedule has been selected. The selected filename is illustrated in the text display field within this group box. Since only one actuator can be selected to lead, the Mode Transition GUI will only allow one radio button to be selected at a time. Because of the CCE-LIMX mechanical design, it is possible to schedule actuator crashes. To minimize this probability, the Mode Transition GUI provides the availability of the Visual Tool component that displays a graphic schematic representation of the CCE-LIMX. As the operator enters a new value for the lead actuator position, the Visual Tool will dynamically calculate and illustrate the final position of all actuators upon application of a newly chosen lead actuator controller setpoint. This graphic makes available the opportunity for visual inspection of the final hardware configuration and to reveal potential hardware crashes. If no hardware crashes are revealed and the new configuration is desired, pressing the "Update Setpoint" button will instruct the Target computer to start applying new setpoint signals to the controllers. As these new setpoint signals are applied, their values can be monitored in the "Setpoint Values Out" column of the "Actuator Monitoring Display" group. This column consists
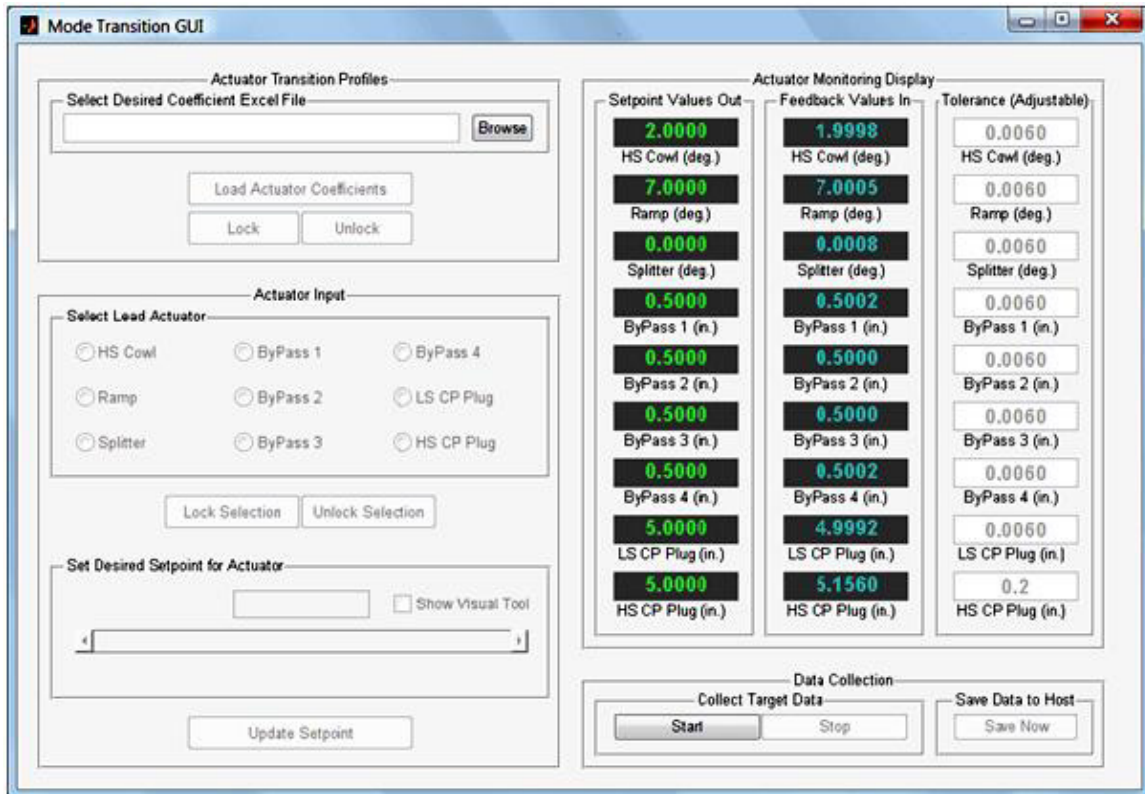
Figure 3.—Mode transition GUI as presented to operator upon initiation of the Phase I Host Model.

of continuously updating numeric display fields—one field for each actuator. Alongside this column is a similar column of continuously updating numeric fields labeled "Feedback Values In" that display the monitored values of the feedback signals from each actuator. A third corresponding column labeled "Tolerance (Adjustable)" consists of numeric input fields that allow the operator to view and set the allowable difference between each actuator's setpoint signal and the corresponding feedback signal. In the event that a tolerance is exceeded, the associated field will warn the operator of this condition by changing to a red display color. Default tolerance values are loaded during initialization. However, these default tolerances can be individually adjusted for any actuator by entering new values into the corresponding input field. The Mode Transition GUI was designed to safely lead the operator through the sequence of steps involved in managing a mode transition by displaying the mode transition filename, activating and deactivating fields as appropriate, posting lead actuator travel limits, and illustrating the final position for all actuators after selecting the "Update Setpoint" button.

