Application of the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) for Dynamic Systems Analysis

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The aircraft engine design process seeks to achieve the best overall system-level performance, weight, and cost for a given engine design. This is achieved by a complex process known as systems analysis, where steady-state simulations are used to identify trade-offs that should be balanced to optimize the system. The steady-state simulations and data on which systems analysis relies may not adequately capture the true performance trade-offs that exist during transient operation. Dynamic Systems Analysis provides the capability for assessing these trade-offs at an earlier stage of the engine design process. The concept of dynamic systems analysis and the type of information available from this analysis are presented in this paper. To provide this capability, the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) was developed. This tool aids a user in the design of a power management controller to regulate thrust, and a transient limiter to protect the engine model from surge at a single flight condition (defined by an altitude and Mach number). Results from simulation of the closed-loop system may be used to estimate the dynamic performance of the model. This enables evaluation of the trade-off between performance and operability, or safety, in the engine, which could not be done with steady-state data alone. A design study is presented to compare the dynamic performance of two different engine models integrated with the TTECTrA software.

Nomenclature

CMAPSS40k	Commercial Modular Aero-Propulsion System Simulation 40k
DSA	Dynamic Systems Analysis
Engine A	Scaled version of CMAPSS40k
Engine B	Scaled version of CMAPSS40k with smaller acceleration limiter
FAR	Federal Aviation Regulations
HPC	High-Pressure Compressor
LPC	Low-Pressure Compressor
NPSS	Numerical Propulsion System Simulation
PI	Proportional-Integral
Ps3	High Pressure Combustor Static Discharge Pressure (psi)
SA	(Steady-state) Systems Analysis
SM	Surge Margin (%)
TSFC	Thrust Specific Fuel Consumption
TTECTrA	Tool for Turbine Engine Closed-loop Transient Analysis
T40	Turbine Inlet Temperature (degrees Rankine)

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Wf	Fuel Flow (lb/s)

I. Introduction

SYSTEMS analysis (SA) is a complex process that uses steady-state system-level simulations to evaluate performance, weight, and cost of a given design. The process requires extensive analysis of trade-offs in order to optimize and evaluate individual technology benefits offered by the system. When applied to aviation propulsion systems, these analyses produce results that help guide technology investment, architecture, and program planning and formulation throughout the life of the program.

There are a multitude of tools available for SA that may be used to determine the steady-state performance of a conceptual design, such as custom cycle decks, which are steady-state engine models typically developed by engine manufacturers, and the Numerical Propulsion System Simulation (NPSS), developed by NASA.[1,2] These tools can be integrated with other software to perform a steady-state system-level optimization. During these simulations, an engine model is driven to specific power reference values, typically defined by fuel flow, thrust, or fan speed, and the engine and engine components' data are recorded for analysis. This analysis usually includes several specific flight conditions of importance, such as at takeoff and cruise. The engine components' actual transition from one operating point to another is not taken into consideration by traditional systems analysis. The goal of dynamic systems analysis (DSA) is to incorporate the performance data during a transition early in the design process and in parallel with traditional SA. DSA requires that the control system can be modeled, and that a dynamic engine model, containing at least rotor speed states, is available. Some software tools, such as NPSS, already have the open-loop dynamic simulation capability.

The dynamic performance of an engine is regulated by a closed-loop controller designed to ensure that the engine is capable of moving from one operating point to another while maintaining adequate operability margins.[3,4] These margins are preserved through the inclusion of limiters in the controller, but not all of the limiters have a large impact on the closed-loop dynamic performance. The limiters that protect the engine's physical bounds, such as rotor speeds and pressures, primarily affect the amount of thrust produced but not the transition between operating points. To capture the relevant impact of the controller on the overall system performance for DSA, a primitive controller containing only the structure that directly impacts the transient response of the engine must be included in the simulations. The Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)[5] software package provides this capability. The TTECTrA software integrates with a user's engine model, and designs a controller that meets user-defined performance specifications, such as bandwidth and operability margin limits. With this controller, the TTECTrA software provides an estimate of the transient capability of the conceptual engine design at a given flight condition. Since this analysis does not require the full-envelope nonlinear controller to be designed, the time and effort required to obtain the transient data are reduced, making DSA more accessible earlier in the engine design process.

