Adaptive Gas Turbine Engine Control for Deterioration Compensation Due to Aging

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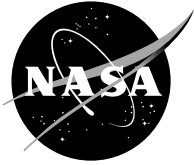
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Abstract

This paper presents an ad hoc adaptive, multivariable controller tuning rule that compensates for a thrust response variation in an engine whose performance has been degraded though use and wear. The upset appears when a large throttle transient is performed such that the engine controller switches from low-speed to high-speed mode. A relationship was observed between the level of engine degradation and the overshoot in engine temperature ratio, which was determined to cause the thrust response variation. This relationship was used to adapt the controller. The method is shown to work very well up to the operability limits of the engine. Additionally, since the level of degradation can be estimated from sensor data, it would be feasible to implement the adaptive control algorithm on-line.

Introduction

Turbofan engine performance varies from engine to engine due to manufacturing tolerances, aging, and deterioration caused by use [1]. Generally the control system developed for the engine is robust enough to keep it operating within acceptable boundaries for several thousand flight cycles, even though the degradation will eventually require the engine to be overhauled as limits are reached. These limits include operability constraints such as maximum temperatures, and performance constraints such as the FAA's rise time requirement for thrust in commercial engines.

Generally, turbofan engines control Engine Pressure Ratio (EPR) or fan speed to generate the desired thrust, since thrust can not be measured directly during flight. Although these regulated variables are maintained at their setpoints regardless of engine degradation, the non-regulated parameters shift from their nominal values with deterioration [2]. Thus, in the degraded engine, the actual thrust output, which is indirectly controlled through the regulation of other variables, may be shifted from the expected value. Undesirable thrust responses due to engine degradation and an adaptive scheme to recover the nominal thrust response are investigated in this paper using the research engine simulation MAPSS (Modular Aero Propulsion System Simulation) [3].

Off-nominal values of specific internal engine parameters representing component efficiencies and flow capacities are often used to account for these performance variations. These adjustment parameters are called *health parameters* [4] because they indicate the level of engine deterioration. The equations describing the degraded engine's behavior are given by

$$\dot{x}(t) = f(x(t), u(t), p)$$
$$y(t) = g(x(t), u(t), p)$$

where p represents the vector of health parameters. When obtaining a standard linear point model of an engine, the health parameters are treated like inputs.

$$\Delta\dot{x}(t) = A\Delta x(t) + B\Delta u(t) + L\Delta p$$
$$\Delta y(t) = C\Delta x(t) + D\Delta u(t) + M\Delta p \tag{1}$$

Depending upon how the health parameters manifest themselves, the system dynamics may or may not change with degradation, but in equation (1) the state equation clearly demonstrates that steady state is only obtained when the $x(t)$ and $u(t)$ vectors shift to compensate for p, and the output equation shows how nonzero values of p can produce additional steady state shifts in the output variables. These equations also imply that degradation causes shifts in the engine's trim values, and it is these shifts that can result in unacceptable operation. In general the health parameters vary slowly enough with time that

they are treated as constants in equation (1). Trending of the health parameters is achieved by an estimation algorithm known as a tracking filter. Tracking filters have been successfully used to estimate health parameters from measured variables ([4] and [5]), allowing more accurate tracking of unmeasured engine variables such as thrust.