Another GUI was developed to support the Phase II SysID experiments. This GUI is the CCE_GUI illustrated in Figure 4 and is part of the Phase II Host Model. The fields on the CCE_GUI are used to help the operator perform the following tasks with the SysID Rack:

- Reconfigure the CCE-LIMX geometry.
- Prescribe and initiate SysID experiments.
- Start and stop data acquisition.
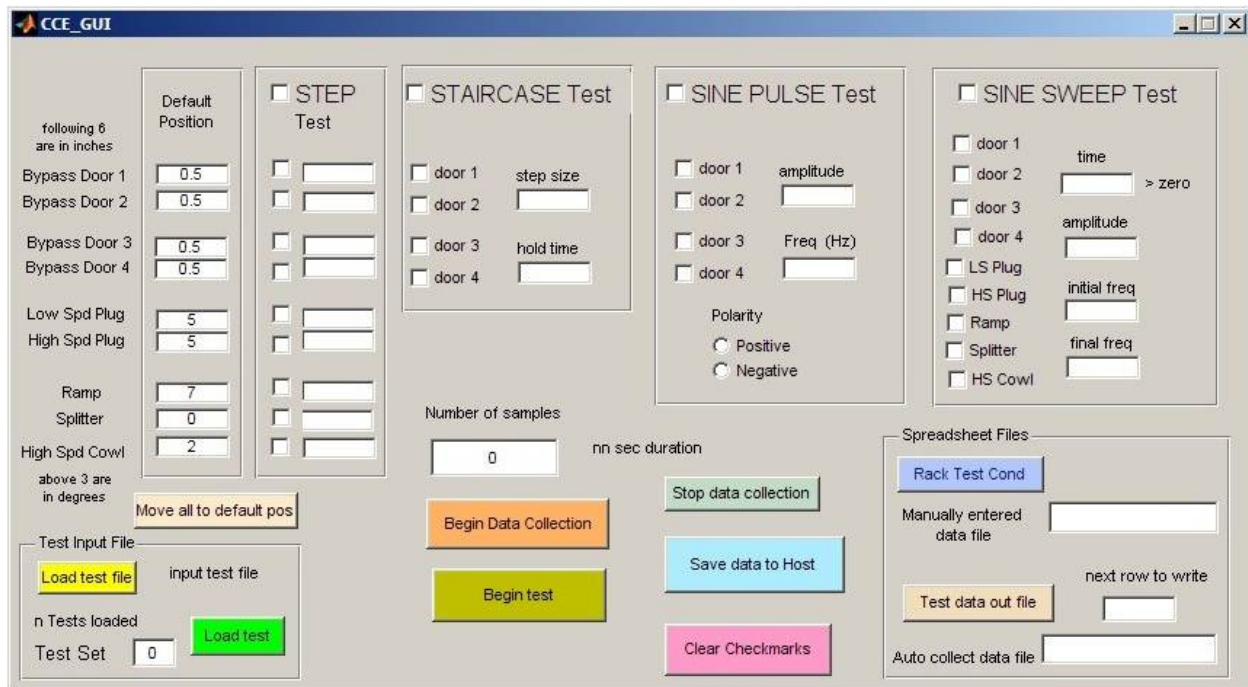- Electronically document an experiment.

Figure 4.—SysID experiment GUI as presented to operator upon initiation of the Phase II Host Model.

The CCE_GUI receives new desired CCE-LIMX geometries by reading values entered into the "Default Position" group fields. The CCE-LIMX can be reconfigured, as described by the "Default Position" values, by selecting the "Move all to default pos" button. This button initiates the process that applies a stream of setpoint values (V) to the CCE-LIMX actuator hydraulic cylinder controllers that will promote a ramping movement of all actuators to a configuration as described by the "Default Position" fields.

All SysID experiments involve one of the following types of perturbation tests: step, staircase, sine pulse, or sine sweep. The check boxes and numeric entry fields within the SysID experiment groups identify the perturbation type and the actuator(s) that will be perturbed. The step size and amplitude fields define the perturbation amplitudes, in either degrees or inches, with respect to the default positions. The time fields have units of seconds and the frequency fields have units of Hertz. When conducting a step, staircase, sine pulse, or sine sweep test, the signals applied to the actuator controller setpoints are not rate limited—a step test will apply a step change in setpoint value.

The buttons and display fields within the "Spreadsheet Files" group are for conveniently identifying documents that are suitably formatted for reading and editing with Microsoft Excel software. The document identified using the "Rack Test Cond" button includes information pertaining to the experiment environment. This document will be manually populated at test time using Microsoft Excel software and includes much information that will be applied to the documentation file. The document identified using the "Test data out file" button will be populated with information that electronically documents the experiments. When viewing the contents of the test documentation file using Microsoft Excel software, each experiment will be displayed in cells corresponding to a unique row number—the unique row number is identified under the "next row to write" label. Each column in the documentation file will have information pertaining to a specific test parameter.

The five buttons located in the lower middle of the CCE_GUI are used to start or stop data acquisition, initiate an experiment, document an experiment, or clear the CCE_GUI. This GUI also incorporates an internal algorithm to check for potential hardware crashes. Finally, the fields within the "Test Input File" group are for reading documents that contain information for populating the CCE_GUI.

Each test phase will span multiple evenings (runs)—up to five runs per week. For each test run, Phase I or Phase II, the CCE-LIMX will be configured to minimize drag while the 10x10 SWT is brought to a desired free-stream operating condition using facility control. After the wind tunnel has settled and all instruments indicate flow within and around the inlet have stabilized to a steady-state condition, control of the CCE-LIMX geometry can be transferred from 10x10 SWT facility to the SysID Rack. Up to this point, the signals being applied to the actuator hydraulic cylinder controller setpoint nodes are coming from the SWT facility control panel. Until this path is redirected from the SWT facility control panel to the SysID Rack, through single-pole double throw (SPDT) relay contacts, all signals from the SysID Rack D/A channels are open and will not affect the CCE-LIMX hardware. Transferring control to the SysID Rack will occur while the air is flowing supersonic in the wind tunnel; therefore, care must be taken to be sure the outgoing setpoint values from the SysID Rack match the current setpoint values applied to the actuator controllers. A mismatch will result in a geometry step change at the onset of control transfer. To minimize this mismatch risk, feedback signals that reveal current actuator positions will be manually compared with SysID rack D/A signals—both sets of signals are electronically translated and displayed in engineering units for ease of operator inspection. Furthermore, an indicator will change from green (safe to transfer control) to red (unsafe to transfer control) if a mismatch between the values are beyond a safe range. Therefore, upon settling at a tunnel operating condition and all indicators are green, hydraulic actuator controller setpoint signal control can be transferred from the 10x10 SWT facility controllers to the SysID Rack.