This paper is organized as follows. Section II of this paper provides a high-level overview of SA and describes the information regarding dynamic performance of the design that is made available through SA. The TTECTrA tool is discussed briefly in Section III. Section IV contains a high-level overview of the DSA concept along with a discussion of the general results anticipated from this process. To illustrate this concept, and the type of information gained from DSA, a design study is presented in Section V, where a relationship that can used to evaluate the dynamic performance of a model is defined. Conclusions can be found in Section VI.

II. Systems Analysis and Engine Performance

A turbine engine is designed to satisfy criteria ranging from system-level objectives (weight, thrust, and fuel burn rate goals) to component and sub-component-level limits (on efficiency, rotor speed, pressure, and temperature). These objectives are usually evaluated in steady-state. Safe operation of an engine requires that operating margins, such as surge margin, are not exceeded during the transition from one operating point to another. These margins take into consideration off-nominal operation due to engine degradation, atmospheric disturbances, vehicle maneuvers, angle-of-attack, etc., and attempt to account for dynamic changes as well. Current steady-state SA is not adequate for evaluating the ability of advanced technologies to meet transient performance requirements without better-defined requirements for the component operating margins. The dynamic performance of a design is only observed through the use of detailed physics-based models of the engine components along with a detailed controller. The development and maturation of these models and controller are typically done later in the design process, offering little opportunity for information regarding the dynamic capabilities of the engine to influence the design process.

Designing an engine component through SA to meet both system and component-level objectives yields steady-state operating data representing the best performance given the design constraints. For example, a design constraint for a compressor is the surge margin, which is the distance the compressor operates from the surge line. The target operating line in a compressor, the relationship between corrected flow through and the pressure ratio across the compressor, is designed such that the compressor operates the most efficiently while still meeting the constraints; this corresponds to the lowest acceptable surge margin in steady-state.

Steady-state surge margin fundamentally accounts for two types of surge margin reduction: the uncertainty allowance and the transient allowance. These allowances affect the transient performance, safety, and efficiency of the engine but cannot be analyzed individually with steady-state data. The uncertainty allowance represents the maximum reduction anticipated in surge margin due to mechanical imperfections and tolerances (engine-to-engine variation), Reynolds Number effects, inlet distortion, tip clearances, and engine degradation (or aging), etc. The transient allowance accounts for the reduction in surge margin that occurs during the transition from one operating point to another. Combining the uncertainty allowance and transient allowance produces the target operating line, as shown in Figure 1 for the generic high-pressure compressor (*HPC*) map (left) and low-pressure compressor (*LPC*) map (right). Also shown in the figure are the theoretical surge line, the uncertainty allowance, and the transient allowance for each compressor. If the allowances are defined correctly, a new engine operating in normal conditions (no engine damage or severe faults) at steady-state will do so along the target operating line and will be able to transition from one operating point to another without entering a surge condition.

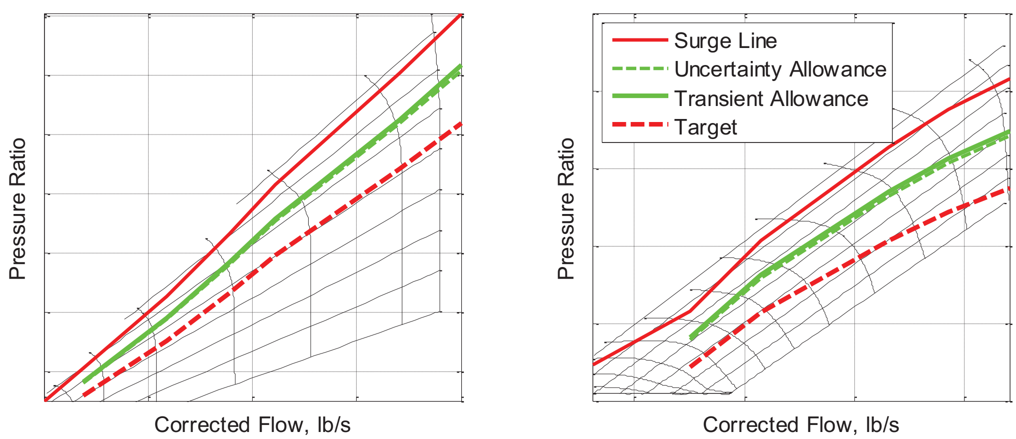

Figure 1 Generic high-pressure compressor (left) and low-pressure compressor (right) maps illustrating the theoretical surge line (solid red), the uncertainty and transient allowances (green dashed and solid), and the target operating line (red dashed).

