PERFORMANCE-SEEKING CONTROLS

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INTRODUCTION

Constantly increasing fuel costs justify the investigation of control methods to optimize the performance of aircraft propulsion systems. The task requires a method to trim engine control variables to an optimum condition. Engine control schedules are usually developed during the design and testing stages. However, since perfect engine control matching is time consuming and costly, control schedules are usually less than perfect. More important is the fact that engine-to-engine component variations are normally sufficient to cause the engine to operate at a nonoptimum condition. Also, during the life of the engine, component and sensor degradation can result in a higher fuel consumption to maintain a particular engine thrust.

This paper describes a performance-seeking logic algorithm (PSL) that optimizes the performance of propulsion systems for component and sensor degradations.

PERFORMANCE-SEEKING LOGIC

The objectives of the performance-seeking logic (PSL) algorithm are to monitor the performance of the engine system and to minimize thrust specific fuel consumption (TSFC) while retaining a constant engine net thrust. Engine constraints such as surge margin, speed, pressure, and temperature must be observed. The PSL algorithm was applied to the quiet, clean, short-haul experimental engine (QCSEE) (refs. 1 and 2). This NASA-funded research program was undertaken to develop future STOL engine technology. The QCSEE propulsion system features a high-Mach-number inlet, a variable-pitch fan, and a variable exhaust nozzle (fig. 1). A digital electronic controller and a hydromechanical fuel system are used to implement required control functions. The four QCSEE variables to be controlled are engine pressure ratio (EPR), inlet-duct Mach number, fan speed, and compressor stator angle. The function of the hydromechanical fuel control is to control EPR; fan speed control is achieved by varying the pitch fan angle. A constant inlet-duct Mach number is maintained by varying the exhaust nozzle area in order to reduce aircraft noise problems. The compressor core stator angle is scheduled by the digital controller, which also incorporates the engine control limits. The PSL algorithm only modifies the reference set-point schedules for three of the four engine variables. These include EPR, fan speed, and inlet Mach number. The PSL algorithm does not attempt to modify the compressor stator angle schedules. The hard engine limits are not violated and must be maintained for safe engine operation.

The PSL algorithm was applied to a real-time digital engine simulation. Figure 2 presents a simplified block diagram of the controller, the PSL algorithm, and the engine. The function of this diagram is to illustrate the nominal set-point schedules required to set the control input variables. The PSL algorithm (lower portion of fig. 2) is a secondary controller that operates in conjunction with the normal engine controller. Specific engine output variables can be connected to the PSL block that contains the optimization algorithm to minimize thrust specific fuel consumption subject to selected engine constraints. The output information from the PSL algorithm represents a change from the nominal values for the control input variables. The output of the PSL algorithm modifies the set-point schedules to restore the propulsion system to optimum condition. The PSL algorithm performs system optimization under steady-state conditions.

PERFORMANCE CRITERION

The important consideration in any optimization problem is the selection of a performance criterion. The performance function for the PSL algorithm is

$$J = Q_1 \left(1 - \frac{TSFC}{TSFCN}\right)^2 + Q_2 \left(1 - \frac{FN}{FNNOM}\right)^2 + Q_3 \left(1 - \frac{NL}{NLNOM}\right)^2 + Q_4 \left(1 - \frac{NH}{NHNOM}\right)^2$$

where Q_1, Q_2, Q_3, and Q_4 are weighting factors. The first term identifies the minimization variable TSFC; the remaining terms are the penalty functions. These terms penalize the performance criterion for deviations from their nominal values. The nominal values are dependent on the engine operating condition. Thus scheduling of these nominal values must be considered to make the PSL algorithm effective over the flight envelope. The penalty terms were selected to cause the specific engine variables of the degraded engine system to return to near the design values. By allowing the engine speeds to vary, it could be possible to generate an improved value for TSFC for the degraded engine condition. A thrust measurement must be available for the PSL algorithm. For the actual engine the engine pressure ratio or engine fan speed can be used to generate an equivalent thrust value. A Kalman estimator could also be used for this application. The Q factors provide a weighting capability to increase the effect of a selected parameter. For example, the weighting for net thrust was increased in relation to other weighting factors to assure a nearly constant net thrust.

OPTIMIZATION TECHNIQUES

Several optimization algorithms (refs. 3 to 8) were considered to determine a method that was best suited for the PSL algorithm. The requirement was that the routine be efficient, accurate, and insensitive to initial conditions. The tested methods are as follows:

(1) Fletcher-Reeves - problems encountered due to constraints
(2) Hooke-Jeeves - did not yield minimum value for all cases
(3) Powell - efficient method; no problems encountered
(4) Zangwill-Powell - efficient method; no problems encountered

The various methods determine the unconstrained minimum of multivariable functions. The methods require a unimodal type of function; otherwise several initial starting values must be considered to assure a true minimum point. The well-known Fletcher-Reeves method is a conjugate gradient method that requires calculation of gradients. Some difficulties with this method were encountered because of the hard engine constraints. The routing has a tendency to become lost during the search process. The Hooke-Jeeves, Powell, and Zangwill-Powell optimization methods are search routines that do not require calculation of the gradients. The Hooke-Jeeves was disregarded since convergence and the minimum value were not achieved for all test cases.