10x10 SWT Test Plans

For the Phase I testing, the SysID Rack will periodically be used to sample steady-state signal noise levels on all A/D channels and to log dynamic sensor data during CCE-LIMX geometry transitions. While performing these tasks, the SPDT relay will be configured so that only the facility controllers can apply signals to the actuator hydraulic cylinder controller setpoint nodes—all SysID Rack D/A channels are open. Therefore, these tasks are started and stopped independent of and without interruption to the Phase I testing schedule.

The SysID Rack will also be available to facilitate demonstrating mode transition schedules. When a mode transition schedule demonstration is desired, control authority to the CCE-LIMX hardware can be transferred from the 10x10 SWT facility controllers to the SysID Rack following set procedures. After the SysID Rack assumes control, the Mode Transition GUI will streamline the process for a safe demonstration. In the event that a mode transition schedule puts the CCE-LIMX geometry into an undesirable configuration, such as one that promotes violent shaking of the hardware, control authority can quickly be returned to the facility controller with the SPDT relay. The results, due to a certain step change in applied setpoint signals, from this corrective action are acceptable.

Another possible recourse is to instruct the CCE-LIMX actuators to reconfigure to a Safe configuration. This action is instigated by issuing a 10x10 SWT facility command, termed "Safe the inlet," that will switch the controller setpoint signal sources to a set of preset voltage signals. The Safe signals are preset and hardwired to a switch that will result in all actuators moving to a configuration that was previously tested and deemed safe. Therefore, signal flow priority to the actuator controller setpoints by facility permission is: Safe hardwire, facility controller, SysID Rack.

For the Phase II testing, up to three candidate mode transition schedules will be identified for SysID study. One schedule will be determined to be the Main and will be subject to the most attention. The other schedules will be alternates and the SysID experiments will not focus on these as much as the Main. The following SysID experiments are planned for and about each inlet operating point identified along the mode transition schedules: step, staircase, sine sweep, and transient stability index (T_{si}).

The CCE-LIMX in the 10x10 SWT facility will have the following configuration for each of the SysID experiments. For the LSFP, bypass gates located at the aft end of the diffuser will be used to create small pressure perturbations in the diffuser. For the HSFP, the cold-pipe mass flow plug will be used to create small pressure perturbations in the isolator. For each candidate mode transition schedule, seven

splitter positions will be chosen that nonlinearly span the range from operating point to LSFP cut-off. An example set of splitter positions would be to define an operating point such that a 10° rotation of the splitter will close off the LSFP, then the seven splitter positions, that are offsets from the operating point, would be 0°, 1°, 2°, 4°, 6°, 8°, and 10°. Each splitter position on the Main mode transition schedule will be subject to five SysID experiments. Experiments will be conducted at each splitter position with the ramp on the operating point, the ramp raised a small Δ° off the operating point, and the ramp lowered a small Δ° off the operating point. Furthermore, with the ramp located on a Main operating point, SysID experiments will be conducted with the splitter rotated open and closed by a small angle off of the operating point. For the HSFP, SysID experiments will be conducted with the splitter on a Main point and the high-speed cowl located on a Main point, rotated slightly open, and rotated slightly closed. Therefore, each splitter position on the Main schedule will be subject to eight SysID experiments.

For the alternate mode transition schedule candidates, SysID experiments will only be conducted on the operating points. Therefore, each splitter position on each alternate schedule will be subject to only two SysID experiments. To conservatively reduce the number of experiments to be conducted, the time consuming measurements to obtain T_{si} data will be limited to only the LSFP and four of the seven splitter positions.

Data Reduction Tools

Experiment parameter settings, stimulating signal amplitudes and durations, will be determined based on the CCE-LIMX system performance during testing. The system performance will be analyzed first with the step test experiment. The step test will reveal information to define the system S/N and settling time. This information will be used to set the step size and hold times for the staircase test. To minimize errors while reducing the test data and to streamline the process so as to maximize useful test time, several custom data reduction tools have been developed. They are designed for rapid data reduction to move forward with the experiments. The following data reduction tools were developed using MATLAB software to support the SysID experiments: Steady-State Noise Analysis, Step Signal Analysis, Staircase Signal Analysis, and Sin Sweep Analysis. Each of the tools are GUI applications developed to streamline the following data analysis procedures: documentation file selection, experiment data selection, perform various data analysis routines, and plot analysis results.

The Steady-State Noise Analysis tool is a GUI driven software tool. The GUI for this tool, SS_NoiseGUI, is illustrated in Figure 5 as it appears when initially called. The following are the four general steps for using the SS_NoiseGUI:

1. Select a documentation file.
2. Select an experiment.
3. Define the range of interest.
4. Plot the results.

The documentation file is a custom formatted file that is populated whenever the experimenter selects the "Save Data To Host" button on the SysID experiment control Host Model GUI (CCE_GUI), see Figure 4. This documentation file includes calibration coefficients for all actuator feedback signals, calibration coefficients for all pressure tap sensors, calibration coefficients for all actuator setpoint signals, free stream conditions at time of experiment, test type, test parameter settings, bleed settings, and a few static pressure tap measurements. Each documentation file can hold data that documents multiple experiments. A wind tunnel test run, that spans several hours, can all be documented within the same documentation file. For ease of identifying a desired documentation file, the naming convention used includes the test run date.
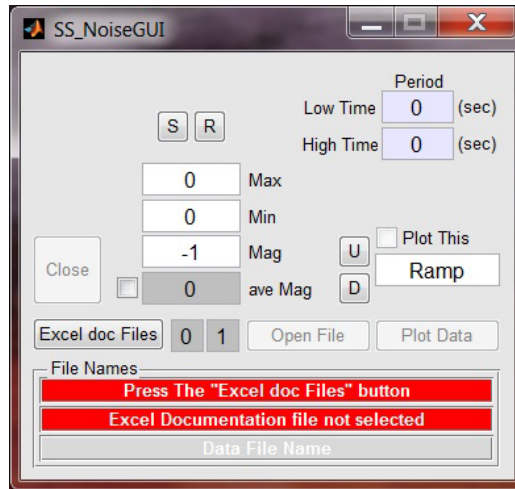
Figure 5.—Steady-state noise analysis GUI.