Often the defined size of the total surge margin allowance, a generic name referring to the sum of the uncertainty and transient allowances, is determined based on historical data and generic rules-of-thumb. Even though this process produces compressor designs that provide adequate steady-state performance, the system may be designed to operate with a transient allowance that could turn out to be too small or too large. Even though the surge margin allowances could be adjusted later in the design process, before production begins, not accounting for this in the SA phase could potentially result in a performance reduction. With the total surge margin allowance fixed, if the transient allowance is defined too large, during a large transient the engine (compressor) may operate closer to the surge line than intended, potentially leading to compressor surge, particularly in off-nominal operation with a degraded engine. Conversely, a transient allowance that is defined too small could produce an overly-conservative engine response that may be unable to meet Federal Aviation Administration (FAA) Federal Aviation Regulation (FAR) Part *33*, Section *33.73*(b), which regulates the transient thrust response. Failure to meet this regulation could prevent the aircraft from attaining the dynamic performance for necessary maneuvers such as an aborted approach or go-around. The relevant portion of the FAA FAR Part *33*, Section *33.73*(b) reads:

From the fixed minimum flight idle power lever position when provided, or if not provided, from not more than 15 percent of the rated takeoff power or thrust available to 95 percent rated takeoff power or thrust in not over 5 seconds...

This regulation can be used as a transient goal for DSA.

While SA may indicate that a specific engine design operates at a high efficiency for a defined operating line (surge margin allowance), DSA may reveal that this increased efficiency comes at the cost of an unacceptable decrease in transient performance or an unacceptable surge margin reduction in order to meet the transient performance requirement. This delicate balance between performance and operability, in terms of transient response and other factors such as efficiency and safety, should be accounted for more accurately as may be accomplished through modeling of the closed-loop dynamic response of the system.

III. The Tool for Turbine Engine Closed-loop Transient Analysis

Any tool used for transient analysis must be able to model the dynamic operation of an aircraft engine, which is dependent on the closed-loop controller. From a high-level perspective, the engine controller can be considered to perform two functions: power management and engine protection.[4] The power management function regulates the controlled variable (typically engine pressure ratio or fan speed) based on the thrust commanded by the pilot via the throttle. The engine protection controller ensures that the engine does not violate any physical bounds, such as those on the rotor speeds and pressure, and ensures safe operation by avoiding compressor surge and engine flame out. The power management and engine protection controllers are integrated via min/max logic. The min/max logic compares the output of each individual controller to determine which is closest to meeting its setpoint, and then selects this as the control input to the engine. For DSA, it is necessary to consider the impact of both the power management function and the engine protection function on the transient operation of the engine.

A tool has been developed to demonstrate and estimate the dynamic performance of the closed-loop system through the design of a simple controller. Known as the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA), this semi-automated control design tool can be easily integrated with subsonic turbine engine simulations developed in the MATLAB®/Simulink® environment (The MathWorks, Inc.). At a single flight condition, defined by an altitude and Mach number, TTECTrA is capable of automatically designing a controller containing only the fundamental limiters that affect the transient performance based on the user's specifications; this controller is a subset of the standard full-envelope controller designed for high-bypass turbofan engines, found in other work.[3,4] Simulation of the engine model with this controller allows for the collection of realistically-achievable dynamic performance data for the design.

The general architecture of the TTECTrA controller is shown in Figure 2. The Pre-Filter and Actuator subsystems are implemented as unity gain first order filters with user-defined bandwidths. The Setpoint subsystem is an empirically derived relationship between thrust and control variable, which is model dependent (typically fan shaft speed or engine pressure ratio). The Proportional-Integral (PI) controller gains are calculated to meet user-defined bandwidth requirements. The Accel Limiter is designed to prevent the HPC from surging during engine acceleration by restricting the fuel flow delivered to the engine. This maintains the core shaft acceleration below its limit for a given core speed. The Decel Limiter preserves a minimum surge margin in the LPC through a limit on the relationship of fuel flow divided by the compressor static discharge pressure (*Wf*/*Ps3*).

