International Journal of Scientific Research and Engineering Development-– Volume 4 Issue 3, May -June 2021

Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Adaptive Control System in a Aircraft Gas Turbine Engine

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Abstract:

This paper presents an adaptive control technique to compensate the thrust variation in an aircraft engine whose performance has been disturbed due to atmospheric conditions. The course of dysfunction is appear when a large throttle transient is performed such that engine switched from low to high speed mode. A relationship is observed between engine disturbance and the overshoot in engine shaft rpm, compressor discharge pressure and turbine temperature, which is determined to cause the thrust variation. This relationship is used to adapt the control. This method works very well up to the operability limit of an engine. Additionally, the type of disturbance identified from sensors data will be useful to implement the adaptive control in real time operation.

Keywords **—Electronic Engine Control, FADEC, Adaptive Control.**

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I. INTRODUCTION

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Aircraft engine performance varies from engine to engine due to manufacturing tolerances, ageing, atmospheric conditions and deterioration caused by use. 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, aircraft engines control Engine Pressure Ratio (EPR) or shaft speed to generate the desired thrust, since thrust cannot measured directly during flight. Although these regulated variables are maintained at their set points regardless of engine dysfunction, the non-regulated parameters shift from their nominal values with deterioration. 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 engine simulation.

Off-nominal values of specific internal engine parameters representing component efficiencies and flow capacities are often used to account for these performance variations. The equations describing the degraded engines behavior are given by

$$X(t) = f(x(t), u(t), p)$$
$$Y(t) = g(x(t), u(t), p)$$

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. Depending upon how they manifest themselves, the system dynamics may or may not change with degradation. But the state equation clearly demonstrates that steady state is only obtained when the $x(t)$ and $u(t)$ vectors shift to compensate 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 engines trim values and these shifts that can result in unacceptable operation.

II. ENGINE MODEL

The engine models in simulink are needed for control system analysis and design, because most control varies with respect to engines. The engine GE T700 is a turbo shaft engine used in apache and Blackhawk. The engine has been rebuilt to a linear state for testing.

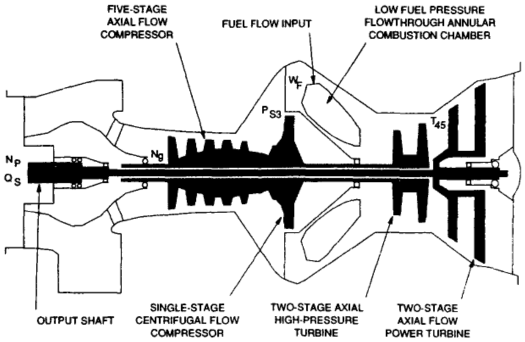

Fig - 1, Cross section of T700 engine.

III. MODEL BASED ADAPTIVE CONTROL

Models can be integrated into the control loop to identify the system's state and derive prognostic actions. This offers completely new possibilities in engine control. On-board models may be used to provide engine parameters, which cannot be measured directly due to the sensor location or their physical property. They may replace sensed parameters due to faults or low frequency response and can be used to predict upcoming events.

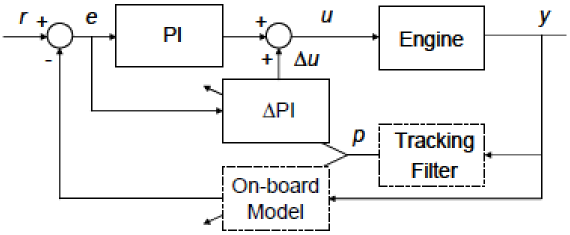

Fig - 2, Adaptive Controller Block Diagram

Adaptive control refers to a self adjusting controller that can modify the controller action depending on the transient external circumstance. An extra layer of control allows adjusting the closed loop filter in a way that the control action is optimized for all conditions. Typically, the parameter that requires a change in the controller setting varies much more slowly than the closed loop controller. A more extended view of an adaptive control system that provides a self calibration. Even the most accurate mathematical model of a real system cannot be more than an approximation of its real dynamics. There are several sources of uncertainty that may unfavorably influence the stability and performance of the control system, which can be categorized as parametric and unknown uncertainties. The controller used here is a multi mode multi variable PI controller. The performance modes are a low and high speed mode. The safety modes are over speed mode and stall margin mode. Over speed 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.