After selecting the documentation file, the number in the field immediately to the right of the "Excel doc Files" button will indicate the number of experiments documented in that file. The next field immediately to the right will be highlighted in yellow upon successful selection of a documentation file, and allows the operator to choose which experiment will be analyzed with the tool. The "Open File button" will then become available to read the data files (saved in voltage units) that were saved from the Target Model file scopes and translate the data to engineering units using the calibration coefficients retrieved from the documentation file. The time to perform this last step is dependent on the size of the data files.

After opening the data files, figures can be created to illustrate the saved data with respect to time. Curve traces for each signal sampled and saved with the SysID Rack can be plotted in these figures. To open figures for all signals, select the "Plot Data" push button. The figure placed on top will correspond with the signal name identified immediately to the right of the "U" and "D" buttons. However, to select a specific curve trace for plotting, first use the "U" (Up) and "D" (Down) buttons to scroll through the list of signal names. Then place a check mark in the square field above the signal name, next to the label "Plot This", to have that data illustrated in a figure. Using the "U" and "D" buttons along with the "Plot This" check box, multiple figures can be created illustrating select curve traces with respect to time.

The numerical input fields with the blue highlight background require operator input to clarify data analysis boundary conditions. This GUI has a low time and a high time field that defines the evaluation period. These fields need information from the operator to properly assess the data—by default, the evaluation considers all data. Finally, the fields to the left of the Max, Min, and Mag labels are software populated with data that pertains to the period of the identified data set—Ramp for the example illustrated in Figure 5. The Mag value is the difference between the Max and Min.

The Step Signal Analysis tool is also a GUI driven software tool. The GUI for this tool, Step_NoiseGUI, is illustrated in Figure 6 as it appears when initially called. Working with this GUI, the initial steps to recall saved experiment data is similar to the steps identified above for the SS_NoiseGUI. Operator attention is required to complete the following fields highlighted in blue: Data analysis period (Period), step time (Step T), settling time (T_s), and time to first peak (T_p). Each of these values have units of seconds. The four blue fields below the Period label identify the data analysis periods. The "Low" row defines a period before the step point and the "High" row defines a period after the step point. The Step time value should coincide with the time the step signal was applied to the actuator. The Settling Time value pertains to when the signal has settled after the step. Finally, the value for Time to first peak is the time point of maximum signal immediately following the step. The Step time, the Settling Time and Time to first peak can be determined through inspection of the signal traces in the figures. With these user-provided information, the software will reduce the data to populate the remaining fields: delT, Peak, fr,
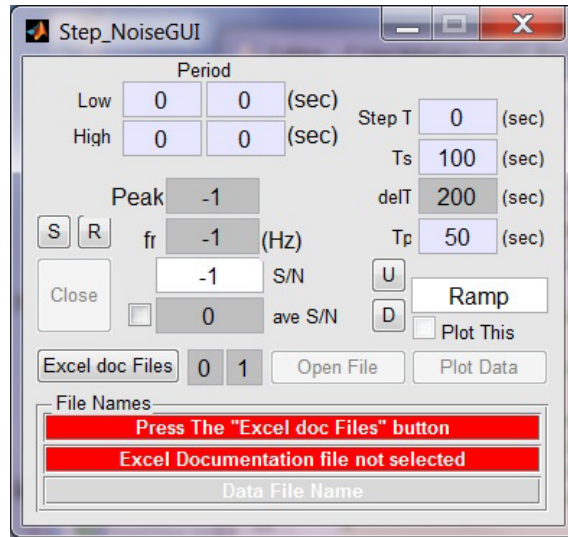
Figure 6.—Step signal data reduction GUI.

S/N, and ave S/N. The value applied to the "delT" field is simply, 2x the difference between the settling time (T_s) and the step time (Step T). This span will be applied to the staircase experiments. The value applied to the "Peak" field is the signal value at the T_p mark. The value applied to the "fr" field is the corner frequency of interest for the sinusoidal sweep experiments. This frequency is calculated based on the T_p value entered and the step response normalized peak (M_p) measurement. The value of M_p is the peak measurement normalized with respect to the settling value; where, the settling value is the average signal in the High Period window. To compute a corner frequency, first calculate a damping ratio (ξ) based on M_p and then calculate the corner frequency using ξ and T_p as described in the following two equations (Ref. 18):

$$\frac{\ln(M_p - 1)}{\pi} + \frac{\xi}{\sqrt{1 - \xi^2}} = 0 \tag{1}$$

$$fr = \frac{\pi\sqrt{1 - \xi^2}}{2\pi T_p} \tag{2}$$

The sinusoidal frequency sweep experiment must include the fr value determined in Equation (2) and the minimum frequency which will be less than the reciprocal of T_s. The value applied to the field adjacent to the S/N label is the calculated signal-to-noise ratio for the step test. This calculation is the ratio of the trim value for the high period to half the noise magnitude for the high period. This parameter is feedback on the acceptability of the applied step amplitude. It is desired to have a S/N ratio greater than 10.0. The illustration in Figure 7 is that of a populated Step_NoiseGUI and an example of a data trace for the step response of a simulated Ramp actuator. Using the View zoom feature, the values for Step T and T_p can be determined.