The TTECTrA software package contains a Simulink block that the user can integrate in his/her engine model in Simulink. The Simulink block contains other functions that produce the inputs necessary for designing the setpoint controller. In addition to integrating this block with his/her model, the user must also modify a custom MATLAB

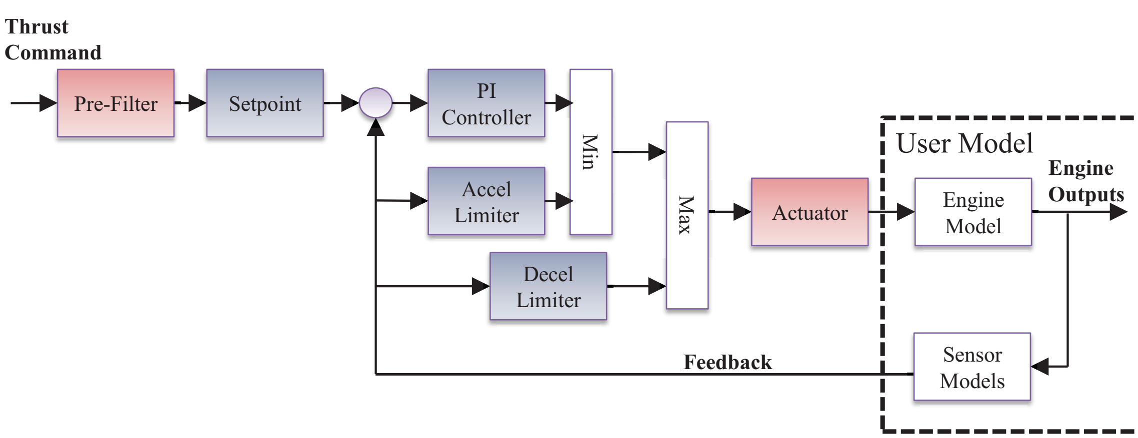

Figure 2 The TTECTrA generic closed-loop architecture. The Setpoint, PI controller, Accel Limiter, and Decel Limiter subsystems are designed by the TTECTrA controller, whereas the Actuator and Pre-Filter subsystems are user-defined.

script to allow the TTECTrA tool to set up and run a simulation of the Simulink model file by passing data to and from the model. For more information regarding the TTECTrA tool, the reader is referred to the TTECTrA User's Guide.[5]

IV. Dynamic Systems Analysis

The main objective of dynamic systems analysis is to incorporate dynamic performance data with the steady-state data used in traditional SA. These transient operating data include the pressures, temperatures, and surge margins of the engine components, some of which are traditionally unmeasured. Generic maps for the *HPC* and *LPC* in a high-bypass two-spool turbofan engine are shown in Figure 3 (left and right, respectively), where SA data (blue circles) and DSA data (cyan dots) are plotted in relation to the surge line (solid red line) and uncertainty allowance (dash-dotted red line). The DSA data were obtained by applying a burst-and-chop thrust profile at a takeoff flight condition. Assuming that the operating line defined by the SA data meets the designed surge margin allowance, it can be seen from Figure 3 that this large engine transient causes a small violation of the transient allowance in the *HPC*. This implies that, at this particular flight condition, an engine operating under worst-case conditions (used to define the uncertainty allowance) may operate on or over the surge line. Based on these data, there are three possible choices to make regarding this engine design: increase the transient allowance, accept small violations of the uncertainty allowance, or modify the transient limiter in the controller. Each choice has drawbacks. By moving the steady-state operating line farther from the surge line and increasing the transient allowance, the efficiency of the compressor would be reduced. The decision to allow small violations of the uncertainty allowance requires accepting that the uncertainty allowance is overly conservative, an assumption that may not be valid. If the transient limiter is modified to slow the engine response, it must still be able to meet the FAA 5-second requirement. The drawbacks related with this latter choice may be addressed by TTECTrA, which enables investigation of the trade-off between response time and surge margin in evaluating an engine design.