The Powell and Zangwill-Powell methods are essentially similar and generated the minimum values for the various test conditons. The methods converged rapidly and were insensitive to initial conditions. The Zangwill-Powell method was selected since it reflects a departure from the original Powell method in that it tests for linear dependence of the conjugate direction vector. This test assures that a true minimum value will be achieved.

APPLICATION

The effectiveness of the PSL algorithm was evaluated as shown in figure 3. As mentioned previously the digital simulation of the QCSEE engine was used to perform the evaluation phase. An engine component was degraded from its nominal condition with a resultant loss in thrust. For example, the efficiency of the low-power turbine could be reduced by several percentage points. Thrust was then restored by two different methods. A basis for comparison (reference) was then established by a manual method in which the throttle was varied until the net thrust was fully restored to the nominal value of the nondegraded engine. The fan and compressor speeds were scheduled by the throttle and were not constrained. Furthermore the engine control limits were effective for this process. The thrust specific fuel consumption (TSFC) was computed. To evaluate the PSL algorithm, the simulation was returned to nominal and the PSL algorithm was activated. The component degradation was inserted, and the PSL algorithm reoptimized the TSFC and restored thrust to its nominal value. For this case the engine speeds were constrained to their nominal values at the steady-state condition. The two values of TSFC were compared.

The results for several engine component degradations are shown in table I. Typical degradations include loss of efficiency and power requirements for the engine components. With the manual procedure used as the reference, cases B, C, E, and H did not exhibit an improvement for the PSL algorithm. The notations η and P designate a change in efficiency and power requirement. For these malfunctions the pilot can restore the loss of thrust and obtain comparable values of TSFC. For real engine operation the change in component efficiencies and power requirements is a gradual, long-term effect that will be continually corrected by the PSL algorithm. The large perturbations were chosen to accentuate the process and so that we could observe the effectiveness of the "smart" logic. For excessively large variations the algorithm might not correct for the deficiencies unless certain constraints can be relaxed.

The results obtained for conditions A, D, F, and G indicate that the PSL algorithm was able to optimize and generate an improved TSFC over that generated by the manual method. For example, a lower low-pressure-turbine efficiency resulted in a 1.8-percent higher value for TSFC; a higher fan power requirement caused a 1.6-percent higher value of TSFC. Similarly a combination of deficiencies (i.e., A-B, A-D) provided a higher value of TSFC for the manual throttle change. These latter cases imply that the scheduling of the control input variables for the region might not be optimum and thus that a higher fuel flow would be required to restore the nominal thrust. An interesting test was case I, where the thrust could not be fully restored to the nominal value. For the manual case thrust was restored to within 2.5 percent of nominal; the PSL algorithm was able to return the thrust to within 0.8 percent of nominal. These results indicate that if some engine constraints were relaxed and speeds allowed to seek a new value, improved results might be obtained for the PSL algorithm.

Although a limited number of test conditions were demonstrated, it can be deduced that the PSL algorithm can do as well or better than the manual control. Since degradation effects are minimal, accruable, and long term, it is evident that the added secondary controller serves a useful purpose in maintaining optimum system performance and in relieving the pilot of an added burden.

CONCLUSIONS

The objective of the PSL algorithm is to optimize the performance of the propulsion system at a steady-state condition. The major function is to modify the engine control set-point schedules for component degradations in order to restore the nominal net thrust. The results of the study indicate that this task can be achieved with the PSL algorithm. Convergence to the optimum value can be obtained within 60 to 90 seconds, which makes the program acceptable for on-line operation with present state of the art minicomputers.

Several optimization procedures were evaluated; however, difficulties were experienced with the Fletcher-Reeves and Hooke-Jeeves methods. These problems are attributable to the hard engine limits. The selected method was the Zangwill-Powell technique, which offered rapid and accurate convergence. The tests indicate that in most cases the PSL algorithm offers some improvement in thrust specific fuel consumption over the manual throttle.

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TABLE I. - RESULTS OF ENGINE COMPONENT DEGRADATION

[Throttle was adjusted for constant thrust at steady-state condition.]