The Staircase_Analysis_GUI is a GUI developed to support the Staircase Analysis tool. This GUI is used to reduce staircase experiment data to figures that illustrate the staircase response. An example of this GUI is illustrated in Figure 8, along with a staircase response trace. Although there is no information to retrieve from analysis of the Staircase response pertinent to discerning sinusoidal experiment setup parameters, this GUI is useful to assure the operator that the staircase data was successfully captured and will be available for post processing analysis, and that the system appears linear within two amplitude steps.
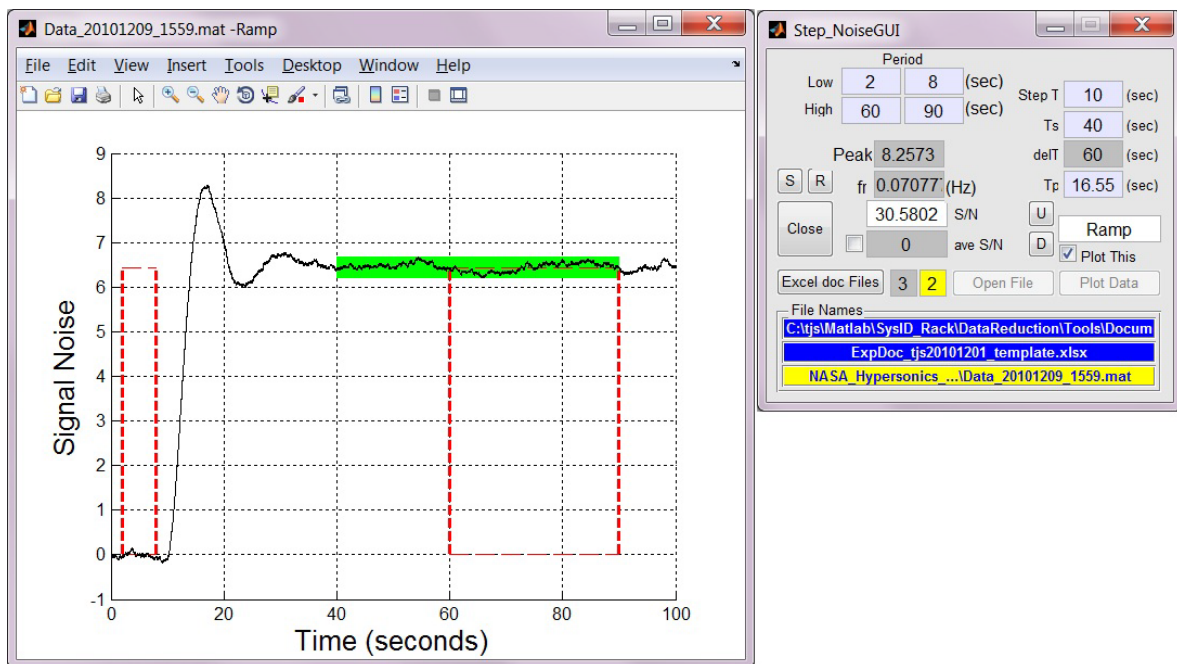
Figure 7.—This figure illustrates an example of a populated Step_NoiseGUI and one step response plot—the Ramp actuator as indicated in the GUI. The rectangular red dash traces indicate the periods specified in the GUI. The green band highlights the range of data considered steady-state. The trace in this illustration is to aid explanation only and not based on hardware performance.
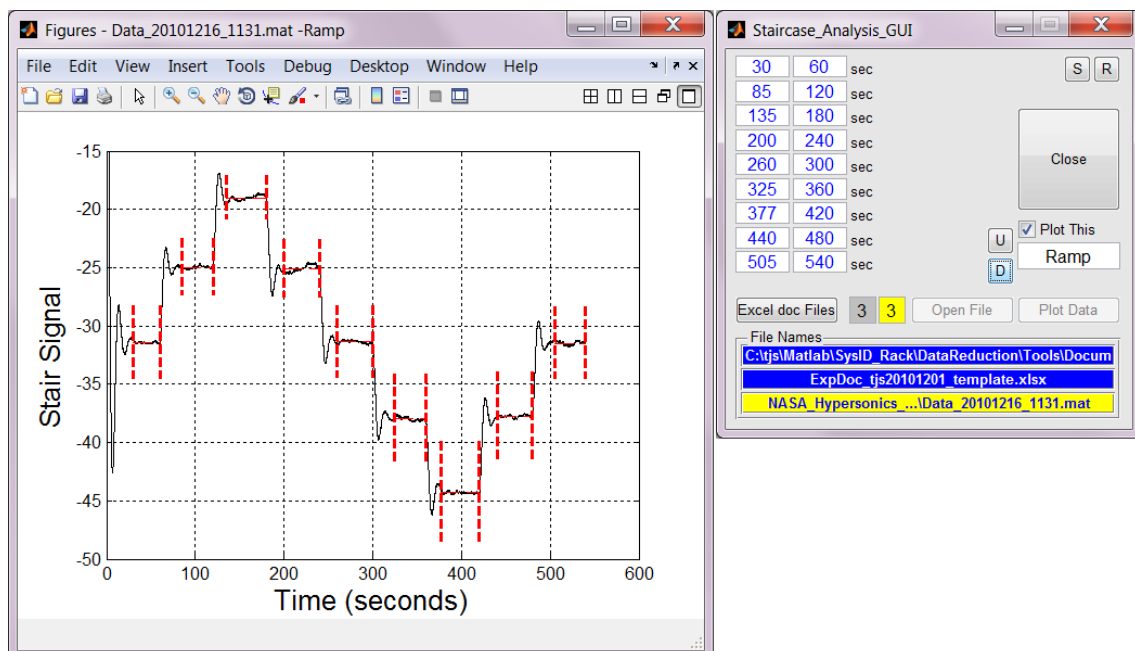

Figure 8.—This figure illustrates an example of a populated Staircase_Analysis_GUI and one of its plots. As indicated in the GUI, this plot graphically displays the data for the staircase response of the Ramp actuator. The red dash traces indicate the periods specified in the GUI. The trace in this illustration is to aid explanation only and not based on actual or expected hardware performance.

