



A Modular Aero-Propulsion System Simulation of a Large Commercial Aircraft Engine

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Abstract

A simulation of a commercial engine has been developed in a graphical environment to meet the increasing need across the controls and health management community for a common research and development platform. This paper describes the Commercial Modular Aero Propulsion System Simulation (C-MAPSS), which is representative of a 90,000-lb thrust class two spool, high bypass ratio commercial turbofan engine. A control law resembling the state-of-the-art on board modern aircraft engines is included, consisting of a fan-speed control loop supplemented by relevant engine limit protection regulator loops. The objective of this paper is to provide a top-down overview of the complete engine simulation package.

Nomenclature

e	solver error
HPC	high pressure compressor
HPT	high pressure turbine
J	solver Jacobian
LPC	low pressure compressor
LPT	low pressure turbine
MM	model matching control design scheme
MN	Mach number
N_1	fan speed
N_1^R	corrected fan speed
N_2	core speed
N_2^R	corrected core speed
P_i	pressure at station i
PR	pressure ratio
SM	stall margin
T_i	temperature at station i
TRA	throttle resolver angle

VBV	variable bleed valve
VSV	variable stator vane
W_f	fuel flow
W_i	flow at station i
x	solver state
φ_i	corrected mass flow rate at station i
η	adiabatic efficiency

I. Introduction

There is great interest in the development of advanced control and health management algorithms for aircraft turbofan engines. However, a practical yet realistic non-proprietary simulation of a commercial turbofan engine did not previously exist on which to develop these algorithms. This has been a barrier to progress, especially in regard to collaboration between NASA researchers and their counterparts in academia and industry who must develop their new technologies in a realistic test-bed. Previously, a NASA-developed generic military turbofan engine simulation, the Modular Aero-Propulsion System Simulation (MAPSS), had been released for public use as a means to rapidly implement and test control algorithms on a validated engine model (ref. 1). Since then, other industrial and military gas turbine models tailored for controls and diagnostics research have been described in some recent papers as platforms in support of various programs (refs. 2 to 5). However, most of these are not available to the general public. Because many problems of interest are directly applicable to the commercial platform, there remains a strong need for a common non-proprietary *commercial* engine simulation from those in the community. Indeed, the differences between the commercial and military platforms are significant. Aside from the obvious differences in thermodynamic operation, the actuators, sensors, time constants, controller, and solution method are categorically dissimilar.

The Commercial Modular Aero-Propulsion System Simulation (C-MAPSS) has been developed in the Matlab/Simulink (The Mathworks, Inc.) environment as a multifunctional simulation of a large commercial turbofan engine with a realistic engine control system. The engine represents a modern dual-spool, high-bypass ratio turbofan engine of the type on which many controls and diagnostics/health management studies have concentrated in recent years. The key function of C-MAPSS is to provide the user with a graphical turbofan engine simulation environment in which advanced algorithms can be implemented and tested. The software provides the user easy access to health, control, and engine parameters through a graphical user interface (GUI). A controller that is representative of the control logic within a Full Authority Digital Engine Controller (FADEC) on board current commercial engines is also part of the package.

The C-MAPSS paradigm provides functionality for the following: engine initialization at arbitrary (valid) flight conditions in the flight envelope, generation of linear point models at operating conditions for system analysis and design, design of linear point compensators, and rapid generation of closed-loop simulations and visualization of the results. All of these capabilities have been automated for the end user through use of the Matlab GUI environment. The usually tedious task of constructing a gain-scheduled controller, for example, may be greatly facilitated by the GUI's built-in capabilities. To be specific, the design of a point controller, as an elemental part of the gain-scheduled controller, is consolidated into a point-and-click operation that leverages the data capture/retrieval capabilities of Matlab. The basic features are supplemented with capabilities to simulate effects such as engine deterioration or faults by adjustment of the health parameter modifiers, as is common practice.

Each of the basic engine components has been coded as a Simulink s-function script (a computer program, interpreted or compiled, written in one of several standard programming languages within a Simulink block), which brings several advantages including execution speed and line-by-line validation/modification. Owing to the Matlab/Simulink environment in which it was developed, the model is capable of being eventually deployed (all or in part) as compiled code for hardware-in-the-loop

applications such as flight simulators and other real-time validation studies. This would require further development, and is not within the scope of this paper.

It should be noted that C-MAPSS has been made available as an initial release (version 1.0) through the NASA Glenn Software Repository website (<http://technology.grc.nasa.gov/software/>) and has been reported in reference 6. A more recent version that has been developed (to be designated version 2.0 in a possible future release) is the focus of this paper. The second version differs from the first release in a number of areas. First, several new model features have been added. These include actuator and sensor dynamics, variable geometry effects, Reynolds' number effects (in the high pressure compressor), and representation of the combustion transport delay. Changes have been made to the gain-scheduled controller structure and implementation of the limit logic. Several improvements have been made to the GUI to offer the user greater flexibility in performing the built-in functions in a more streamlined manner.

The following sections outline the basic engine model from a top-down perspective. Section II presents important details of the C-MAPSS engine and provides some scope of the modeling techniques used for this engine system. Implementation details of the aero-thermodynamic model, the solution method, and the control logic are described in Section III. A simple flight scenario example, highlighting aspects of the simulation's functionality as a controls and diagnostics development and prototyping tool, is presented in Section IV. Section V summarizes the C-MAPSS program.

II. Overview of the C-MAPSS Engine Platform

The C-MAPSS engine represents a conceptual 90,000-lb thrust class turbofan engine with high-bypass ratio and a two-spool configuration. Figure 1 shows the various components of the engine. The five rotating components consist of the fan, low pressure compressor (LPC), and low pressure turbine (LPT) on the fan shaft, and the high pressure compressor (HPC) and high pressure turbine (HPT) on the core shaft. The station designations are shown along the bottom of the figure. To give some perspective for size, the engine has been designed to operate with a bypass ratio (BPR) of 8.4, an overall pressure ratio (OPR) of 36, and has a fan diameter of approximately 100 in. The design speeds for the fan and core shafts are 2450 and 9300 rpm, respectively. The control inputs to this engine are fuel flow (W_f), variable stator vane (VSV) angle, and variable bleed valve (VBV) position. Two spool rotation and six gas path sensors are considered as inputs to the control logic: N_1 , N_2 , P_{20} , T_{20} , T_{24} , P_{S30} , T_{48} , and P_{50} . This is representative of the sensors, in terms of type and quantity, used in most commercial turbofan engines.

