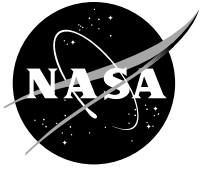


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# Dynamic Systems Analysis for Turbine Based Aero Propulsion Systems

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# Dynamic Systems Analysis for Turbine Based Aero-Propulsion Systems

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## Abstract

The aircraft engine design process seeks to optimize the overall system-level performance, weight, and cost for a given concept. Steady-state simulations and data are used to identify trade-offs that should be balanced to optimize the system in a process known as systems analysis. These systems analysis simulations and data may not adequately capture the true performance trade-offs that exist during transient operation. Dynamic systems analysis provides the capability for assessing the dynamic trade-offs at an earlier stage of the engine design process. The dynamic systems analysis concept, developed tools, and potential benefit are presented in this paper. To provide this capability, the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) was developed to provide the user with an estimate of the closed-loop performance (response time) and operability (high pressure compressor surge margin) for a given engine design and set of control design requirements. TTECTrA along with engine deterioration information, can be used to develop a more generic relationship between performance and operability that can impact the engine design constraints and potentially lead to a more efficient engine.

## Nomenclature

CMAPSS40k	Commercial modular aero-propulsion system simulation 40,000
DSA	Dynamic systems analysis
HPC	High-pressure compressor
HPT	High-pressure turbine
LPC	Low-pressure compressor
LPT	Low-pressure turbine
$N_c$	Core speed (rpm)
$N_f$	Fan speed (rpm)
NPSS	Numerical propulsion system simulation
PI	Proportional Integral
PLA	Power lever angle (degrees)
PR	Pressure ratio
$P_{s3}$	High pressure compressor static pressure (psi)
SA	Systems analysis
SLS	Sea-level static, defined as 0 ft altitude and 0 Mach number
SM	Surge margin (%)
T-MATS	Toolbox for the modeling and analysis of thermodynamic systems
TTECTrA	Tool for turbine engine closed-loop transient analysis
Wc	Corrected air flow (lb/s)
dTamb	Delta ambient temperature, from 59 °F

## I. Introduction

Current conceptual aircraft engines are designed through a complex process, known as systems analysis, which relies on steady-state system-level simulations to evaluate the performance, weight, and cost of the given design. Systems analysis requires extensive analysis of trade-offs in order to optimize the system and evaluate individual technology benefits. When applied to aviation propulsion systems, these analyses produce results that help guide technology investment, system architecture, and program planning and formulation throughout the life of the program.

The aircraft propulsion system is designed to meet requirements ranging from system-level objectives (weight, thrust, fuel burn, etc.) to component and sub-component-level constraints (stresses, rotating component surge margin, etc.). The propulsion system is designed to meet these objectives at the design point, also referred as the on-design, which is typically a cruise condition since optimizing the fuel burn rate at cruise provides the most economic benefit; the majority of fuel and time is spent at cruise. The engine model can then be analyzed at other flight conditions, such as takeoff or climb, to determine how the model operates at these conditions, known as off-design or off-nominal. Both the on-design and off-design conditions are evaluated with steady-state data.

In order to maintain safe operation, the engine must not exceed any of its constraints; including when transitioning from one flight condition or operating point to another. Operating margins are defined to consider both off-nominal steady-state operation due to engine degradation, atmospheric disturbances, vehicle maneuvers, angle-of-attack, etc., and attempt to account for changes due to transitioning between operating points (dynamic) by adding in extra margin. However, defining and analyzing the operating margins based only on steady-state simulation data offers little opportunity for information regarding the actual dynamic capabilities of the engine to influence the design process, such as the time it takes to spool the engine up and remaining surge margin.

The idea behind dynamic systems analysis (DSA) is to analyze the dynamic performance of the engine and determine if the current constraints are appropriate. Open-loop dynamic simulations provide insights into engine transient performance, but they do not capture the necessities of transient performance under the constraints imposed by limit regulation, which always must be included in the engine system. Closed-loop simulations containing a controller designed to protect violating any operational constraints, which are heavily influenced by transient operation, must be conducted.

This paper is organized as follows. An engine model that will be used as a test case for dynamic systems analysis is described in Section II. The dynamic systems analysis concept is discussed in Section III, followed by advancements made in Section IV. An analysis of the concept is contained in Section V, with Section VI providing conclusions from this study.