When an engine utilizes a single-mode multivariable controller across the operating envelope, and control authority is available, the controlled variables will track their respective setpoints, even with engine degradation, though the other uncontrolled variables may stray into unacceptable ranges. When an engine uses a multi-mode multivariable controller where power level request determines the active mode or the blending of modes, degradation can cause undesirable responses in certain variables. This may occur when a variable that was previously floating is now regulated by the active control mode, and its value, shifted from the nominal due to degradation, has excessive error at the controller mode transition. Thus the interaction of variables in a multivariable controller tuned for a nominal engine can potentially cause large response excursions as degradation shifts the relative positions of these variables. This is demonstrated starkly in figure 1, which contains several thrust responses from the MAPSS engine, which uses a multi-mode multivariable Proportional-Integral (PI) controller. Figure 1 shows that the thrust excursion from the nominal increases as the degradation worsens from Case 1 through Case 3, and the worst of the engine responses is jerky. In a twin-engine airplane, a response like this due to an increase in thrust command can result in an unacceptably large yawing moment. The interaction of variables in a multi-mode controller is very
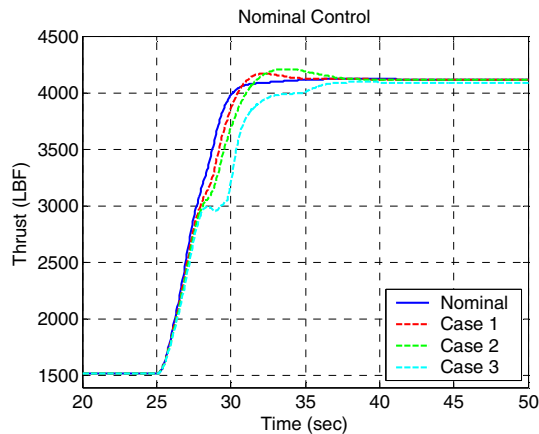
complex, and when it results in such a response, the controller gains must be adaptively tuned to avoid disturbances due to degradation.

The Modular Aero Propulsion System Simulation MAPSS

The Modular Aero Propulsion System Simulation (MAPSS) model is a component level Simulink® model of a twin spool low bypass turbofan engine representative of engines for modern fighter aircraft (figure 2). It has three state variables, three independently commanded actuators, several open-loop scheduled actuators, and multiple outputs. The simulation was developed to provide a realistic public domain test bed engine model that allows access to any engine variable. Thus it is suitable for the design and evaluation of control, estimation, and diagnostics algorithms.
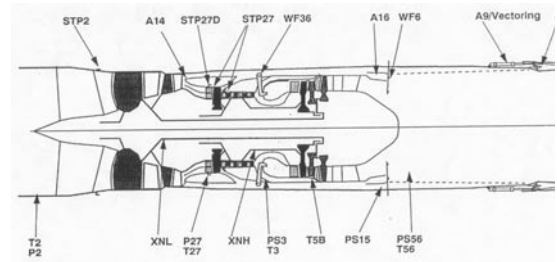

Figure 2. The MAPSS engine.

The MAPSS Controller

A model-based approach was used to develop the MAPSS controller. This means that in a real implementation, unmeasurable variables such as thrust and stall margin should be available to the controller through an on-board model that accounts for degradation [6]. Because MAPSS is a simulation, however, all variables are directly available, so it can run in closed loop as is, without an on-board model or tracking filter. Thus control modes can be evaluated free from implementation issues associated with the on-board model and tracking filter. The controller in MAPSS is a multi-mode multivariable PI controller. The performance modes are a low- and high-speed mode. The safety modes are overspeed mode and stall margin mode. Overspeed mode prevents the engine from running too fast, and stall margin mode takes over as the engine operation approaches the stall line to prevent the engine from stalling.

The low- and high-speed engine controllers are designed for performance. Safety is not explicitly accounted for in these modes because the two safety modes are blended in as needed. In the baseline

Figure 1. Series of thrust responses of the MAPSS engine with various levels of degradation. Degradation increases as case number increases.

MAPSS controller, the stall margin mode is at least partially on almost everywhere in the flight envelope. In standard engine control systems, the acceleration schedule maintains a minimum stall margin transiently by limiting fuel flow, and steady state stall margin is maintained by actuators that control exit areas. Because the MAPSS controller is model-based with access to stall margin and it contains a stall margin mode, the operation is allowed much closer to the stall line than with traditional controllers. Since here we are concerned with performance and are running with stall margin mode off, we will allow what would normally be unacceptable values of stall margin, realizing that a different acceleration schedule and steady-state actuator trim values would shift the operation further from the stall line.