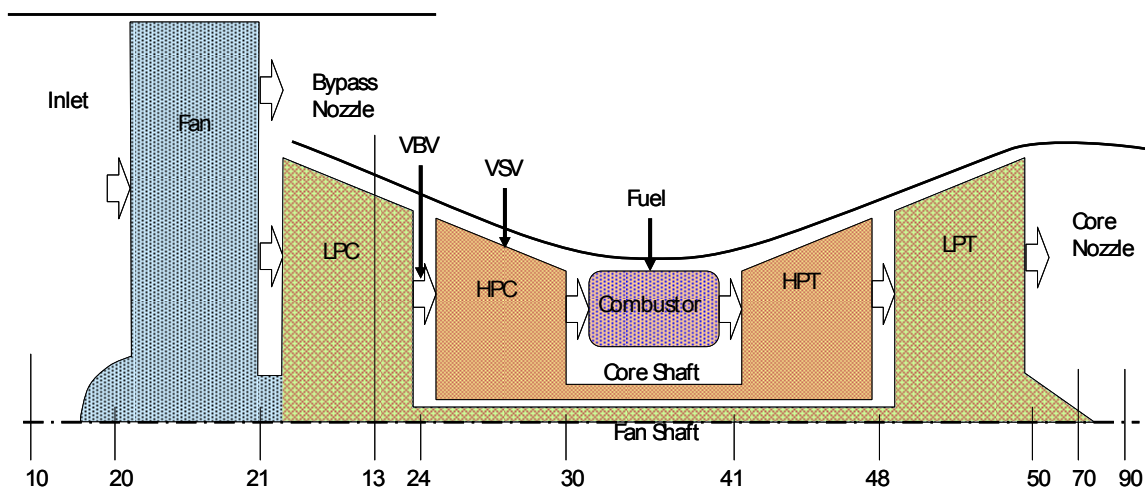


Figure 1.—Diagram of the C-MAPSS engine components and station designations.

The component maps and other parametric data have been generated at NASA using a variety of high-fidelity sources. The map data are loaded at startup from Matlab script files, which are then read as global variables at the component s-function level. As such, the simulation is easy to adapt with different cycle deck data representative of different turbofan engines. The model has been constructed to ensure steady-state validity over altitudes ranging from sea level to 40,000 ft, Mach numbers (MN) between zero and 0.85, and sea-level temperatures between -60 and 103 °F. Details of the implementation are discussed in the remainder of the paper.

III. Description of the Engine Model and Control System

This section is devoted to providing the reader with an understanding of the formulation and construction of the aero-thermodynamic model and control system. In addition to providing an overview of the modeling method, this section details the conventions used for modeling physical features such as stall margin, health parameters and component maps. Detailed accounts of the thermodynamic models for gas turbines can be found elsewhere in the literature (refs.7 to 10).

A. Aero-Thermodynamic Model

In order to capture the essential thermodynamic effects of the five rotating components, each has been represented by maps relating pressure ratio, corrected flow rate, and adiabatic efficiency, which are indexed by corrected shaft speed. The procedure and conventions for correcting gas path flow rates W and spool speeds are well known and well documented (see ref. 11). The corrected mass flow rates are designated by “ ϕ ” and the corrected versions of the two spool speeds are designated “ N_1^R ” and “ N_2^R .”

The model operates with thermodynamic parameters that vary with temperature and gas composition. When computing these parameters, it is assumed that the combustion is complete with no unburned combustion products. The polytropic coefficient, for example, is calculated based on the gas temperature and fuel-to-air ratio (FAR). The universal gas constant is computed based only upon the fuel-to-air ratio.

Atmospheric Mode

In order to represent altitude-adjusted air properties, the C-MAPSS package includes an atmospheric model consisting of an altitude-adjusted free-stream temperature. For researchers intending to integrate C-MAPSS with an airframe model, the atmospheric model can be replaced with the aircraft atmospheric model to maintain consistency.

Inlet

The simple model of the inlet consists of a total pressure and temperature computation that is corrected to account for ram pressure recovery. Since C-MAPSS only operates in the subsonic regime, ram recovery typically stays above 99.5 percent.

Fan and Compressors

In the fan and compressors, the torque supplied by the shaft is used to compress the flow. The fan, low pressure compressor (LPC) and high pressure compressor (HPC) are each represented by a performance map that is described by three quantities: pressure ratio (PR), ϕ , and adiabatic efficiency (η). These maps are indexed by shaft speed and *R-line*. The independent variable *R-line* is used instead of PR simply because compressor maps take on a profile such that a given PR may correspond to more than one corrected flow value at a constant corrected speed. An *R-line* value of 1.0 corresponds to the stall line and an *R-line* of 2.0 corresponds to the intersection with the design point. Inter-stage bleeds representing air extracted for customer service, preferential cooling, and overboard bleed have been included as fractional flow debits on the core stream. These have been assumed to be localized at the compressor exit (9th stage), which is a reasonable approximation to make even though the actual bleeds may occur, in some cases,

several stages upstream. Table 1 shows the design-point characteristics of the fan and compressors, which gives the generalist an idea of the size of each component, and may be used as a basis for scaling the entire map to assume the form of a different engine cycle.

TABLE 1.—FAN/COMPRESSOR/TURBINE
DESIGN POINT CHARACTERISTICS

Component	Parameter	Value
Fan	N_1	2654 rpm
	$R-line_{Fan}$	2.0
	PR_{Fan}	1.784
	η_{Fan}	0.8969
	Φ_{Fan}	3655.5 lbm/s
Low Pressure Compressor	N_1	2654 rpm
	$R-line_{LPC}$	2.0
	PR_{LPC}	1.1035
	η_{LPC}	0.9148
	Φ_{LPC}	289.57 lbm/s
High Pressure Compressor	N_2	9210 rpm
	$R-line_{HPC}$	2.0
	PR_{HPC}	21.817
	η_{HPC}	0.8615
	Φ_{HPC}	209.47 lbm/s
High Pressure Turbine	N_2	9119 rpm
	PR_{HPT}	4.239
	η_{HPT}	0.9202
	Φ_{HPT}	17.59 lbm/s
Low Pressure Turbine	N_1	2394 rpm
	PR_{LPT}	5.858
	η_{LPT}	0.930
	Φ_{LPT}	94.64 lbm/s

Combustor

The fuel delivery and combustion process is modeled by a 40-ms transport delay, in conjunction with a slight flow resistance due to losses at the liner and mixer. The model of the heat release process is simplified by assuming that the combustion process is stoichiometric (i.e. no unburned hydrocarbons remain).

Turbines

As with the compressors, the turbines are represented by maps relating shaft speed to ϕ and η , however since the relationship between PR and ϕ is unique, PR is used as the other independent variable (in addition to shaft speed) for indexing the maps. The energy of the gas flow produces work on the shaft, thereby driving the associated fan and compressors. In the HPT and LPT, the cooling bleed flows re-enter the gas stream with a substantial pressure drop due to the cooling passages through which they pass. The map characteristics at the design point for the HPT and LPT are given in table 1.

Nozzles

The core and bypass nozzles are modeled as adiabatic expansion processes. The core and bypass are subsonic in nature, which calls for a converging nozzle design. Standard subsonic compressible flow relationships are used to represent the expansion process.