A. Deteriorated Performance Due to Usage and Ageing:

As the engine is used, wear occurs that affects the engines performance: turbine blades erode, clearances open up, etc. This result 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 cannot 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 engines nominal values and correspond to moderate to severe degradation 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.

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 η≡efficiency

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

B. 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) set point 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 3) 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.

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

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

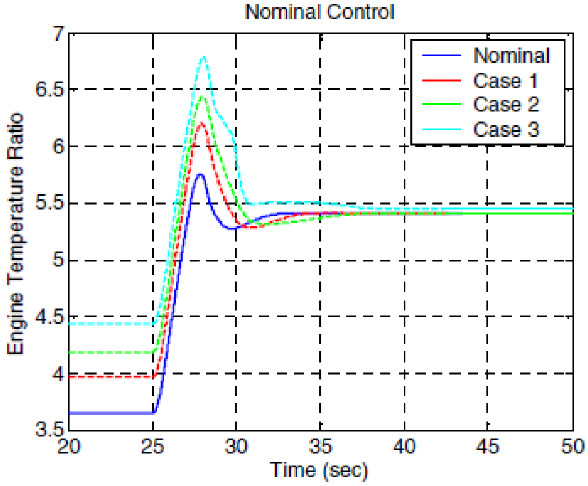

Fig - 3, ETR transient from a PLA ramp for a series of degraded engine.

The engine control is designed to maintain thrust response even under degraded conditions, and the thrust curves in both low and high-speed mode are 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 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. Table - 2 shows the relationships between the degradation, overshoot in ETR, and proposed scale factor for ETR error to recover nominal thrust response.

IV. RESULTS

To test the hypothesis, the scale factors calculated from the transient simulation of the degraded engine. Additionally, two other cases were tried with health parameter values obtained through linear interpolation from Table - 1, corresponding to *teff* of 3750 and 5250 cycles.

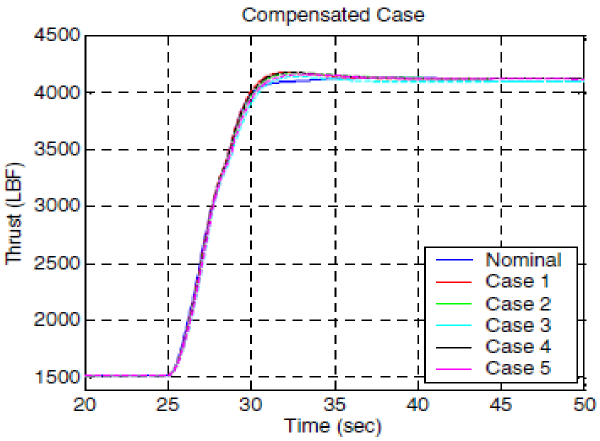

Fig - 4, Compensated thrust response from a PLA ramp for a series of degraded engine.

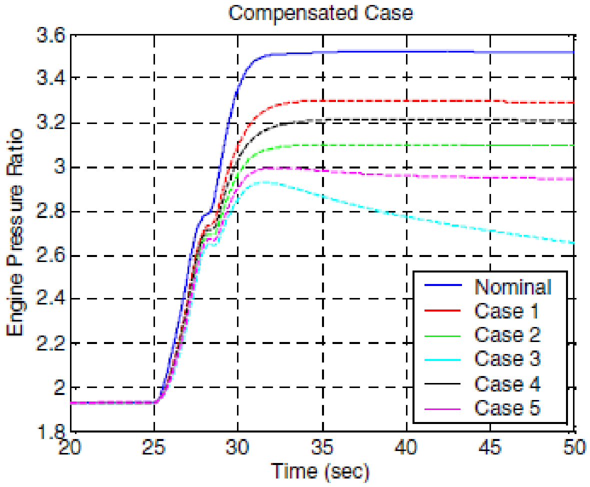

Fig - 5, Compensated EPR response from a PLA ramp for a series of degraded engine

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 4. The other variables demonstrated overall improved response (figures 5 through 9); 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 6) 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.