V. Design Case Study

To demonstrate the concept of DSA through the use of TTECTrA, a design case study was performed to compare two engines related to the Commercial Modular Aero-Propulsion System Simulation (CMAPSS40k).[6] CMAPSS40k is a nonlinear, physics-based, component-level dynamic engine model with a closed-loop controller written in the MATLAB/Simulink environment. CMAPSS40k models a 40,000-pound thrust class, high-bypass, dual-spool turbofan engine. The low-pressure components (fan, *LPC*, and low-pressure turbine) are connected by the fan shaft, and the high-pressure components (*HPC* and high-pressure turbine) are connected by the core shaft. The fan, compressors, and turbines are modeled using performance maps that relate the pressure ratio, mass flow rate, and corrected speed for each component.

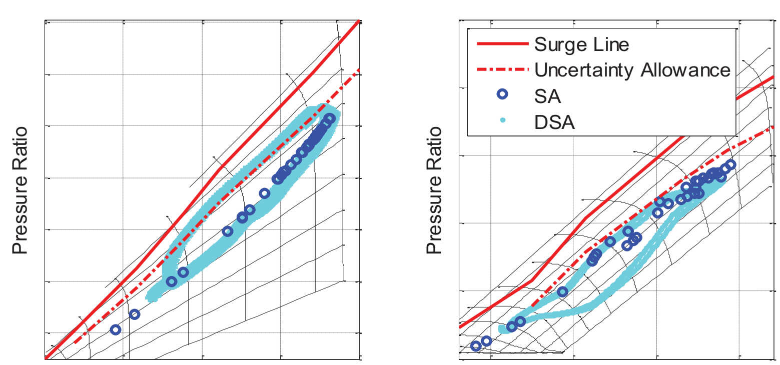

Figure 3 Generic *HPC* map (left) and *LPC* map (right) illustrating the theoretical surge line (solid red), the uncertainty stack (red dashed dotted), steady-state data available from SA (blue circles), and dynamic data available from DSA (cyan dots).

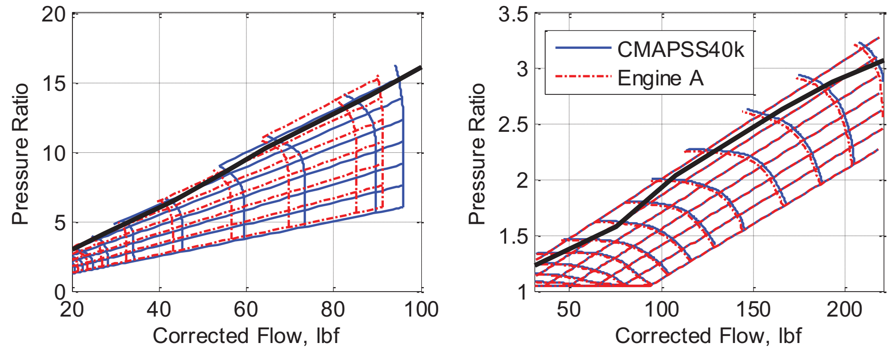

Figure 4 Comparison of the *HPC* map (left) and *LPC* map (right) of the original CMAPSS40k engine design (CMAPSS40k, blue solid lines) and the scaled version of CMAPSS40k (Engine A, red dash-dotted lines). The surge lines for both models (black solid line) are the same.

For this work, TTECTrA was integrated with the standard CMAPSS40k engine model. A second engine model was obtained by scaling the compressor and turbine maps and changing the rotor intertias in the CMAPSS40k engine. The second engine was scaled so that its operating characteristics were different enough from the standard CMAPSS40k engine to make it possible to demonstrate the potential benefits of the TTECTrA tool and DSA. Other aspects of the design, such as the turbomachinery sizing, are not within the scope of this paper. Figure 4 compares the *HPC* and *LPC* compressor maps of both engines, where the maps for the original CMAPSS40k engine are shown as blue solid lines (referred to as CMAPSS40k), and those for the scaled version of CMAPSS40k are shown as red dash-dotted lines (referred to as Engine A). The compressor surge lines, shown as solid black lines, are the same for each engine. The biggest difference between these two engine designs can be seen in the large shift in the speed lines of the *HPC* map. The thrust specific fuel consumption, *TSFC*, at the cruise flight condition of *30,000* ft*., 0.8* Mach is lower for Engine A than for the CMAPSS40k engine, as shown in Figure 5, suggesting Engine A would have a lower operating cost.