## II. Design Example

In this paper a design case study is performed using the Commercial Modular Aero-Propulsion System Simulation 40k (CMAPSS40k) engine model (Ref. 1). CMAPSS40k is a nonlinear, physics-based, component-level dynamic engine model with a closed-loop controller written in the MATLAB®/Simulink® environment (The MathWorks, Inc.). CMAPSS40k models a 40,000-pound thrust class (max power at 0 ft and 0.0 Mach), high-bypass, dual-spool turbofan engine. The low-pressure components - fan, low-pressure compressor (LPC), and low-pressure turbine (LPT) - are connected by the fan shaft, and the high-pressure components - high-pressure compressor (HPC) and high-pressure turbine (HPT) - 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.

The CMAPSS40k LPC and HPC maps are shown in Figure 1. The steady-state data, which includes both the off-design and on-design points, was taken at an altitude of 0 ft, 0.0 Mach, referred to as sea level static (SLS), and standard day temperature, +0 degrees delta Temperature ambient (dTamb). The on-design point is taken at a power lever angle (PLA) of 68°, which is approximately a cruise power

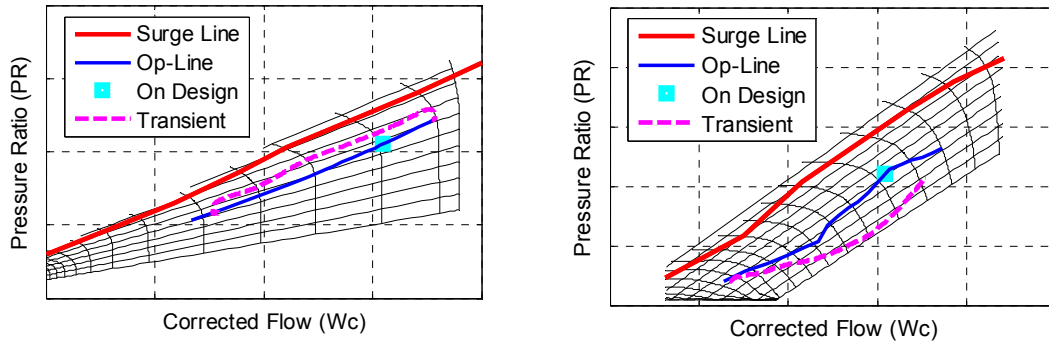


Figure 1.—The HPC map (left) and LPC map (right), showing the on-design point near a cruise power level, and operating line (off design points), and response to a throttle transient from idle to takeoff.

setting at SLS. Off-design data is taken from 5,000 to 40,000 lb thrust, roughly PLA of 44° to 80°, at SLS standard day conditions. Note that steady-state data taken at other flight conditions typically fall on the same steady-state line shown in Figure 1, which is referred to as the operating line or op-line. The op-line is the collection of operating points (corrected flow and pressure ratios) that the compressors/turbines operate at near steady-state or for very small changes. Certain factors shift the steady-state op-line towards the surge line (reducing the surge margin), such as engine degradation, inlet distortion, etc. At the design point (cruise power setting), the HPC surge margin constraint is assumed to be 23 percent. Of the 23 percent, 11 percent is defined as the uncertainty stack which accounts for losses in surge margin due to engine degradation, machining tolerance, engine to engine variation, inlet distortion, and any other unknowns. The remaining 12 percent is reserved for the transient stack which accounts for the loss of surge margin attributed to the compressor operating closer to surge while transitioning from one operating point to another. In this case, the compressor will take a path that does not follow the steady-state op-line.

For this work, the CMAPSS40k engine model was integrated with the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) (Refs. 2 and 3). TTECTrA is an open source, semi-automated control design tool which can be easily integrated with subsonic turbine engine simulations developed in the MATLAB®/Simulink® (the MathWorks, Inc.) environment. TTECTrA has the ability to integrate with cycle design and simulation tools such as the Numerical Propulsion System Simulation (NPSS) (Refs. 4 and 5) and the Toolbox for the Modeling and Analysis of Thermodynamic Systems (TMATS) (Ref. 6). At a single flight condition, defined by an altitude and Mach number, TTECTrA is capable of tuning a control system consisting of only the fundamental limiters and systems which influence the transient performance based on the user's specifications. The TTECTrA control system is a subset of the standard full-envelope controller for high-bypass turbofan engines found in other work (Refs. 7 and 8). Simulation of the closed-loop system (controller and engine model) allows for realistically-achievable performance data to be collected and used for analysis.