After completing the sinusoidal sweep perturbation SysID experiments, the data can be reduced to linear models with the aid of the Sin Sweep Analysis tool. The tool is also a GUI driven tool that is designed to select and format collected data suitable for analysis using the MATLAB System Identification Toolbox (The MathWorks, Inc.) software. An example of this GUI is illustrated in Figure 9. This GUI will determine linear models between sinusoidal sweep perturbed Gate control signals and Ramp position feedback signals. The linear models will be compared to acquired step response signals. The code behind the GUI will create a Fit matrix for operator review based on an iterative process of testing different linear models. The Fit matrix will identify which linear model is representative of the process at a given operating point. The following four lines of MATLAB software code are used to reduce the data files to linear models.

$$Idd_{Step} = iddata\ (Step_{Out},\ Step_{In},\ Ts);$$

$$Idd_{Sin} = iddata\ (Sin_{Out},\ Sin_{In},\ Ts);$$

$$arx_{SYS} = arx\ (Idd_{Sin},'\ na',\ poles,\ 'nb',\ zeros,\ 'focus',\ 'simulation')$$

$$compare\ (Idd_{Step},\ arx_{SYS});$$

Let $Step_{In}$ be the unbiased step perturbation to the DS_Gate_1 actuator and let $Step_{Out}$ be the unbiased Ramp position sensor feedback signal. Similarly, let Sin_{In} be the unbiased sinusoidal sweep perturbation to the DS_Gate_1 actuator and let Sin_{Out} be the unbiased Ramp position sensor feedback signal that responded to the perturbation. Finally, let Ts be the sampling period. The number of Poles and Zeros for this tool will be an integer within the range of one to six.
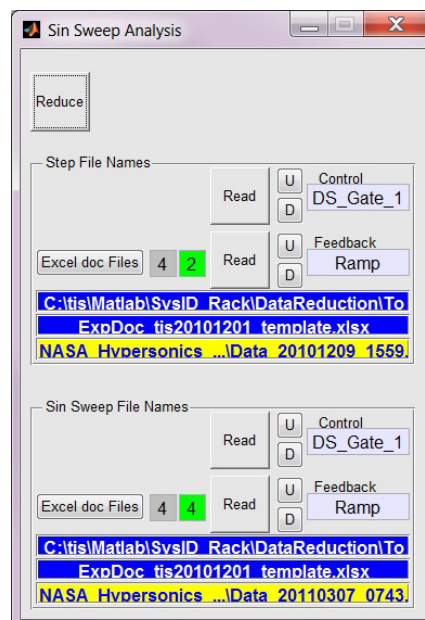

Figure 9.—Sin Sweep Analysis GUI used to reduce data files resulting from sinusoidal sweep experiments and comparing the results to saved step response data.

Conclusions

This paper presented the objectives of the Phase I and Phase II wind tunnel experiments with the combined cycle engine large scale inlet for mode transition (CCE-LIMX). The principle take-away from the Phase I testing is an open-loop mode transition schedule. The mode transition schedule will include multiple operating points to which SysID experiments will be conducted in Phase II testing. The Phase II experiments will conduct further investigations into the operating points for dynamic analysis. The results from these two experiments will be a piece-wise linear model of the inlet diffuser as the system undergoes a mode transition. This paper also gave an overview of the tools developed to support the experiments in an effort to streamline the experiment process, facilitate data acquisition and documentation, and minimize potential for error. The work presented in this paper documents the project's readiness to perform Phase I and Phase II testing efficiently and effectively.

Appendix—Sampling Rate Selection and Anti-Aliasing Filter Design

Since the combined cycle engine, large scale inlet for mode transition study (CCE-LIMX) system identification (SysID) Experiment will use digital equipment to sample and save analog signals from high-speed dynamic pressure taps, appropriate analog filtering and discrete sampling rates need to be determined to satisfactorily acquire data. The analog filter will serve as an anti-aliasing filter to minimize fold-over frequencies that may irreparably corrupt the digitized signals of interest. For the SysID experiments, four bypass doors are located just upstream from the inlet aerodynamic interface plane (AIP) between the inlet and the turbine engine. Since each of these doors will have their own hydraulic cylinder actuator and controller, these bypass doors can be controlled independently or combinations can be operated synchronously.

The purpose for the bypass doors is two-fold. First, these doors will be available as control actuators to attenuate low frequency disturbances forthcoming from the engine. Second, these bypass doors will be able to simulate low frequency disturbances to the inlet low-speed diffuser originating from the engine. Since the passive inlet bleed system is designed to attenuate high frequency disturbances, an active controller will be designed to use the bypass valves to mitigate low frequency disturbances. The cut-off frequency separating disturbance control responsibility between the passive bleed system and the active bypass valve control system is hardware dependant. Based on experience, this cut-off frequency is expected to be higher than 20 Hz and lower than 80 Hz (Ref. 10). To adequately test the responsiveness of the disturbance attenuation system, these bypass doors can be controlled to create disturbances at the AIP. To this end, the bypass doors are designed to operate at frequencies ranging from 0 to 100 Hz. For the SysID experiments, these doors will oscillate over a linear frequency sweep from 0 to 100 Hz. Therefore, the high-speed dynamic pressure taps will pick-up frequencies within this range. Since the SysID experiments are conducted with a cold pipe and mass flow plug assembly in place of a turbine engine, the only disturbances in the LSFP diffuser will be from the bypass gates.