Low-speed mode is fully operational at Power Lever Angle (PLA) or throttle values below 37.5 degrees. High-speed mode is fully operational at PLA values above 42.5 degrees. In between the modes are blended. In low-speed mode, thrust, EPR, and LEPR (Liner Engine Pressure Ratio, which must be above1.0 to keep bypass flow moving from the front of the engine to the back) are controlled; in high-speed mode, thrust, ETR (Engine Temperature Ratio), and LEPR are controlled.

The PI gains for all modes are scheduled based on PCN2R (per cent corrected fan speed, the fan speed as a per cent of design speed, corrected for altitude and Mach number). This means that the gains for the performance modes are determined independently of the stall margin and are thus computed without regard to blending with the stall margin mode. Additionally, since all sets of gains are scheduled based on PCN2R, there is the implicit assumption that a particular value of PCN2R corresponds to a particular dynamical characterization of the engine.

Engine Performance
The MAPSS controller is a state-of-the-art research-type controller. However, closed-loop performance still suffers from the effects of engine degradation, as shown in figure 1. Our objective is to make the deteriorated MAPSS engine behave as much like a new engine as possible for as long as possible. Here we will specifically tackle the issue of thrust response as a function of degradation. The underlying problem of uncontrolled variables trending toward operability limits is not addressed here. The ground rules we will make in setting up the problem are 1) we are particularly interested in performance and will evaluate the performance-related controllers alone, not masked by the safety-related controllers; 2) the nominal response is an acceptable response, i.e. the

goal will be to recover the nominal response with the degraded engine; 3) we may not change the baseline controller, we may only add an incremental control signal to the baseline control signal, as in figure 3, to improve the performance without direct alteration of the nominal control algorithm; and 4) since we are concerned with developing a general adaptive scheme for a model-based controller such as that in MAPSS, we are more concerned with performance trends than with actual variable values specific to MAPSS. In this spirit, therefore, we will not attempt to tune the controller gains to achieve some type of optimal response from the degraded MAPSS engine; rather we seek a generic adaptive rule that can be applied to improve the performance of multi-mode model-based controllers.
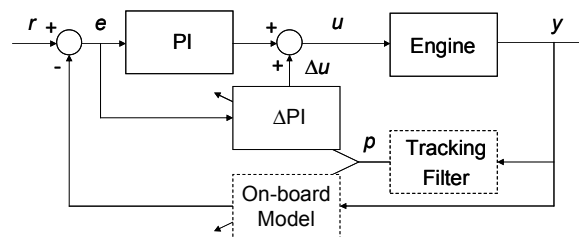

Figure 3.   MAPSS adaptive controller block diagram. Dashed boxes are not currently implemented. The Tracking Filter block is used for estimating health parameters. PI and ΔPI are both of the form $K_P + K_I/s$ where the controller matrices are all 3-by-3. Note that each error signal coming into the controller is normalized using a scale factor, $SF_{variable}$.

Deteriorated Performance Due to Usage and Aging
As the engine is used, wear occurs that affects the engine's performance: turbine blades erode, clearances open up, etc. This results in component flows and efficiencies that are worse than in a new engine and the performance degrades. In order to achieve the same level of thrust as in a new engine, a deteriorated engine must run hotter and/or faster. This shift from nominal operation increases with use, and eventually reaches the point where performance can not be maintained without compromising the safety of the engine or the life of its components. The health parameter values shown in table 1 represent shifts from the MAPSS engine's nominal values and correspond to moderate to severe degradation [1] such as might occur when the engine is due for an overhaul based on flight cycles, or when the engine is used in a particularly harsh environment such as a sandy desert or an area of volcanic activity.

Table 1. Degradation values for health parameters as a change from nominal.