### III. Dynamic Systems Analysis Basic Approach

The main idea behind dynamic systems analysis is to include dynamic performance information into the engine design process. For dynamic information to be included into the design process, the closed loop controller must be taken into account. The closed-loop controller is responsible for driving the engine from one power level to another in the appropriate time while ensuring safe operation, such as avoiding HPC surge. The tool for turbine engine closed-loop transient analysis (TTECTrA) has been developed to provide Matlab/Simulink users the ability to quickly design and simulate the closed-loop design for a given engine model (Ref. 2). To use TTECTrA, the user must supply an engine model capable of integrating with Simulink and the TTECTrA controller block. The user then enters the control design constraints. TTECTrA will step through the control design process and allow the user to modify the control requirements during the design process, via a graphical user interface. Finally, TTECTrA produces the final output showing the response time and engine outputs.

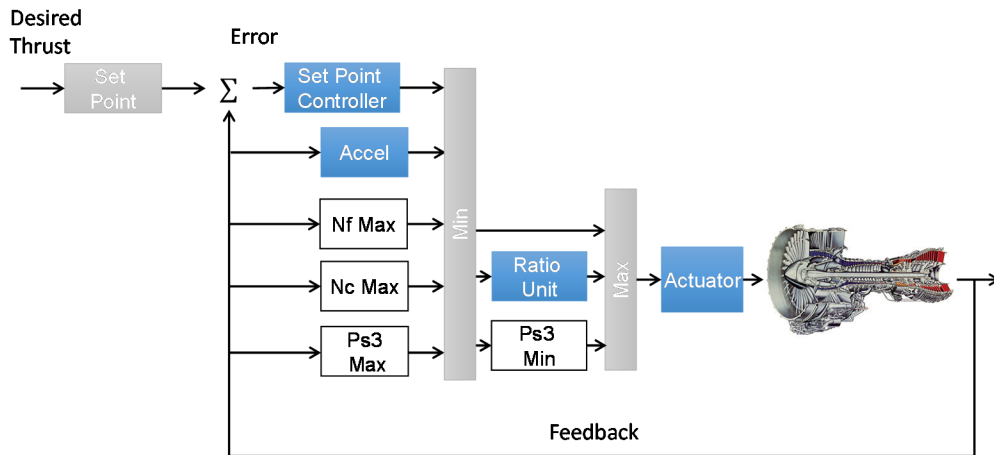


Figure 2.—High-level closed-loop control diagram for a turbofan engine. The functions that are shaded blue have an impact on the dynamic performance of the closed loop system. The shaded blocks have an impact on the system operation. The shaded blocks are implemented in TTECTrA, while the white blocks are ignored for preliminary analysis.

Figure 2 shows a typical high-level closed-loop control diagram for a high-bypass turbofan engine model (Refs. 7 to 9). In this figure the set point, Min, and Max, functions, shown in gray, impact operation of the closed-loop system but not necessarily the dynamic performance. The steady-state limiters, shown in white that include Nf Max limiter, Nc Max limiter, Ps3Max limiter, and Ps3 Min limiter, are ignored since they do not impact the dynamic performance.

The remaining four main functions, shown in blue, impact the dynamic performance of the closed-loop system: the set point controller, accel limiter, ratio unit limiter (fuel flow divided by Ps3), and the actuator. The set point controller is designed to drive the engine to the desired power level with the use of a proportional integral (PI) controller. The set point controller is mainly responsible for responding to small changes in thrust and rejecting any disturbances. Increasing the controller gains and bandwidths leads to a faster thrust response. The accel function, short for acceleration limiter, is responsible for ensuring the engine does not enter a HPC surge, especially during a large, fast transient. Several methods have been proposed to protect against HPC surge, and can also help regulate the HPT inlet peak temperature reached during the transient (Refs. 7 to 9). The acceleration limiter chosen for this work is an acceleration schedule, which regulates the core spool acceleration as a function of the current core flow corrected at station 25 (high pressure compressor inlet) conditions. The ratio unit limiter protects against both the LPC surge and minimum fuel to air ratio being violated (Refs. 7 to 9). The actuator function is often implemented as a low pass filter that has a bandwidth close to that of the fuel flow actuator.