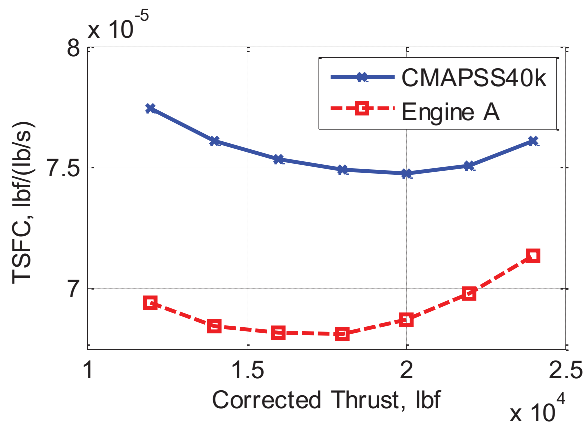

Figure 5 Comparison of the thrust specific fuel consumption *TSFC* of CMAPSS40k (blue solid) and Engine A (red dashed).

The TTECTrA software is used to design a controller for each engine using the control design requirements listed in Table 1. The limits on *T40* and fuel-to-air ratio are set so as not to impact the design of the transient limiters, allowing them to be based solely on the desired compressor surge margin limits. In Table 1, the Acceleration Limit is the minimum HPC surge margin and the Deceleration Limit is the minimum LPC surge margin.

Once the TTECTrA controllers are designed, both closed-loop engine systems are simulated with a burst-and-chop thrust profile to compare their performance. The burst-and-chop profile in this study transitions from a near-idle throttle position to full power (burst) then back to idle (chop), where each transition takes 1 second. Figure 6 compares the thrust output (top left), high pressure turbine inlet temperature *T40* (top right), *HPC* surge margin (bottom left), and *LPC* surge margin (bottom right) for the two models. While the minimum surge margin for each engine satisfies the

Table 1 TTECTrA Tool Control Design Parameters

Parameter	Value
Thrust Range	2,300 – 40,000 lbf
Bandwidth	1.75 Hz
Phase Margin	45°
Feedback Filter Bandwidth	10 Hz
Pre-filter Bandwidth	10 Hz
Acceleration Limit	11%
T40 Limit	3,500°*R*
Fuel to Air Ratio	0.0325
Deceleration Limit	15%

design requirement, at the high power steady-state operating point both the *HPC* and *LPC* surge margins are lower in Engine A. In addition, *T40* is lower for Engine A both in steady-state and during the transient, which may improve engine life/degradation. The improvements in Engine A over the CMAPSS40k engine come at the cost of a longer time to transition from 15% maximum power to 95% maximum power (*5.225* seconds for Engine A, compared to *3.35* seconds for CMAPSS40k).

The controller for each engine was designed for a minimum *HPC* surge margin limit of 11%, which defines the uncertainty allowance in the *HPC* at this flight condition. Because the scaling of the compressor maps reduces the steady-state surge margin of Engine A by 4% compared to CMAPSS40k, the transient allowance for Engine A is reduced when the controller is designed using the same uncertainty allowance as used for the CMAPSS40k engine. This reduced allowance produces the increased transient response time for Engine A observed in Figure 6. By considering the uncertainty allowance for Engine A to be overly-conservative, some of this allowance can be shifted to the transient allowance, preserving the steady-state operating line performance while improving the transient response time. A thrust response similar to the CMAPSS40k engine is obtained through reduction of the surge margin limit to 5%, as shown by the results labeled Engine B in Figure 6. The response time for Engine B is reduced to *3.885* seconds, around *0.5* second slower than the CMAPSS40k engine but almost *1.5* seconds faster than Engine A. This closed-loop engine system also realizes the benefit of a lower *T40*observed for Engine A. The bottom left plot of Figure 6 shows that, during the engine acceleration, the *HPC* surge margin reaches a lower value than for Engine A, but does not violate the limit of 5%, shown as a dashed black line, for which the Engine B controller was designed. The reduction in operability margin (uncertainty allowance) to achieve a performance gain (decreased response time to the 95% maximum thrust point), demonstrates the type of trade-offs that can be studied through DSA.