Shaft Dynamics

The fan and core shaft dynamics are governed by the conservation angular momentum, where the sum of the shaft torques is proportional to the angular acceleration (derivative of the shaft speed, or $N\dot{\theta}$). The lumped shaft inertia governs the acceleration and deceleration of the shaft. The moments of inertia for the low- and high-speed rotors are 533 and 47.7 ft-lb-s², respectively.

Duct Losses

At the exit of each component, a small pressure drop is inserted to represent the frictional losses due to the duct walls lumped at a discrete location.

Variable Bleed Valve

The primary purpose of the VBV is to avoid compressor instability, namely to prevent the compressor from entering stall at an operating condition. As stated above, bleeds are usually modeled as fractional flow extractions from the primary flow. The VBV is capable of actuating a large percentage of the core flow to the bypass duct and must also modulate the flow path at moderate to high power settings, meaning that the flow will be choked under certain conditions. For this reason, the VBV cannot be modeled as a proportional orifice, and is instead modeled using isentropic compressible flow principles, under the assumption of ideal converging-diverging nozzle flow.

Variable Stator Vanes

The VSV are typically located at the forward stages of the HPC and are used as a means to maintain compressor stability and prevent choking of the downstream compressor stages. In the HPC, the VSV effects have been represented by nonlinear modifications to the baseline component maps. The HPC maps were generated with the stator vanes operating on a control schedule; therefore the delta values from this schedule have been approximated from compressor data that is a function of corrected core speed N_2^R and vane angle. The compressor PR , ϕ and η maps are thus formulated in terms of elemental maps of flow coefficient, isentropic work and actual work. With this representation, the effects of the VSV angle have a multiplicative (scalar) influence and are easily incorporated.

Stall Margin

Stall margins (SM_{Fan} , SM_{LPC} , SM_{HPC}) are computed by comparing the actual pressure ratio to the pressure ratio at the stall line for the same corrected flow rate. On a compressor map, this is geometrically visualized as the vertical difference between the current operating point and the stall line.

Health Parameters

Health parameters are useful adjustments to a simulation for representation of damage, deterioration, or a fault condition. In gas-path health-management research, these parameters are essential for studying detection and/or isolation of faults or deterioration. As shown in table 2, there are 13 health parameters, each corresponding to an adjustment to the map parameters in a rotating component. In the fan and each of the compressor routines, there are three health parameters corresponding to a percent corrected flow rate, pressure ratio, or efficiency “delta” relative to the nominal value. Degradation can be approximated by incorporating a steady-state adjustment to the health parameters; a fault can be simulated by imposing a time-dependent shift in the health parameter, by specifying the time-dependent profile that characterizes the fault.

TABLE 2.—HEALTH PARAMETERS

	Parameter	Description
1	$\eta_{\text{mod,Fan}}$	Fan efficiency modifier
2	$\Phi_{\text{mod,Fan}}$	Fan corrected flow modifier
3	$PR_{\text{mod,Fan}}$	Fan pressure ratio modifier
4	$\eta_{\text{mod,LPC}}$	LPC efficiency modifier
5	$\Phi_{\text{mod,LPC}}$	LPC corrected flow modifier
6	$PR_{\text{mod,LPC}}$	LPC pressure ratio modifier
7	$\eta_{\text{mod,HPC}}$	HPC efficiency modifier
8	$\Phi_{\text{mod,HPC}}$	HPC corrected flow modifier
9	$PR_{\text{mod,HPC}}$	HPC pressure ratio modifier
10	$\eta_{\text{mod,HPT}}$	HPT efficiency modifier
11	$\Phi_{\text{mod,HPT}}$	HPT corrected flow modifier
12	$\eta_{\text{mod,LPT}}$	LPT efficiency modifier
13	$\Phi_{\text{mod,LPT}}$	LPT corrected flow modifier

Actuator and Sensor Dynamics

The dynamics of several actuators and sensors have been included in the simulation. The fuel metering valve (FMV) actuator, along with the VSV and VBV servoactuators have been modeled by simple first-order transfer functions, which is a valid approach to use for sample rates as slow as the controller rate. For the VBV and VSV, the actuator commands are open-loop scheduled on corrected fan and core speeds, respectively. The bleed valve is scheduled such that the valve is fully open at low power and closed at moderate-to-high power settings. The variable stators are commanded a positive deflection (50°) at low power and move to zero deflection at high settings. As with the actuators, the sensors are also taken as first-order lags, whose bandwidth parameters are given in table 3.

TABLE 3.—ACTUATOR AND SENSOR DESCRIPTIONS AND BANDWIDTHS

Variable	Description	Bandwidth
Wf	Fuel metering valve	25 rad/s
VBV	Variable bleed valve	23 rad/s
VSV	Variable stator vanes	23 rad/s
N_1	Fan speed	50 rad/s
N_2	Core speed	50 rad/s
T_{20}	Fan inlet temperature	9 rad/s
P_{20}	Fan inlet pressure	25 rad/s
T_{24}	LPC outlet temperature	9 rad/s
P_{S30}	Combustor static pressure	25 rad/s
T_{48}	HPT exhaust gas temp.	9 rad/s
P_{50}	Core exhaust pressure	25 rad/s

It should be evident at this point that the physical engine system represented here is fairly comprehensive in scope. Although three-dimensional flow effects have been eliminated, the effects of heat soakage and tip clearance have not been incorporated, and some simplifying assumptions have been made, the gross aero-thermodynamic effects remain intact. As such, the resulting model is useful for examining important gas-path-related effects of interest for control law or health management system developers.

B. The Engine Balance Solver Routine

The engine has two physical state variables: fan speed and core speed (with respective time constants governed by rotor inertia). The fan, two compressors and two turbines each possess one unknown variable: for the fan and compressors this is the *R-line* value, for the turbines it is pressure ratio. An

iterative solver is used to drive down the flow continuity errors between each of the five major components in order to *uniquely* solve the five unknowns. Although it is more accurate to iterate until a tolerance is reached, the solver is set up to execute only once per sample (every 0.015 s) to improve the execution speed of C-MAPSS.

Due to the two-way coupling that exists between the spool speeds and the thermodynamic processes, the system can be balanced on the basis of the aero-thermodynamic principles. In reality, each component has its own gas volume storage, and this compliance creates a lag between components that allows the solution to be described by these dynamics directly without a dedicated solver. However, the volume dynamics are at a bandwidth far greater than the controller sample rate (by more than an order of magnitude; time constants are typically less than 1 ms). This would require the simulation to operate much faster than the controller rate, to the detriment of execution speed, and is hence not employed here.