The remainder of this appendix reviews the approach for determining an adequate cut-off frequency for a Bessel function anti-aliasing filter and it continues with the approach for determining an appropriate data sampling rate.

Ideally, the anti-aliasing filter will pass, with a gain of 1.0, all frequencies less than 100 Hz and attenuate all signals with frequencies greater than 100 Hz to values less than what can be read by the A/D least significant bit (LSB). This ideal filter would allow for an A/D sampling at 100 Hz. However, low-pass filters such as what would be employed for an anti-aliasing filter, have a frequency roll-off as opposed to an abrupt frequency cut-off. This section addresses the following three tasks for defining the anti-aliasing filter:

1. Define a minimum stopband attenuation, A_{min},
2. Define a minimum sampling rate frequency, f_s, and
3. Identify the level of aliasing error in the passband with respect to the signal and the calculated A_{min} and f_s.

The anti-aliasing filter and the A/D sampling rate hardware available employ 16-bit, 8th order Bessel functions. The anti-aliasing filter should attenuate the signals with frequencies in the stopband to less than the root-mean-square (rms) quantization noise level for the A/D. A 16-bit linear A/D has a quantization level, q, as defined in Equation (A.1) where V_{fs} is the full scale voltage level of the A/D, and $B = 16$ (bits).

$$q = \frac{V_{fs}}{2^B - 1} \approx \frac{V_{fs}}{2^B} \tag{A.1}$$

The quantization error (q_e) that will not be detectable or removable after digitization by the linear A/D, is half of the quantization level ($q/2$). This discussion assumes the quantization errors for each sample are random and uniformly distributed within $\pm q/2$ with zero mean. Therefore, the quantization noise power is the variance as described in Equation (A.2) (Ref. 19).

$$\sigma^2 = \int_{\frac{-q}{2}}^{\frac{q}{2}} q_e^2 \, p(q_e) dq_e \tag{A.2}$$

Over an interval from $-q/2$ to $q/2$, the probability density function ($p(q_e)$) of a continuous uniform distribution is as defined in Equation (A.3) (Ref. 20).

$$p(q_e) = \begin{cases} \dfrac{1}{\frac{q}{2} - \frac{-q}{2}} = \dfrac{1}{q} & \text{for } \dfrac{-q}{2} < q_e < \dfrac{q}{2} \\ 0 \text{ else} \end{cases} \tag{A.3}$$

Therefore, the variance equation simplifies by applying (A.3) to (A.2) as described in (A.4) and solving to arrive at Equation (A.5).

$$\sigma^2 = \frac{1}{q} \int_{\frac{-q}{2}}^{\frac{q}{2}} q_e^2 \, dq_e \tag{A.4}$$

$$\sigma^2 = \frac{1}{q} \left[\frac{\left(\frac{q}{2}\right)^3}{3} - \frac{\left(\frac{-q}{2}\right)^3}{3} \right] = \frac{q^2}{12} \tag{A.5}$$

The rms level for a Gaussian probability density function is the standard deviation σ. Therefore, set the desired stopband signal level to the rms quantization noise level, σ, as defined in Equation (A.6).

$$\sigma = \sqrt{\sigma^2} = \frac{q}{2\sqrt{3}} \tag{A.6}$$

For the SysID experiments, the sensed signal traces will be sinusoidal. Therefore, let the maximum rms passband signal be as defined in Equation (A.7).

$$V_{rms} = \frac{V_{fs}}{\sqrt{2}} \tag{A.7}$$

Rearranging (A.1), the full scale voltage can be represented as described in Equation (A.8).

$$V_{fs} = q2^B \tag{A.8}$$

Substitute Equation (A.8) into Equation (A.7) results in the Equation (A.9) expression for maximum rms pass-band signal in terms of quantization level and number of bits in the A/D.

$$V_{rms} = \frac{q2^B}{\sqrt{2}} \tag{A.9}$$

The ratio of maximum rms passband signal to the desired stopband signal level is defined in Equation (A.10).

$$\left(\frac{q2^B}{\sqrt{2}} \right) \Bigg/ \frac{q}{2\sqrt{3}} = \frac{q2^B}{\sqrt{2}} \frac{2\sqrt{3}}{q} = 2^B \sqrt{6} \tag{A.10}$$

The minimum attenuation in the stopband for the anti-aliasing filter is determined with Equation (A.11).

$$A_{\min} = -20\log_{10}\left(2^B \sqrt{6}\right) = -104.11 \text{ dB at } B = 16 \text{ bits} \tag{A.11}$$

The 8th order Bessel function analog filters will apply a –48 dB/octave roll-off. This specification can be translated to db/decade understanding that one octave is a factor of 2 and given the relationships described in Equations (A.12) and (A.13).

$$\log_{10}(2) = 0.301 \text{ decades}\big/\text{octave} \tag{A.12}$$

$$-48\left(\text{dB}\big/\text{octave}\right)\frac{1}{0.301}\left(\text{octaves}\big/\text{decade}\right) = 160 \text{ dB}\big/\text{decade} \tag{A.13}$$

Next, the anti-aliasing Bessel filter is designed and the required A/D sampling rate is determined. Let the frequency of interest (f_i) for data acquisition be twice the highest signal frequency expected ($f_i = 200$ Hz). Since the frequency of interest is much higher than the highest signal frequency expected, a Bessel filter designed for –3 dB attenuation at f_i should be acceptable. The Bessel filter for this application, designed with a –3 dB attenuation at 206 Hz, will fall below the desired stopband attenuation of –104 dB at approximately 1.8 kHz. Therefore, the minimum sampling rate necessary is 2 kHz (f_i + 1.8k Hz)—fold-over frequency of 1 kHz. The Bode plot illustrated in Figure 10 is an 8th order Bessel function filter with a cut-off frequency at 206 Hz.