Case	Flight Cycles t_{eff}	Fan		Low Pressure Compressor		High Pressure Compressor		High Pressure Turbine		Low Pressure Turbine	
		η %	Flow %	η %	Flow %	η %	Flow %	η %	Flow %	η %	Flow %
0	0	0	0	0	0	0	0	0	0	0	0
1	3000	-1.5	-2.04	-1.46	-2.08	-2.94	-3.91	-2.63	1.76	-0.538	0.2588
2[‡]	4500	-2.18	-2.85	-2.04	-3.04	-6.17	-8.99	-3.22	2.17	-0.808	0.3407
3	6000	-2.85	-3.65	-2.61	-4.00	-9.40	-14.06	-3.81[*]	2.57[*]	-1.078[*]	0.4226[*]

[‡]all values in this row obtained by linear interpolation of cases 1 and 3.   [*]extrapolated value $\eta \equiv$ efficiency

In this work the health parameters are assumed to follow an average degradation profile which consists of a fast rise into a ramp. The initial rise is due to rub-in and related new engine deterioration mechanisms [1]. As the engine ages, the health parameter degradation tends to become more linear, as shown in references [7] and [8] and figure 4. The general equation is of the form

$$p_i = a_i \cdot (1 - e^{-b_i \cdot t_{eff}}) + c_i \cdot t_{eff} \qquad (2)$$

where a_i, b_i ($b_i > 0$), and c_i are shape parameters for the ith health parameter p_i. The independent variable t_{eff} represents the average time at which the given level of degradation is reached. It is measured in time or flight cycles but accounts for operating conditions that might accelerate or retard wear, i.e. t_{eff} represents the *physical age* of the engine rather than its *chronological age*; t_{eff} is sometimes called *effective cycles*. Once the initial break-in period is

over, we assume the health parameters degrade as linear functions of t_{eff}.

The MAPSS engine was run at the health conditions in table 1, and the effect of the health degradation on select engine variables is shown in figures 5 through 9; the corresponding thrust plots are shown in figure 1. The operating point used for the simulation transient examples is defined by an altitude of 36,089 ft, and a Mach number of 0.8. The rate-limited PLA step command ramps from 30 to 48 degrees in about 3.5 seconds. During the simulation, the active controller transitions from low-speed to blended mode at about 27.3 seconds, and from blended to high-speed mode at about 28.2 seconds. This encompasses the peak overshoot in ETR shown in figure 6. Note that the uncontrolled (floating) value of ETR (in low-speed mode) increases with degradation. This indicates an operating temperature increase with degradation. Figure 9 shows how PCN2R (speed) increases with degradation.
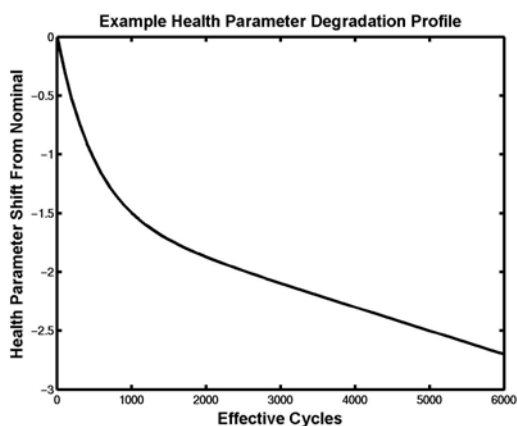

Figure 4. Typical degradation profile for a health parameter. Most health parameters decrease with wear, turbine flows increase with wear.
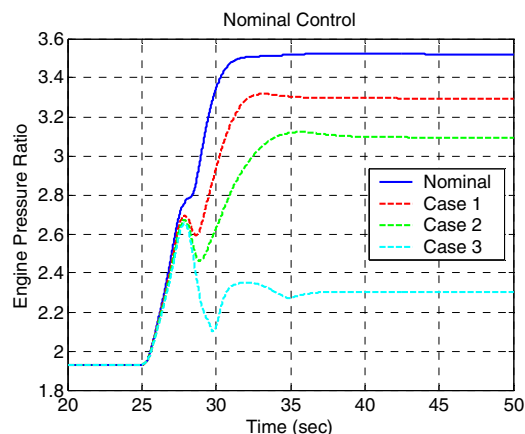