Since the spool dynamics are slower than the controller dynamics, the closed loop system is operated at the controller 67 Hz update rate (0.015 s period) and an iterative solver used to balance the engine at this discrete update rate. The solver is based on a Newton-Raphson scheme using a static Jacobian matrix J obtained at a single operating point. The errors are driven toward zero through the following difference equation

$$x_{k+1} = x_k - J^{-1}e_k$$

where e_k is an error vector of the same dimension as the vector of independent parameters x_k . The error parameters are each taken to establish flow continuity between components (flow exiting a component equals the flow entering the next component, minus any bleeds). In the turbines, the independent parameters are taken simply as the pressure ratios, while in the fan and compressors these are taken as the *R-line* values. A listing of the five flow continuity errors and the five independent parameters is given in table 4. Even using the fixed-Jacobian single-iteration solver, the flow continuity errors remain within 15 percent at worst (continuity of flow across the HPC) for a typical large-magnitude burst transient. This is due in part to the controller limiting the speed of the engine. Although these errors may be undesirable for detailed performance studies, for most controls and diagnostics studies, this approach should prove to be sufficient.

TABLE 4.—COMPRESSOR/TURBINE SOLVER PARAMETERS
[W_i represents mass flow at station i .]

	Flow continuity error quantity	Independent parameter
1	$W_{21} - W_{13} - W_{24}$	$R\text{-line}_{\text{Fan}}$
2	$W_{24} - W_{30}$	$R\text{-line}_{\text{LPC}}$
3	$W_{48} - W_{40} - W_{\text{HPTbld.1}} - W_{\text{HPTbld.2}}$	$R\text{-line}_{\text{HPC}}$
4	$W_{50} - W_{48} - W_{\text{LPTbld.1}} - W_{\text{LPTbld.2}}$	PR_{HPT}
5	$W_{50} - W_{90}$	PR_{LPT}

C. Control System

The default control system that is provided with C-MAPSS is a gain-scheduled linear control law with a simplified limit protection scheme, which is representative of the state-of-the-art in digital engine control systems employed by industry. The specifics of engine control systems are proprietary, so details of the actual limit schedules, controller time constants, and mode selection thresholds have been constructed based on knowledge of the safety, stability, and operability margins of the C-MAPSS engine.

The comprehensive control system consists of a fan-speed compensator, four limit regulators, and core speed acceleration and deceleration limiters. Three high-limit regulators prevent the engine from exceeding its design limits for core speed (N_2), combustor static pressure (P_{S30}), and HPT exit temperature. The core speed limit is designed to prevent mechanical failure of the rotating components,

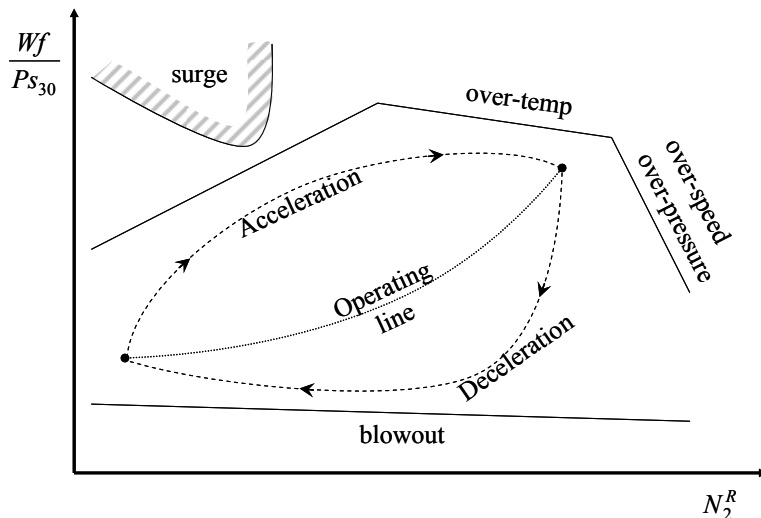


Figure 2.—Illustration of the limit protection philosophy.

while engine pressure ratio and temperature limits are set up to prevent failure of the high pressure and high temperature components. A fourth limit regulator is instituted to prevent the static pressure at the exit of the HPC from going too low to prevent lean combustor blowout. The operation of the control limits is illustrated in figure 2.

As shown in figure 2, acceleration and deceleration limits are implemented primarily to prevent compressor stall during transients. Secondly, the acceleration limit is an additional measure to prevent over-stress of the rotor and the deceleration protects against blowout. As is common among manufacturers (ref. 12), the variable $\Phi = Wf/Ps_{30}$ is used to prevent stall; the maximum Φ is set to prevent HPC stall and the minimum is set to prevent LPC stall. This is because the HPC stall margin experiences undershoot as compressor through-flow *increases*, while the LPC stall margin experiences its undershoot as the through-flow *decreases*. In C-MAPSS, margins are maintained at 15 percent in the HPC and 6 percent in the LPC. The minimum and maximum values of Φ are determined to maintain these margins as N_2^R varies. This control limit differs from the four limit regulators in that the fuel flow is saturated (by setting the derivative to zero) when acceleration or deceleration exceeds tolerance. To calculate the minimum and maximum Wf limits, the minimum and maximum values of Φ are scheduled against N_2^R and are multiplied by Ps_{30} . As will be shown, the fuel flow derivative is accessible for the saturation limit since it is the controlled variable.

The fan speed regulator and limit regulators are designed using the model-matching (MM) method, formalized by Edmunds (ref. 13). With this technique, the desired closed-loop transfer function and the compensator poles are specified and the compensator's gain and zeros are obtained to provide the best match to the desired transfer function in a least-squares sense. The gain and feedthrough matrices of the fan speed regulator are scheduled versus N_2^R and P_{20} . The P_{20} schedule is necessary to consolidate the effects of altitude and Mach number variations into one parameter. Each of the limit regulators consists of static parameters designed at a representative flight condition consistent with the limit.

In actual FADEC control systems, extensive provisions are made in the logic structure to avoid integrator-windup problems and ensure smooth, chatter-free transition between control modes. The C-MAPSS controller emulates these provisions by incorporating an incremental control command and interpolating the scheduled linear gains that discretize the entire flight envelope. With the plant augmented with a free integrator, the second-order MM regulators are referred to as "incremental" (rate) regulators. To prevent integrator windup, only one free integrator is required for all control modes since only one is active at any time. Therefore, all control modes operate on the control derivative, instead of the absolute (integrated) signal.