The Bode plot illustrated in Figure 10 was generated by applying the following two commands to the MATLAB software where 400 is a group delay that essentially places the cut-off frequency:

- [b8, a8] = besself (8, 2*π*400);
- Bode(b8, a8, 'r');

To promote further attenuation of the aliased signals, a sampling rate of 2.5 kHz was chosen for this application.
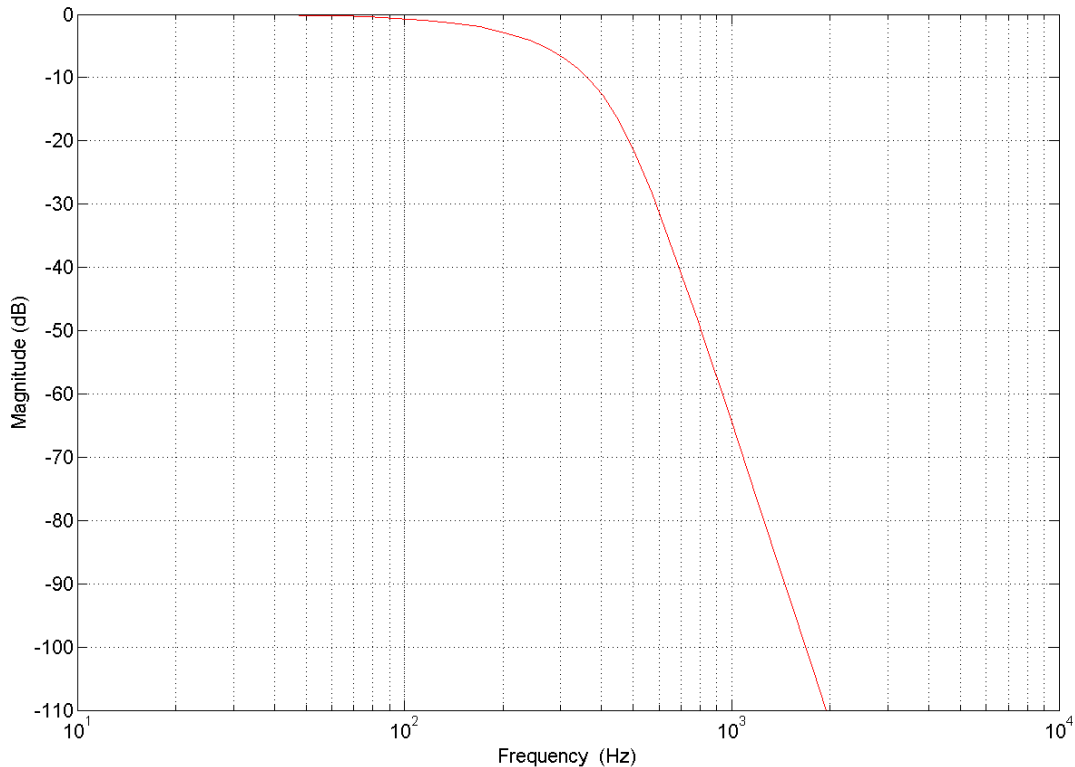

Figure 10.—Bode plot for an 8th order Bessel Function filter with a cut-off frequency of 206 Hz.

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14. ABSTRACT
NASA is interested in developing technology that leads to more routine, safe, and affordable access to space. Access to space using airbreathing propulsion systems has potential to meet these objectives based on Airbreathing Access to Space (AAS) system studies. To this end, the NASA Fundamental Aeronautics Program (FAP) Hypersonic Project is conducting fundamental research on a Turbine Based Combined Cycle (TBCC) propulsion system. The TBCC being studied considers a dual flow-path inlet system. One flow-path includes variable geometry to regulate airflow to a turbine engine cycle. The turbine cycle provides propulsion from take-off to supersonic flight. The second flow-path supports a dual-mode scramjet (DMSJ) cycle which would be initiated at supersonic speed to further accelerate the vehicle to hypersonic speed. For a TBCC propulsion system to accelerate a vehicle from supersonic to hypersonic speed, a critical enabling technology is the ability to safely and effectively transition from the turbine to the DMSJ-referred to as mode transition. To experimentally test methods of mode transition, a Combined Cycle Engine (CCE) Large-scale Inlet testbed was designed with two flow paths-a low speed flow-path sized for a turbine cycle and a high speed flow-path designed for a DMSJ. This testbed system is identified as the CCE Large-Scale Inlet for Mode Transition studies (CCE-LIMX). The test plan for the CCE-LIMX in the NASA Glenn Research Center (GRC) 10- by 10-ft Supersonic Wind Tunnel (10x10 SWT) is segmented into multiple phases. The first phase is a matrix of inlet characterization (IC) tests to evaluate the inlet performance and establish the mode transition schedule. The second phase is a matrix of dynamic system identification (SysID) experiments designed to support closed-loop control development at mode transition schedule operating points for the CCE-LIMX. The third phase includes a direct demonstration of controlled mode transition using a closed loop control system developed with the data obtained from the first two phases. Plans for a fourth phase include mode transition experiments with a turbine engine. This paper, focusing on the first two phases of experiments, presents developed operational and analysis tools for streamlined testing and data reduction procedures.

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