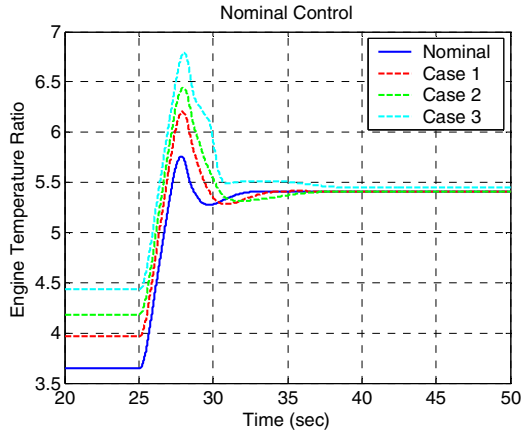**Figure 5. EPR transient from a PLA ramp for a series of degraded MAPSS engines.**

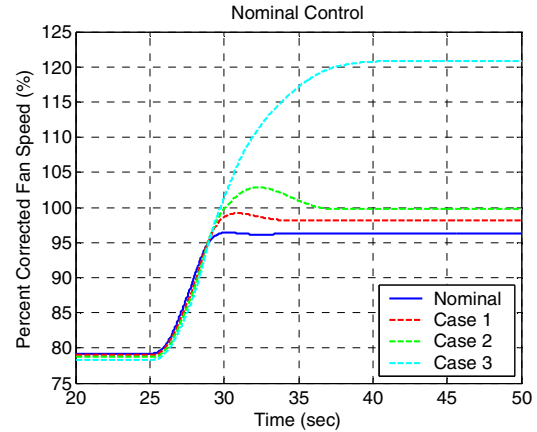**Figure 6. ETR transient from a PLA ramp for a series of degraded MAPSS engines.**

Figure 7. LEPR transient from a PLA ramp for a series of degraded MAPSS engines.

Figure 8. Fan stall margin transient from a PLA ramp for a series of degraded MAPSS engines.

Figure 9. PCN2R transient from a PLA ramp for a series of degraded MAPSS engines.
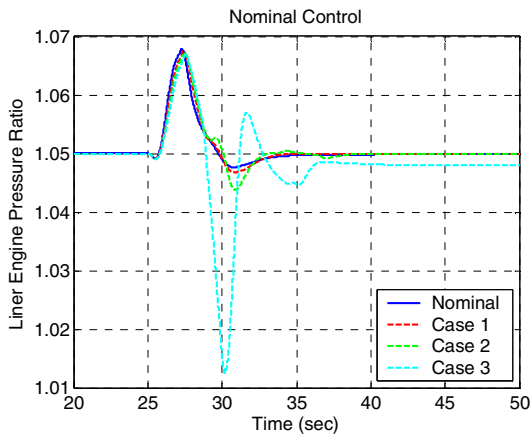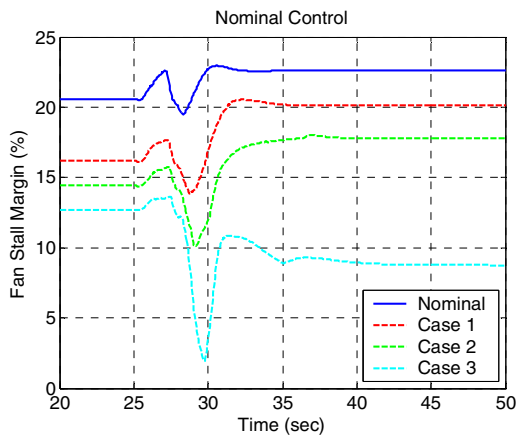
Analysis of the Degraded Responses