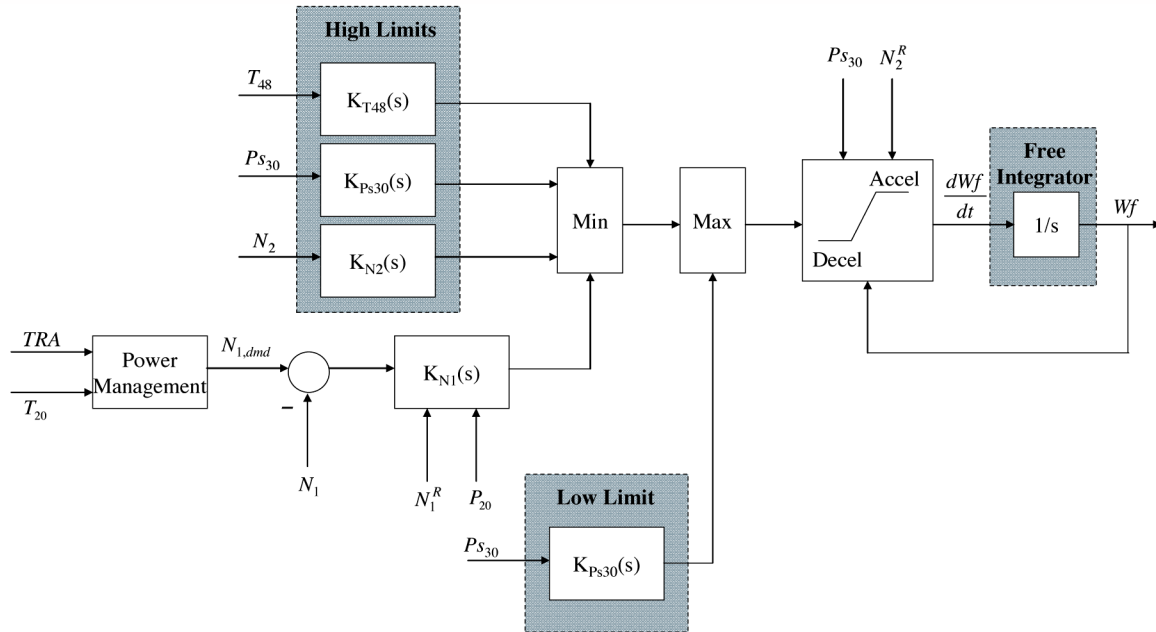


Figure 3.—Fuel flow control logic. Inputs refer to the sensor measurements and the output is the fuel flow command.

A power management system has been included in order to relate the pilot's TRA (throttle resolver angle) input to a demanded corrected fan speed. In order to approximate a linear TRA-to-net thrust relationship, a table lookup is used whose profile is such that the sensitivity of N_1^R to TRA increases as TRA increases. By correcting fan speed with respect to T_{20} , it allows the engine to be operated over a wide range of thrust levels throughout the full range of flight conditions. Figure 3 depicts the complete fuel flow control architecture.

IV. The C-MAPSS Program User Interface and Operation

The C-MAPSS program consists of Matlab code, a GUI, and Simulink diagrams which appear to the user as shown in figures 4 and 5. Note the user-specified flight condition down the center of the GUI (fig. 4) and the user-selected profiles of the three control inputs (TRA, VSV and VBV) and the three environmental parameters (altitude, Mach number, and delta ambient temperature) on the right side of the GUI. The GUI is structured to facilitate the following basic tasks: generation of flight conditions and input profiles; construction of linear models; design of engine controllers and limit regulators via the MM method; execution of open-/closed-loop simulations and examination of the results. Thus the user is able to perform several practical functions through a point-and-click approach using the menu picks along the top of the GUI. Each GUI task is carried out via a Simulink representation of the C-MAPSS engine (fig. 5) that is configured appropriately. This section details the various features of the C-MAPSS user interface and provides a simple example to demonstrate the operability of the simulation.

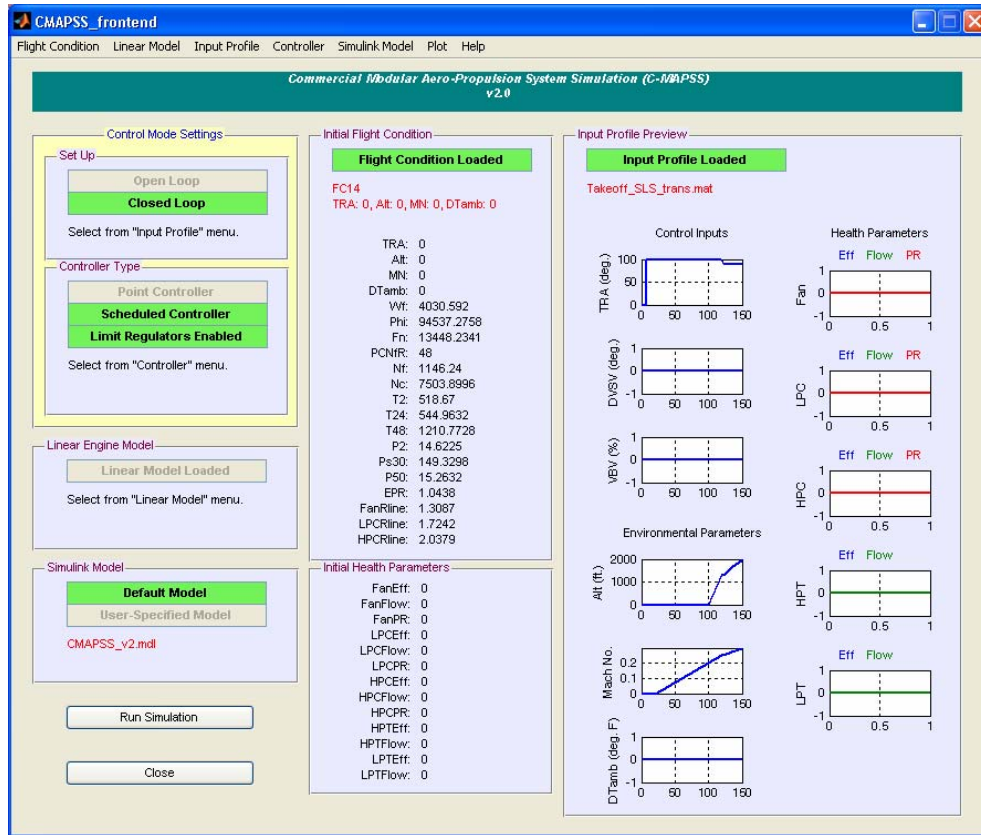


Figure 4.—Front-end GUI of C-MAPSS, for setting up and running the simulation.

Commercial Modular Aero-Propulsion System Simulation (C-MAPSS) (ver. 2.0)