Case	Effect	Fuel flow - TSFC (PSL improvement over throttle), percent
A	Low-pressure turbine, $\Delta\eta = -10$ percent	1.8
B	High-pressure turbine, $\Delta\eta = -10$ percent	No change
C	Compressor power, $\Delta P = 10$ percent	No change
D	Fan power, $\Delta P = 10$ percent	1.6
E	Accessory equipment, $\Delta P = 100$ percent	No change
F	Cases A and B	.6
G	Cases A and D	4.1
H	Cases A, B, C, and E: A and B, $\Delta\eta = -5$ percent C, $\Delta P = 5$ percent E, $\Delta P = 100$ percent	No change
I	Cases A, B, C, and E: A and B, $\Delta\eta = -10$ percent C, $\Delta P = 5$ percent E, $\Delta P = 100$ percent	(a)

[a] Nominal values of thrust could not be achieved.

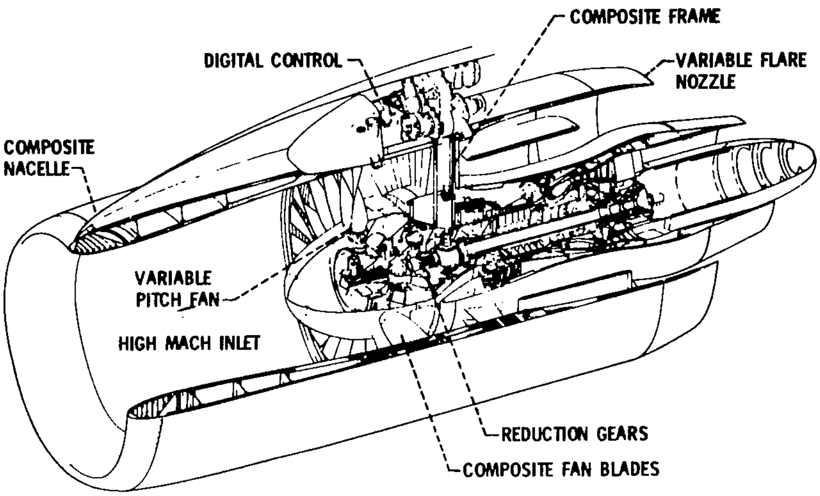

Figure 1. - QCSEE UTW engine.

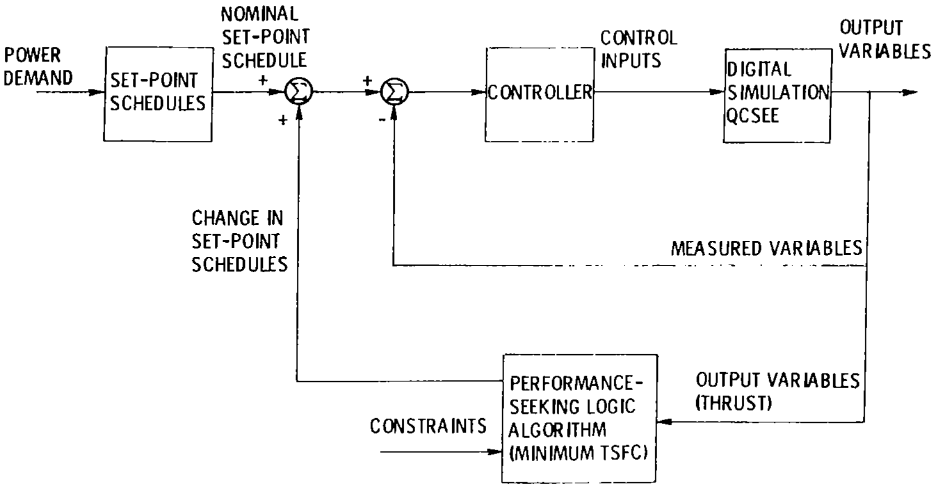

Figure 2. - Block diagram of performance-seeking logic algorithm applied to QCSEE.

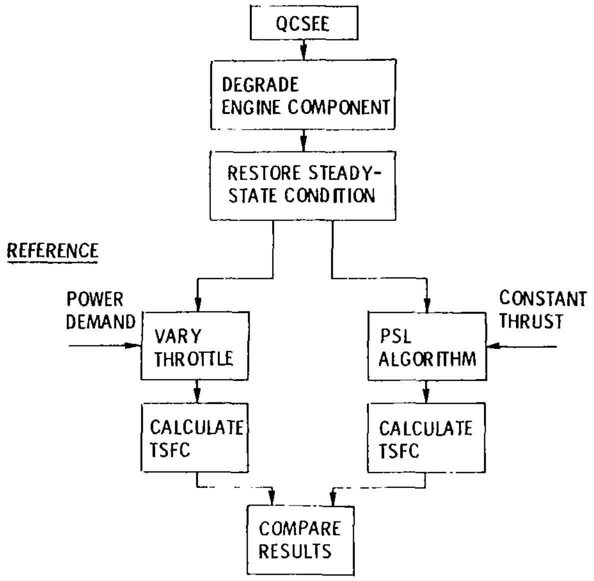

Figure 3. - Evaluation procedure.