Since the only structural difference between the active performance controllers as the engine moves through a large transient is the replacement of EPR control with ETR control, that is a likely cause of the disturbance in thrust. For the new engine, ETR is quickly brought under control with little overshoot. For the degraded cases, even though the initial (low-speed) steady-state (uncontrolled) value of ETR is closer to the final (high-speed) setpoint as the mode switches than in the nominal case, significant overshoot seems to cause an upset in thrust due to the interaction of the variables. The various plots of ETR (figure 6) exhibit overshoot that varies with degradation, i.e., as degradation worsens, overshoot increases, apparently as a function of the steady-state shift from nominal, and the hitch in thrust response seems directly related to the amount of overshoot in ETR. The engine control is designed to maintain thrust response even under degraded conditions, and the thrust curves in figure 1 show that in both low- and high-speed modes the rate of increase essentially matches the nominal response; it is only during the mode transition that the response curves are delayed. Thus an approach to minimize the variation in thrust response is to adapt the controller as a function of degradation to decrease the interaction between the controlled variables. Since the ETR overshoot of the degraded response is hypothesized to be the cause of the problem, we shall reduce its influence to the level in the nominal response. This can be achieved by increasing the scale factor on the ETR error (nominally 10) entering the controller, lessening its importance in the control scheme. Thus we propose to divide the scale factor by the ratio of the degraded ETR overshoot to the nominal ETR overshoot. Since this is equivalent to reducing the columns of the

Table 2. Effective cycles, ETR overshoot and Scale Factor for each case.

Case	t_{eff}	ETR overshoot	ETR Scale Factor, SF_{ETR}
0 (nominal)	0 cycles	0.37	10 (nominal)
1	3000 cycles	0.88	23
2	4500 cycles	1.1	29
3	6000 cycles	1.3	37

controller matrices corresponding to ETR (the middle column), it exactly fits the proposed ΔPI controller scheme shown in figure 3 as

$$\Delta PI_{high\text{-}speed} = PI_{high\text{-}speed} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \left(\frac{1}{SF_{ETR}} - \frac{1}{10} \right)$$

$$= \left(K_P^{high\text{-}speed} + \frac{K_I^{high\text{-}speed}}{s} \right) \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \left(\frac{1}{SF_{ETR}} - \frac{1}{10} \right)$$

Table 2 shows the relationships between the degradation, overshoot in ETR, and proposed scale factor for ETR error to recover nominal thrust response.

As shown in the table, the level of degradation from equation (2) in terms of effective cycles, t_{eff}, is: none, moderate, worse (1.5 times moderate), and severe (2 times moderate). The relationship between t_{eff} and the scale factor is of the general form

$$SF_{ETR} = m_{ETR} t_{eff} + b_{ETR} \qquad (3)$$

Fitting a line through the 3000, 4500, and 6000 cycle points shown in Table 2 resulted in values of m_{ETR}=0.0047 and b_{ETR}=8.7. The linear fit of the
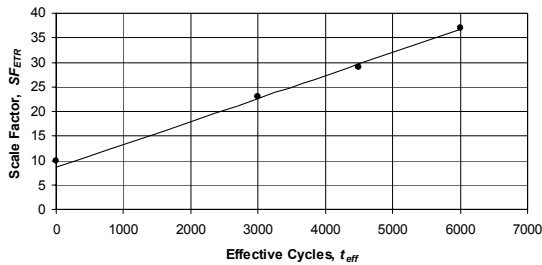

Figure 10. Straight line fit through the three high effective cycle data points from Table 2.

points and the SF_{ETR} values from Table 2 are shown in figure 10.

Thus the actual degradation p, as estimated by a tracking filter, may be used to directly calculate the scale factor for the ETR error from equation (3) using equation (2) to calculate t_{eff} (after the initial break-in period) as

$$t_{eff} = \frac{p_i - a_i}{c_i}$$

Results
To test the hypothesis, the scale factors calculated from equation (3) were used for the transient simulation of the degraded MAPSS engines. Additionally, two other cases were tried with health parameter values obtained through linear interpolation from Table 1, corresponding to t_{eff} of 3750 and 5250 cycles (Case 4, SF_{ETR}=26, and Case 5, SF_{ETR}=33, respectively).