The TTECTrA controller is integrated with the CMAPSS40k engine model. TTECTrA is used to design and simulate the closed-loop system based on the TTECTrA control design parameters shown in Table 1. Based on these parameters, TTECTrA is used to design the controller and simulate the closed-loop response, which is shown in Figure 3. In Figure 3, the thrust requirement is to be able to reach 95 percent of max power in less than 5 s (top plot) and the HPC surge margin is to remain above 11 percent (bottom plot). Both requirements are met. Using the TTECTrA tool, the acceleration limit value, which is the HPC surge margin, can be modified and the closed-loop response observed. As the acceleration limit value decreases, the response time also decreases, providing better transient performance for smaller operability margins (surge). This would shift the transient data on the HPC map, left plot of Figure 1, closer to the surge line. Likewise, as the acceleration limit increases, the response time increases, moving the transient data on the HPC map, left plot of Figure 1, further from the surge line. From these simulations, the key pieces of information are 1) the time it takes to reach the 95 percent thrust requirement (performance) and 2) the minimum HPC surge margin (operability). The performance and operability data is collected for the varying HPC surge margin design values. Performance and



TABLE 1.—TTECTrA CONTROL DESIGN PARAMETERS

Parameter	Value
Bandwidth	1.75 Hz
Phase margin	45°
Feedback filter bandwidth	10 Hz
Pre-filter bandwidth	10 Hz
Acceleration limit	11%
T40 limit	3,500°
Fuel to air ratio	0.0325
Deceleration limit	15%

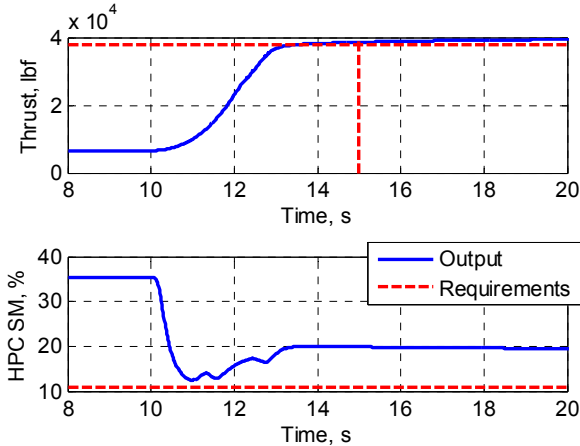


Figure 3.—The TTECTrA thrust response (top plot) and HPC surge margin (bottom) showing the output of the closed loop system and the dynamic requirement.

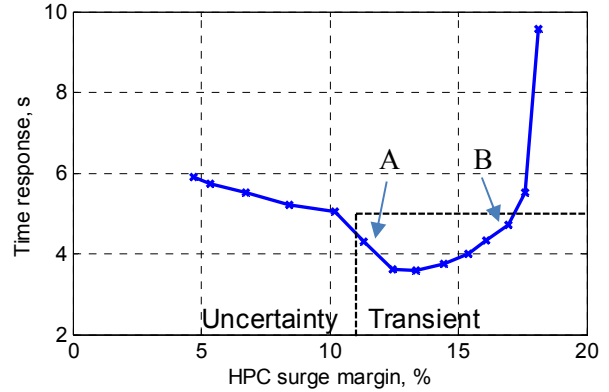


Figure 4.—Performance and operability for the baseline CMAPSS40k engine at 50 percent deterioration level and Sea Level Static/Standard day conditions.

operability data for varying acceleration limit values can be plotted against each other, as shown in Figure 4. This plot shows the relationship between the minimum HPC surge margin (x-axis) and the 95 percent time response (y-axis) for CMAPSS40k at sea level static standard day conditions for 50 percent degraded engine. The acceleration limit from TTECTrA, 11 percent from Table 1, is plotted as well as the 5 percent time response limit. Any of the acceleration limits which lies to the right of the acceleration limit, minimum HPC surge margin greater than 11 percent, and has a time response less than 5 percent is an acceptable closed-loop solution. In Figure 4, the point marked as A with a surge margin of 11.5 percent marks the response with the lowest acceptable surge margin remaining, while point B at a surge margin of 17 percent represents the slowest acceptable response time. Any controller designed with a minimum surge margin between these points is deemed acceptable.