The overall dynamic performance of the closed-loop system design may be evaluated by more closely examining this trade-off between performance and operability. For a given engine model, a controller can be designed with several acceleration limits (minimum surge margins) using TTECTrA, as in the previous example. The relationship between the response time and actual minimum *HPC* surge margin of each design can be plotted to visualize the trade-off, as shown in Figure 7 for both CMAPSS40k and Engine A. The baseline minimum surge margin for the

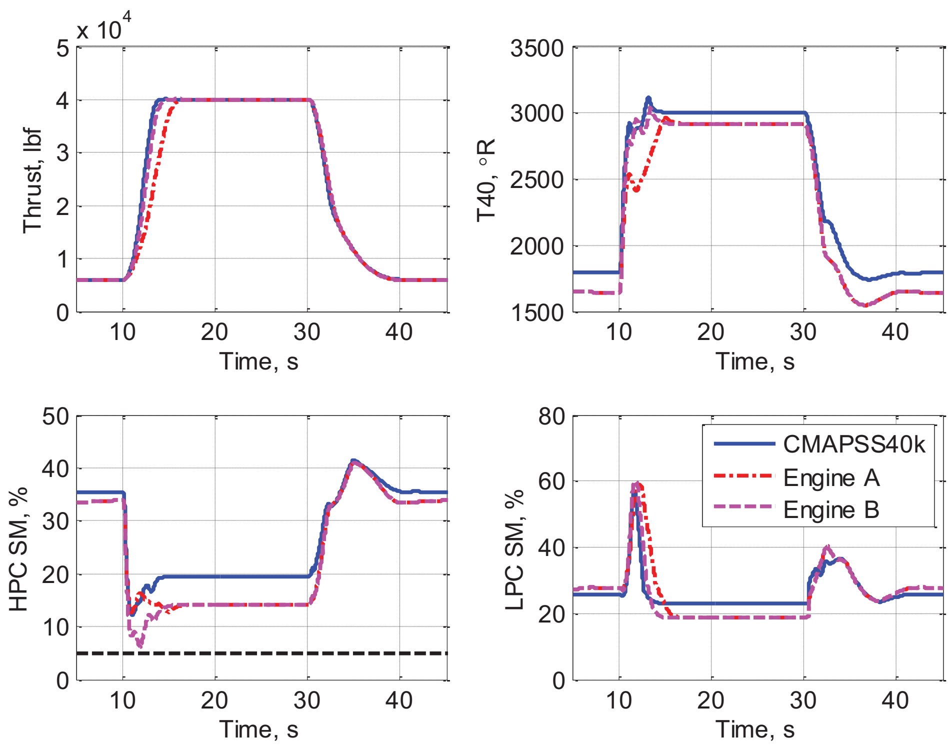

Figure 6 Comparison of the CMAPSS40k engine (CMAPSS40k), the scaled version of CMAPSS40k (Engine A), and the scaled version of CMAPSS40k with a modified transient limiter (Engine B). The dashed black line represents 5% HPC surge margin.

CMAPSS40k design was chosen to replicate the performance of the full CMAPSS40k simulation. TTECTrA designs the acceleration schedule with a fuel flow ramp as the input to the engine model, bypassing the fuel metering valve, and the output of the engine helps shape the acceleration schedule. During actual use, the controller and fuel metering valve actually filter out the high frequency component of the fuel flow signal and often the actual minimum surge margin differs from the design value by a small value, typically ±0.5%.

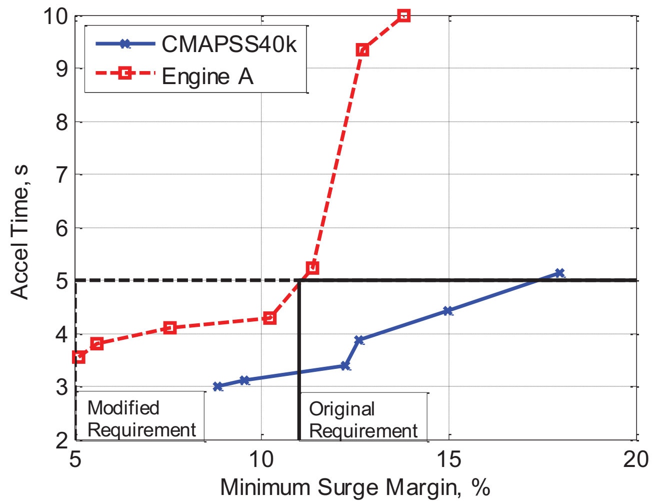

Figure 7 Dynamic performance evaluation plot which demonstrates the trade-off between performance (acceleration time) and operability (surge margin).