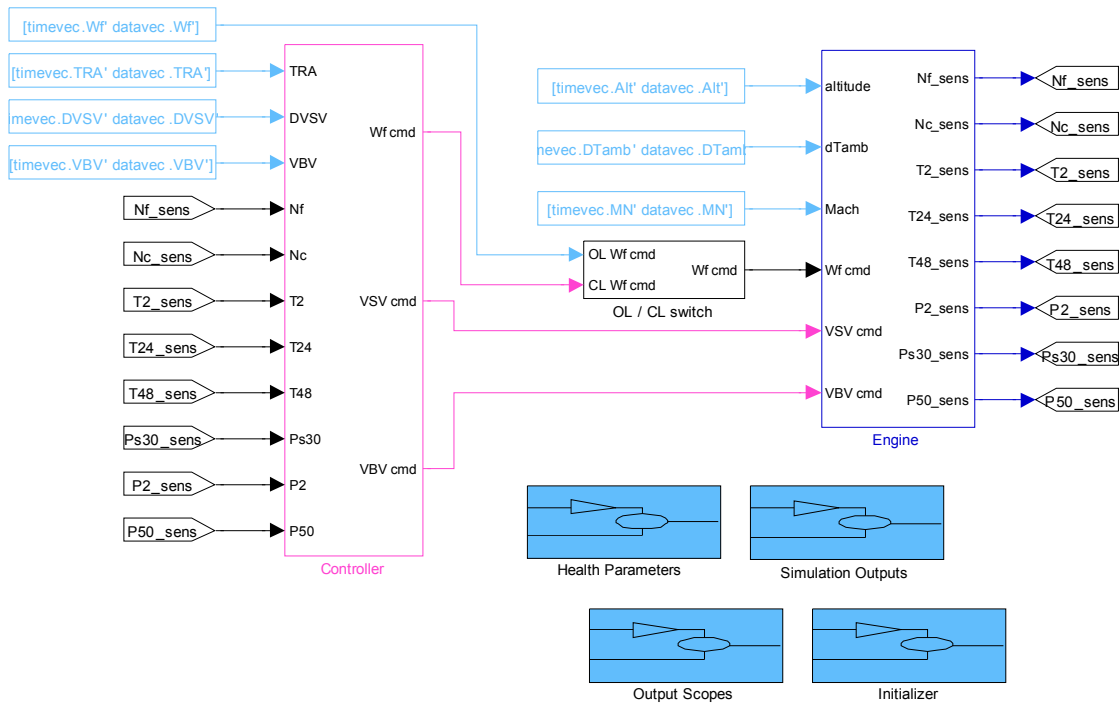


Figure 5.—Top-level Simulink diagram.

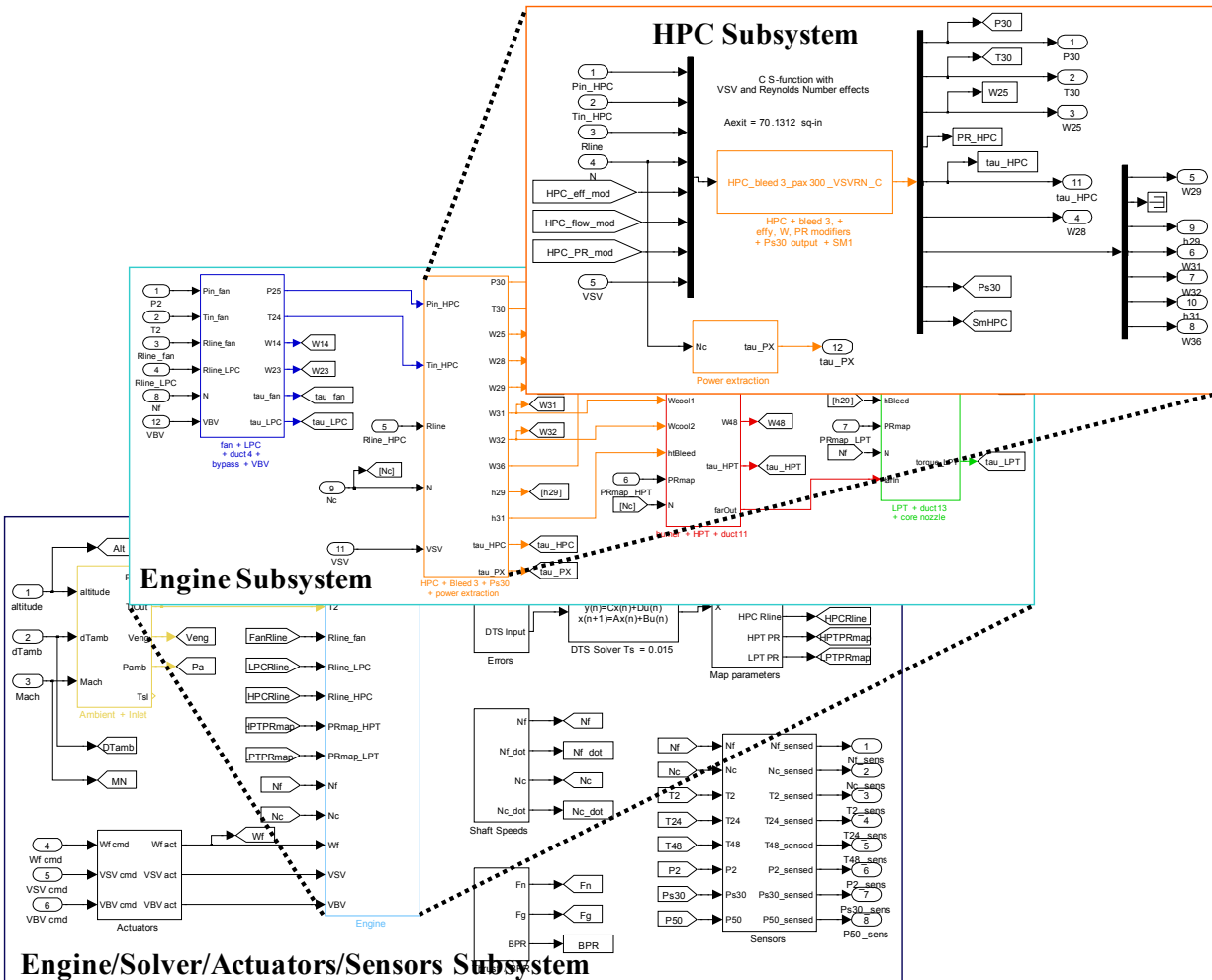


Figure 6.—Illustration of C-MAPSS subsystem hierarchy.

A. Implementation and Use

The engine-level subsystem is shown in figure 6, which is the subsystem that contains the solver, shaft dynamics, sensors, actuators, atmospheric model, and engine aero-thermodynamic model. At the lowest level of the Simulink hierarchy, the aero-thermodynamic model is comprised of s-functions that represent the engine’s major components. The inputs and outputs of the 10 major components and the design characteristics for each are given in table 5. In the table, note that the Fan exit flow is split between the bypass duct and the LPC inlet. As a result of the split, it should be clear that the pressures, temperatures, and flows are related by $P_{21} = P_{13} = P_{22}$, $T_{21} = T_{13} = T_{22}$, and $W_{21} = W_{13} + W_{22}$.

TABLE 5.—MAJOR COMPONENT MODULES FOR C-MAPSS,
ALONG WITH THEIR INPUTS AND OUTPUTS

[Fg , h , FAR and τ represent gross thrust, enthalpy, fuel-to-air ratio, and torque, respectively.]