Figure 4 contains additional information regarding the operability margins. The acceleration limit used in TTECTrA represents the uncertainty stack, which is the region to the left of the 11 percent surge margin and noted as Uncertainty in Figure 4. The uncertainty stack accounts for surge margin losses due to engine degradation, inlet distortion, engine to engine variations, etc. In Figure 4, any data points to the left of the 11 percent HPC surge margin limit corresponds to the closed loop design violating the design constraint. The region to the right of the 11 percent limit in Figure 4 up to the surge margin constraint value is the transient stack. The transient stack is the amount of surge margin reserved for transient operation. In general, as the transient stack increases the engine response time should decrease (better performance). Having too large of a transient stack implies that the engine design constraint may be too large and the current engine design may not be optimal in terms of weight, efficiency, etc. The transient stack should be sized such that the data curve of Figure 4 intersects the performance and operability limit lines; 11 percent HPC surge margin and 5 s time response.

## IV. Dynamic Systems Analysis—Advanced Approach

The closed-loop system should provide some guaranteed level of performance throughout the engine life cycle. As the engine ages, both performance and operability are effected. With information regarding the change in performance and operability over the engine life cycle, better design choices or constraints can be made to optimize the performance while ensuring sufficient margins exist. The previous section focused on developing a methodology to assess the capability of an engine design to meet closed-loop performance and operability margins (Ref. 10). The focus of this section is capturing the effect of engine aging, describing the impact on the performance level and operability, and developing design requirements to meet the performance level requirements throughout the engine life cycle.

The first step is to collect the deterioration data. In particular, the deterioration data is collected from two sets of data; 1) known life conditions (new 50 hr engine, mid-life engine, and end of life engine), and 2) randomly aged conditions that are bounded by the new and end of life deterioration values. For this work, a health parameter vector is defined which contains a flow and efficiency modifier for each of the major component of the engine; fan, LPC, HPC, HPT, and LPT. Each element of the health parameter vector will be between 0 (50 hr engine value) and an end of life value of 1 (Ref. 1). The TTECTrA tool, integrated with the CMAPSS40k engine model, is used to design the controller for a particular acceleration limit and baseline engine (mid-life). With this controller, the engine is then simulated with both the three known life conditions and one thousand randomly aged conditions. Figure 5 shows the response time and HPC surge margin closed-loop simulation data with a controller designed for a particular acceleration limit. In Figure 5, the three known life conditions, 50 hr engine (pentagram), mid-life (hexagram), and end-of-life (diamond), and the one-thousand randomly aged engines are shown as dots. The Figure 5 data shows how much the response time and HPC surge margin changes based on engine degradation.

Once the closed-loop data is collected, an ellipse which fits the data is constructed. The length and rotation of the ellipse x-axis is based on the known life conditions and the length of the top and bottom half of the ellipse is based on the Monte Carlo data. From this, four ellipse parameters are used to describe the ellipse; x-axis length, y-axis length from the center to the bottom of the ellipse, the y-axis length from the center to the top of the ellipse, and rotation of the ellipse x-axis. Detail regarding this method can be found in Reference 10.

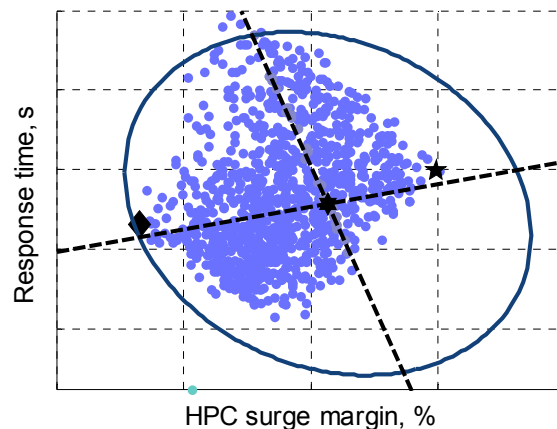


Figure 5.—Performance and operability plot for the one thousand randomly aged engines and three known life conditions 50 hr engine (pentagram), mid-life (hexagram), and end-of-life (diamond). Also shown is an ellipse which fits the collected data and is used to characterize the data to the performance level.