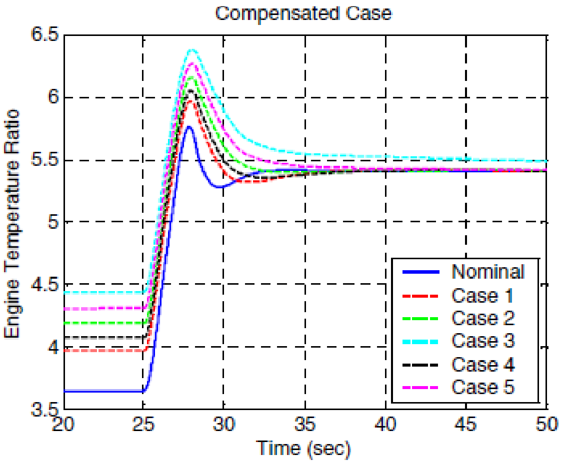

Fig - 6, Compensated ETR response from a PLA ramp for a series of degraded engine.

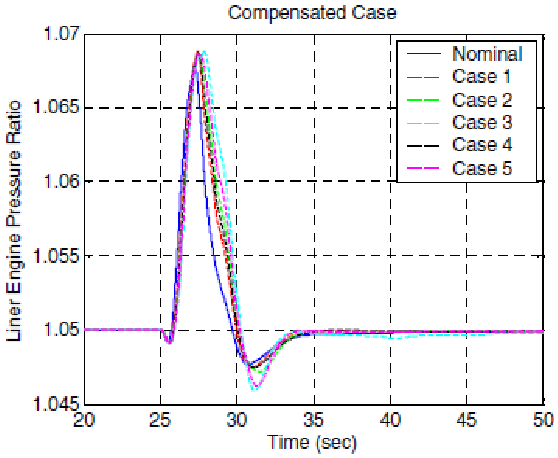

Fig - 7, Compensated LEPR response from a PLA ramp for a series of degraded engine.

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 over speed limit of 105 percent, as when the nominal controller was used. Thus it seems that level of degradation presents a hard limit on the engine operability.

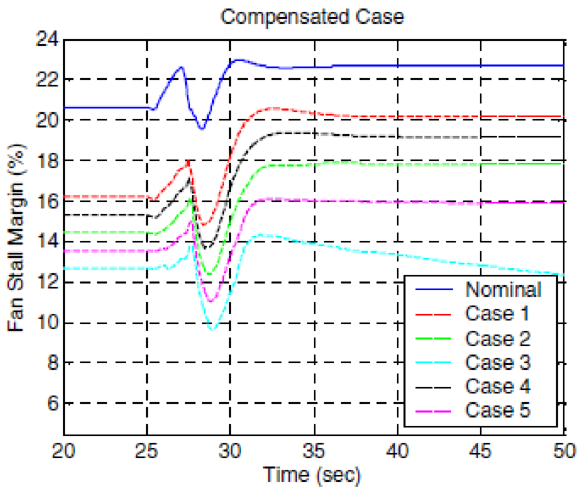

Fig - 8, Compensated stall margin response from a PLA ramp for a series of degraded engine

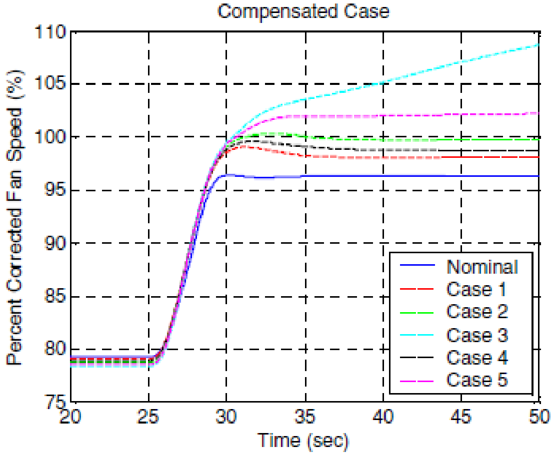

Fig - 9, Compensated PCN2R response from a PLA ramp for a series of degraded engine.

V. CONCLUSIONS

The proposed adaptive rule works very well for thrust response recovery of the GE T700 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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