Component	s-function inputs	s-function outputs
Inlet	T_{10}, P_{10}, MN	T_{20}, P_{20}
Fan	$T_{20}, P_{20}, N_1, R\text{-line}_{Fan}$ $\eta_{mod,Fan}, \phi_{mod,Fan}, PR_{mod,Fan}$	$T_{21}, P_{21}, W_{21}, \tau_{Fan}, SM_{Fan}$
Bypass Nozzle	$T_{13}, P_{13}, P_{amb}, W_{VBV}$	W_{13}, Fg_{Bvp}
Low Pressure Compressor	$T_{22}, P_{22}, N_1, R\text{-line}_{LPC}$ $\eta_{mod,LPC}, \phi_{mod,LPC}, PR_{mod,LPC}$	$T_{24}, P_{24}, W_{24}, \tau_{LPC}, SM_{LPC}$
Variable Bleed	$VBV, T_{24}, P_{24}, W_{24}, T_{13}, P_{13}, W_{13}$	W_{VBV}
High Pressure Compressor	$T_{25}, P_{25}, W_{VBV}, N_2, R\text{-line}_{HPC}, VSV$ $\eta_{mod,HPC}, \phi_{mod,HPC}, PR_{mod,HPC}$	$T_{30}, P_{30}, Ps_{30}, W_{25}, W_{36}, \tau_{HPC}, SM_{25}$ $h_{LPTbld}, W_{LPTbld,1}, W_{LPTbld,2}, W_{Cust_bld}$ $h_{HPTbld}, W_{HPTbld,1}, W_{HPTbld,2}$
Combustor	$T_{30}, P_{30}, W_{36}, Wf$	$T_{40}, P_{40}, W_{40}, FAR_{40}$
High Pressure Turbine	$T_{40}, P_{40}, FAR_{40}, N_2, PR_{HPT}$ $h_{HPTbld}, W_{HPTbld,1}, W_{HPTbld,2}$ $\eta_{mod,HPT}, \phi_{mod,HPT}$	$T_{48}, P_{48}, W_{48}, FAR_{48}, \tau_{HPT}$
Low Pressure Turbine	$T_{48}, P_{48}, FAR_{48}, N_1, PR_{LPT}$ $h_{LPTbld}, W_{LPTbld,1}, W_{LPTbld,2}$ $\eta_{mod,LPT}, \phi_{mod,LPT}$	$T_{50}, P_{50}, W_{50}, FAR_{50}, \tau_{LPT}$
Core Nozzle	$T_{50}, P_{50}, P_{amb}, FAR_{50}$	W_{90}, Fg_{Core}

At this point, it is worth noting how the s-functions are composed. Because there are certain advantages and disadvantages of Matlab-based and C-based s-functions, each component has been coded in both formats. In short, the Matlab functions are useful for editing the module without needing to reprogram and recompile the s-function code, but tend to have long execution times. The C functions, while more complicated to implement, allow the full simulation to be executed much more quickly (about seven times faster than real time on a standard desktop equipped with a 2.2 GHz processor).

The C-MAPSS user interface environment is now discussed in greater detail. As has been stated, each of the automated functions is accessible from the front-end GUI, which is powered in the background by Matlab scripts and the main Simulink file. The various functions are accessed by the menu options at the top of the GUI.

Initialization

The simulation is initialized by simply balancing the engine to equilibrium for a prescribed set of inputs (flight, power setting, and deterioration conditions). The speed of convergence is expedited by removing the controller and engine dynamics and replacing these with an augmented, eight-state Newton-Raphson solver. The errors in this case include the five continuity errors, the net torques on the two shafts, and the controlled variable. In open-loop, the controlled variable is fuel flow, while in closed-loop, this may be chosen as either TRA or net thrust in the GUI. As with the standard five-state discrete-time solver, the engine balancing solver operates with a static Jacobian matrix to rapidly solve for the independent variables. Unlike the standard solver, however, limits are treated by swapping rows of the Jacobian matrix corresponding to the limited/un-limited output variable. Implementation-wise, once a limit is reached, the output variable to be controlled is switched to this limited variable, and an inverse Jacobian corresponding to that variable is selected. The balancing proceeds until the root-mean-square (rms) error falls below a certain user-specified threshold.

Input Profiles

In normal, undegraded operation, the input profile is specified by the three environmental variables (altitude, MN, and delta ambient temperature), the two variable geometry actuator inputs (VSV, VBV), and either fuel flow or TRA, depending on whether the intent is to perform open-loop or closed-loop

simulations. Time-indexed vectors for each of these inputs are specified by either loading an existing profile (e.g., takeoff, climb, descent) or constructing a new step or ramp profile in the Input Profile GUI. The GUI simply facilitates the task of constructing data vectors that are called by the simulation from the Matlab workspace.

Linearization

The open-loop engine may be linearized at any arbitrary flight condition for controls and diagnostics development. The Linear Engine Model GUI facilitates the process by performing the linearization with user-specified perturbation magnitudes on each state and input variable. Once generated, the response of the linear model to an input perturbation may then be compared visually to that of the nonlinear model by making use of the preconfigured plotting routines within C-MAPSS.

Control System

The simulation can be configured to operate open-loop or in one of several closed-loop modes. When simulating in closed-loop, the user can choose to employ a linear point fan speed controller, a gain-scheduled controller without limit regulators, or a gain-scheduled controller with all limits activated. Although a comprehensive set of point controllers has been included with C-MAPSS, users may choose to design point compensators of their own. Once a linear model has been generated, the Controller Design GUI allows the user to rapidly perform the MM design at that flight condition and conduct loop analysis of the compensator design. Of course, the user is free to substitute a customized controller for the standard one by simply replacing the contents of the “Controller” Simulink block with a subsystem containing the new algorithm.

Degraded Operation

Abrupt faults or gradual degradation in the engine can be approximated by use of the health parameter inputs. As with the open-/closed-loop command inputs, this is done by specifying an appropriate time history for any of the 13 health parameter inputs as time vectors in the Matlab workspace or via the Input Profile GUI, where a step or ramp transient may be constructed. The reader is referred to other sources for information on possible settings for simulating deterioration (ref. 14) and faults (ref. 15).

B. Closed-Loop Example

Some illustrative results of the engine simulation are shown in figures 7 and 8. The test case shown is for a burst/chop throttle maneuver between 0° and 100° TRA conducted at sea-level static, standard day conditions. The example illustrates that the fan-speed compensator (in control the majority of the time) produces a smooth fan speed response that does not violate any limits. The VBV and VSV actuators follow schedules that are inversely related to the corrected fan and core speeds, respectively. The only limiter that comes into play is the Φ (W_{ff}/P_{S30}) saturation limit; the maximum is encountered during burst and the minimum encountered during chop. Figure 8 shows the transient response of the stall margins in the fan and compressor components. Viewed on the pressure ratio map, the fan stall margin evolves within a narrow region and hence does not require limit protection. The LPC and HPC, on the other hand, both have large-magnitude transient responses that require protection by the Φ limit. By virtue of their design, the limits prevent the LPC stall margin from falling below 6 percent during chop and the HPC stall margin from falling below 15 percent during burst.