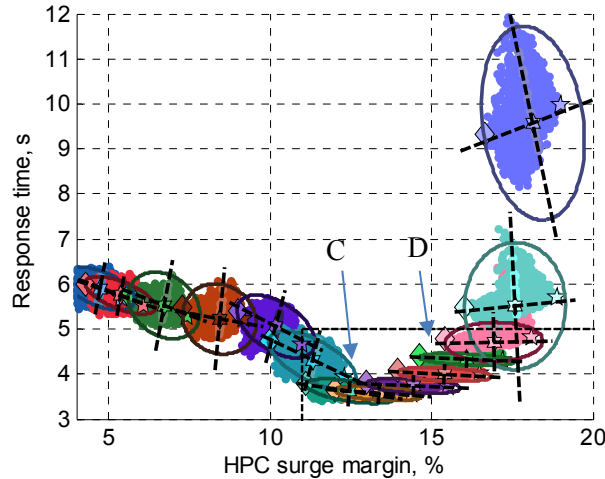


Figure 6.—Monte Carlo data and ellipse for the attempted acceleration limit values applied to the CMAPSS40k engine.

This process of collecting and fitting an ellipse around the Monte Carlo data is repeated for different acceleration limit design values. The idea is to collect enough data to have an approximation of how performance varies throughout both the engine life cycle and with varying acceleration limit. Figure 6 shows the Monte Carlo data and the defined ellipses for the CMAPSS40k engine. Notice that the ellipses change as a function of the acceleration limit value. The four ellipse parameters are described for each acceleration limit that has been defined. Additionally, a binary search procedure can be implemented to find the limiting cases meeting either requirement. This search procedure relies on curve fits and defined relationships to find the limiting case. Reference 10 contains more information regarding the binary search procedure. With bounds known, any acceleration limiter designed between the two bounds results in a controller that meets both the operability and performance levels.

From Figure 6, the surge margin designs which meet both requirements throughout the life of the engine can be identified. From Figure 6, point C with a surge margin of 12.5 percent designed at mid-life, is the lowest acceptable design which ensures that the 11 percent minimum surge margin is met throughout the life of the engine. In this case, all the data points are greater than 11 percent. Point D at a surge margin of 16 percent, represents the slowest response time to meet the 5 s requirement throughout the life of the engine. With the deterioration data added to the analysis, the acceptable range has decreased from 11.5 to 17 percent (from Figure 4) to 12.5 to 16 percent. The deterioration data provides a more accurate estimate of the amount of the performance and operability tradeoff throughout the life of the engine.

## V. Analysis

Analyzing the performance and operability relationship allows for tighter margins to be designed. In Section III, TTECTrA was applied to the CMAPSS40k engine model and used to create the relationship between the HPC surge margin and the closed loop response time. This was accomplished by redesigning the acceleration schedule (limiter) for varying surge margins and executing a closed-loop simulation. The minimum HPC surge margin and settling time was plotted as shown in Figure 4. Figure 4 shows that the performance requirement can be met (response time less than 5 s) with a minimum surge margin of 16 percent, which is greater than the current limit of 11 percent. The range of acceptable surge margin controllers, which meet the 11 percent minimum surge margin remaining and 5 s response time, was determined to be between 11.5 and 17 percent. In Section IV, the impact of engine deterioration was included in the analysis, and the relationship between performance and operability was illustrated in

Figure 6. Figure 6 shows that additional margin is required to meet the performance requirement throughout the life cycle since both the surge margin and performance are impacted by the engine degrading. Even with the impact of degradation, the performance requirement is met with additional margin remaining. Figure 6 also shows that the acceptable surge margin range decreased 11.5 to 17 percent (from Figure 4) to 12.5 to 16 percent with the addition of the deterioration data.