Reduction of the scale factor for the ETR error as a function of degradation did indeed remove the unacceptable variation in the thrust response, as shown in figure 11. The other variables demonstrated overall improved response (figures 12 through 16); they were generally more consistent and faster with less overshoot than in the cases where the nominal controller was used. Even the compensated ETR response (figure 13) had reduced overshoot as compared to the degraded case with the nominal controller, although it took slightly longer to settle. The compensated variables settled out to the same points as their degraded counterparts with the nominal controller.

The 6000-cycle degraded engine seems to be just too deteriorated for the compensation to work properly. Even though the thrust response was vastly improved, PCN2R eventually exceeded the overspeed limit of 105 percent, as when the nominal controller was used. Thus it seems that that level of degradation presents a hard limit on the engine operability.
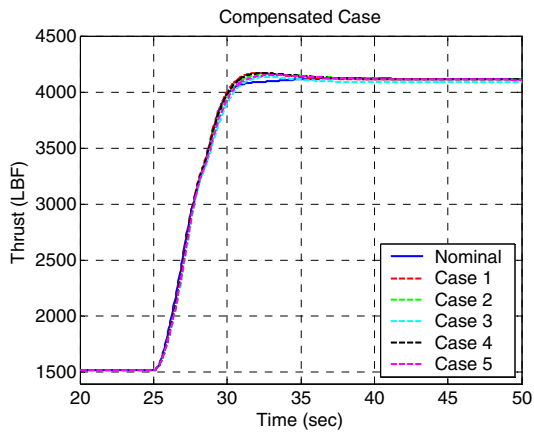
Figure 11. Compensated thrust response from a PLA ramp for a series of degraded MAPSS engines.
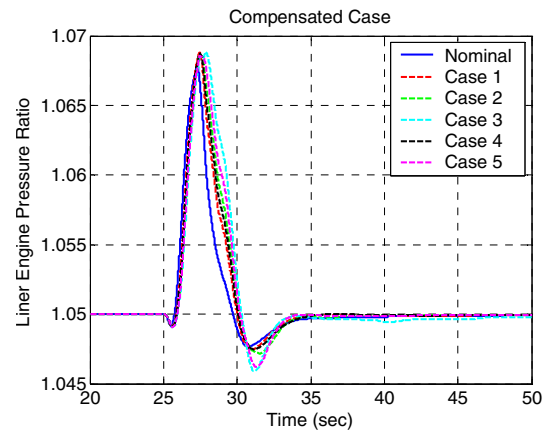

Figure 12. Compensated EPR response from a PLA ramp for a series of degraded MAPSS engines.

Figure 13. Compensated ETR response from a PLA ramp for a series of degraded MAPSS engines.
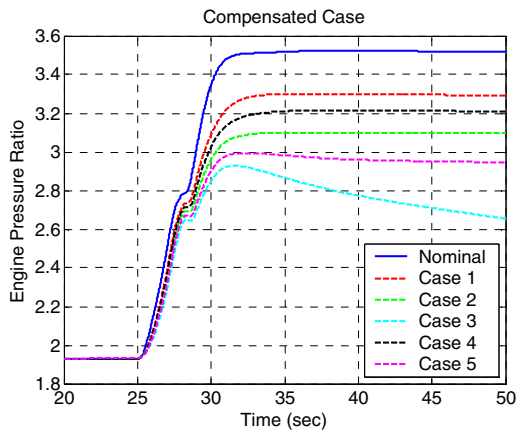

Figure 14. Compensated LEPR response from a PLA ramp for a series of degraded MAPSS engines.

Figure 15. Compensated stall margin response from a PLA ramp for a series of degraded MAPSS engines.