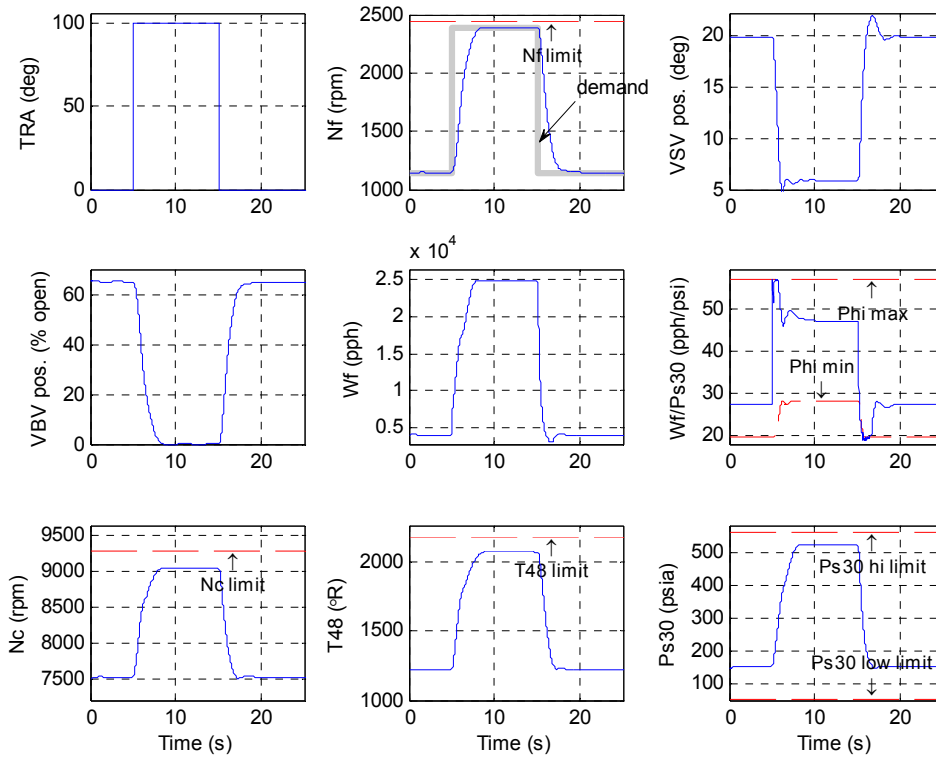


Figure 7.—Time traces for a burst followed by a chop at sea-level static conditions.

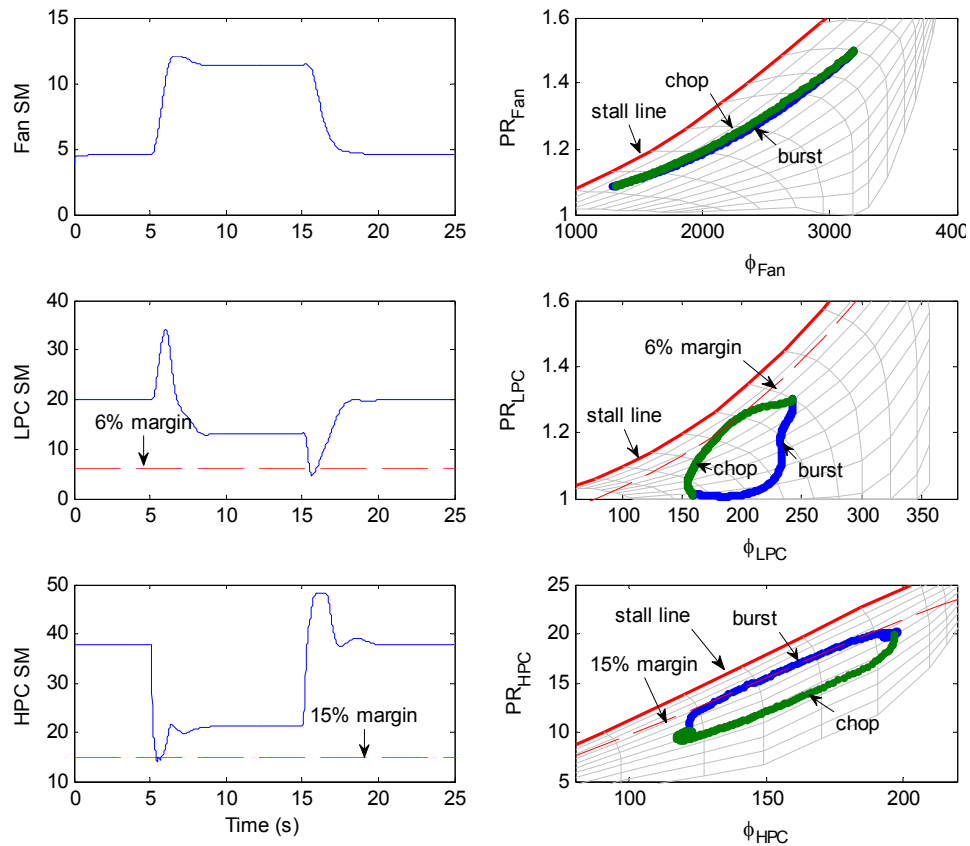


Figure 8.—Burst/chop trajectories shown in relation to the fan, LPC, and HPC pressure ratio versus corrected flow maps.

Summary

This paper presents an overview of the construction and implementation of the Commercial Modular Aero-Propulsion System Simulation (C-MAPSS) version 2 engine simulation. The basic elements of the aero-thermodynamic model have been discussed, as have the details relating to the solver and controller. The open-loop engine model has been constructed to provide comprehensive detail for each of the components and such that all of the relevant control “handles” and sensors that are of interest to users in the engine controls and diagnostics/health management community are provided. The controller has been essentially designed to represent modern digital control laws in a simplified, easily understood fashion. To that end, the controller consists of a gain-scheduled fan speed controller with associated limit logic to prevent the normal over-speed, over-temperature, over-pressure, compressor stall and lean blowout conditions. Due to C-MAPSS’ modular structure, a user-developed control law can be easily substituted for the existing one. In an effort to simplify common tasks, several simulation functions have been automated through the GUI environment. These include initialization of the engine at an arbitrary point, creation of linear models and point controllers, and generation of responses to various input profiles. The various engine components were implemented as Matlab s-functions to facilitate building and refining each of those modules. To promote fast simulations and to provide opportunity for real-time implementation, the modules were also deployed as C language-based s-functions. As a result of the steps taken to construct the simulation, C-MAPSS is a versatile tool that offers a wide array of functionality.

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14. ABSTRACT A simulation of a commercial engine has been developed in a graphical environment to meet the increasing need across the controls and health management community for a common research and development platform. This paper describes the Commercial Modular Aero Propulsion System Simulation (C-MAPSS), which is representative of a 90,000-pound thrust class two spool, high bypass ratio commercial turbofan engine. A control law resembling the state-of-the-art onboard modern aircraft engines is included, consisting of a fan-speed control loop supplemented by relevant engine limit protection regulator loops. The objective of this paper is to provide a top-down overview of the complete engine simulation package.					
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