The real benefit of this analysis is to identify any margins which may be overly conservative. Figure 7 shows the generic relationship between performance and operability. The response time and HPC surge margins are identified for varying acceleration limit values, shown as blue “x” in Figure 7, to create the nominal relationship shown by the blue line. The engine model is then randomly aged to obtain data and ellipses are drawn to encapsulate the Monte Carlo data, shown as the dashed blue lines. Figure 7 shows that the performance requirement can be met for the nominal engine with a minimum surge margin of approximately 16 percent. With engine degradation included, the minimum surge margin would decrease to about 14 percent. The uncertainty stack shown in Figure 7 is 11 percent, which means that with accounting for engine degradation, the current engine constraint has an additional 3 percent surge margin which is calculated by taking the difference of the surge margin required to meet the performance and the uncertainty stack (14 to 11 percent). This would approximately shift the line over to the left and an acceleration limiter would be defined to operate near the desired operating point shown in Figure 7 as the cyan star and labeled Ideal. In this case, the transient stack is perfectly defined to meet the performance and operability margin.

The data contained in Figure 7 can be plotted to show the distance to each constraint from the closest point on the ellipse. For each point of Figure 7, the minimum x-coordinate and maximum y-coordinate is determined. The delta surge margin constraint is computed as the difference between the minimum x-coordinate and the surge margin constraint (11 percent). The delta time constraint is computed as the difference between the response time requirement (5 s) and the maximum y-coordinate. This data is shown as the blue “x” in Figure 8. In the ideal situation, the design point would be at, or very close to, the origin (0,0). However, the designer may choose to define an acceptable band for the design to operate at to avoid violating either constraint. In this example, an acceptable time constraint of 0.5 s and 1 percent surge margin is chosen and plotted in Figure 8 (red dashed line). The ideal design point is plotted as the red circle, which shows that the ideal design point is within the acceptable band.

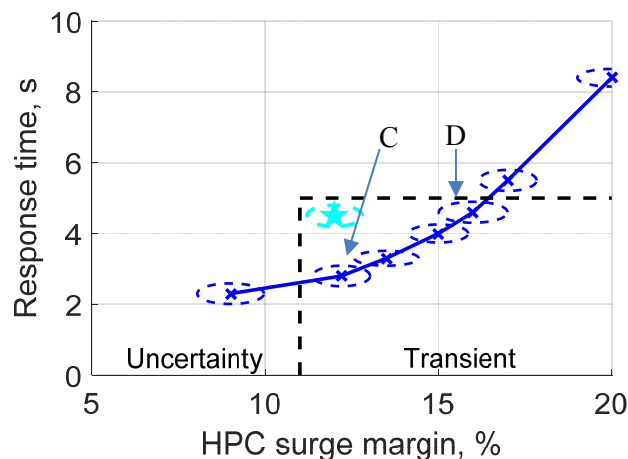


Figure 7.—Generic performance and operability plot showing where the ideal operating point is.

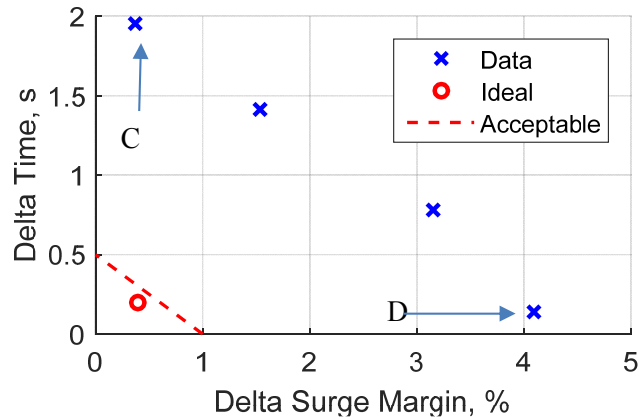


Figure 8.—Generic performance and operability constraint plot, comparing the ideal constraints to the current constraints. Ideally the design would fall into the target range.

## VI. Conclusion

This paper discusses the dynamic system analysis concept, tools, and potential benefit. Current systems analysis processes rely on steady-state design constraints to account for dynamic performance, such as for high pressure compressor (HPC) surge margin. The HPC surge margin constraint is intended to account for steady-state losses due to uncertainty, manufacturing tolerances, engine degradation, etc., and for a temporary loss of surge margin associated with quickly accelerating from a low power to high power. The dynamic portion of the constraint is usually based on previous designs and assumptions. The goal of dynamic systems analysis is to estimate and better define how much margin is really required during engine transients. In this case, the steady-state design constraint may be able to change and a more efficient or lighter engine can be potentially designed. A generic performance and operability constraint plot was constructed to better identify the margin for each constraint and identify an acceptable band in which the designers can design for.

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