Figure 16. Compensated PCN2R response from a PLA ramp for a series of degraded MAPSS engines.
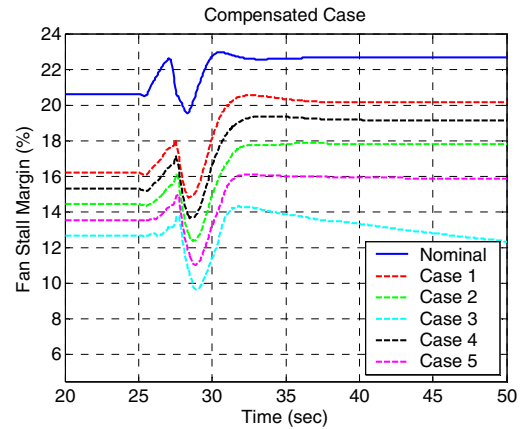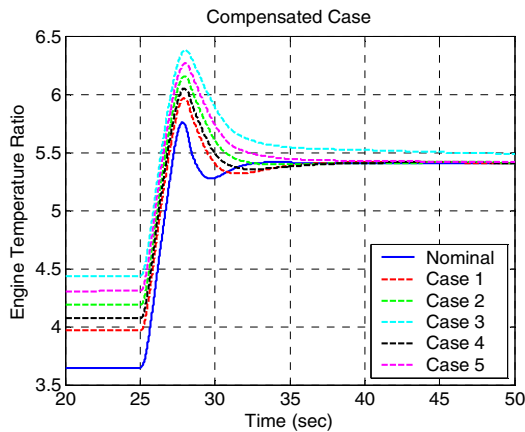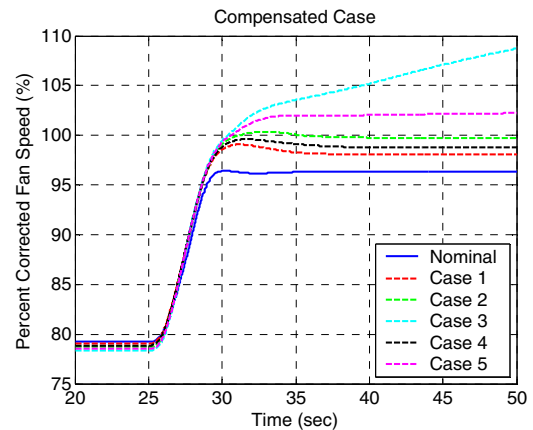
Conclusions

The proposed ad hoc adaptive rule works very well for thrust response recovery of the MAPSS engine, degraded along the expected trajectory at the given operating conditions. More work still needs to be done to evaluate the robustness of the scheme to off-nominal degradation trajectories, and to identify those health parameters that have the most impact on the degraded response, since the technique may be very robust to variations in some parameters but not others.

Additionally, the technique was only demonstrated at one altitude and Mach number point, even though the transient response covered most of the PLA range at that point. It must still be tested at other operating points.

Tuning of the controller gains could improve the responses further, for instance by eliminating the slight overshoot in the compensated thrust curves. The objective of this work, however, was to develop a general strategy for adapting the controller for applicability to other engine/controller pairs. Although each type of engine has its own characteristics, the effects of degradation should be somewhat consistent, meaning that the results shown should be fairly representative of turbofan engines with similar controllers. Thus this method is general for a class of engines and controllers demonstrating the same type of thrust response as a result of degradation.

Finally, although the approach for smoothing thrust response presented here works well, it only addresses a symptom of the real problem associated with engine degradation: the tendency of some variables to shift toward operability limits. Clearly a severely degraded engine will not be able to match the performance of a new engine, but maintaining critical parameters at acceptable levels, both transiently and in steady state, for as many flight cycles as possible, must be the ultimate goal.

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This paper presents an ad hoc adaptive, multivariable controller tuning rule that compensates for a thrust response variation in an engine whose performance has been degraded though use and wear. The upset appears when a large throttle transient is performed such that the engine controller switches from low-speed to high-speed mode. A relationship was observed between the level of engine degradation and the overshoot in engine temperature ratio, which was determined to cause the thrust response variation. This relationship was used to adapt the controller. The method is shown to work very well up to the operability limits of the engine. Additionally, since the level of degradation can be estimated from sensor data, it would be feasible to implement the adaptive control algorithm on-line.

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