The requirements imposed by the original controller (11% minimum surge margin and 5 second response time) are indicated in Figure 7 by the box with a solid outline, labeled Original Requirement; designs "inside" this box satisfy both requirements. As can be seen from Figure 7, only CMAPSS40k satisfies these requirements for the acceleration limiters designed in this investigation.

Assume that the minimum acceptable surge margin could be decreased to 5%. In Figure 7, designs satisfying the new requirements are located "inside" the box outlined with dashed lines, labeled Modified Requirement (this includes the area "inside" the Original Requirement box). With the reduced surge margin limit, both CMAPSS40k and Engine A meet the performance and operability requirement. Since both of these engines meet the dynamic design requirements, other requirements, such as efficiency, may be considered in comparison of the two designs. Engine A has a lower *TSFC*, as shown in Figure 5, suggesting that the additional surge margin in the uncertainty allowance of the CMAPSS40k design is traded for a better *TSFC* in Engine A.

Considering only CMAPSS40k, both the acceleration time and minimum surge margin requirements are met by controllers and limiters designed for a large range of minimum surge margin. This indicates that the transient allowance assumed during the systems analysis phase may be overly conservative and a redesign of the compressor may perhaps move the operating line to a more efficient region. For example, the acceleration schedule for CMPASS40k could be changed from one designed to meet an 11% minimum SM to one meeting a 15% minimum SM without affecting the ability of the system to meet both goals, indicating an additional 4% surge margin in the transient allowance. This 4% surge margin could be reduced by changing the surge margin of the target operating line of the compressors from, say, 23% to 19%, which may allow the compressor to operate more efficiently. To fully evaluate the effects of such a design change requires the redesign of the compressor map and performing additional systems analysis to ensure other higher-level goals are met; this analysis is not within the scope of this paper, but may be pursued in the future.

VI. Summary

Dynamic systems analysis (DSA) seeks to incorporate dynamic performance data with the Systems Analysis (SA) process to improve this process and aid in meeting future engine design goals through better characterization of engine bounds. These bounds are often only reached during an engine transient and therefore are not captured during steady-state operation or analysis. The additional information made available through DSA allows for the trading of overly-conservative operating margins for better engine efficiency, while maintaining the necessary transient performance. The dynamic performance of an engine design can be evaluated by defining the relationship between the response time of the closed-loop design and the minimum surge margin. This relationship allows the closed-loop dynamic performance, and tradeoffs between performance and operability, to be incorporated into the design process by providing information about whether a given engine design is able to meet the performance and operability requirements.

To obtain the dynamic performance data used to define this relationship, the Tool for Turbine Engine Closed-loop Analysis (TTECTrA) was developed. The TTECTrA software is capable of producing a controller at a single flight condition, defined by an altitude and Mach number. This provides an estimate of the closed-loop performance of the engine model. TTECTrA is open source software developed in the MATLAB/Simulink environment that can integrate with any Simulink-compatible engine model.

A case study was presented to demonstrate how TTECTrA may be used as part of a dynamic systems analysis. Two engines were studied, the standard CMAPSS40k engine and an engine constructed by scaling the compressor maps and adjusting the inertias of the rotors in the standard engine. A baseline controller was designed for each engine using TTECTrA with identical controller requirements. While the modified CMAPSS40k engine has better *TSFC*, lower surge margin, and lower *T40* temperature, the response time of the model was unable to meet the 5-second thrust response requirement. Modification of the acceleration limiter to allow for a lower *HPC* surge margin enabled the more efficient engine to meet the 5-second thrust response requirement. Modifying the acceleration limiter in TTECTrA for different *HPC* surge margins also allowed the relationship between the transient performance and operability (surge margin) of the engine to be quantified. The information made available through this relationship provides a quantitative view of the trade-off between operational limits (surge margin) and performance (response time) that otherwise would not be available from traditional (steady-state) systems analysis.

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