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ABSTRACT

Modern aircraft turbine engine designs provide the engine control system a variety of sensors and actuators for use in transient and steady-state operation. In the past, engine controls have been hydromechanical or, more recently, hydromechanical for speed governing with digital electronic trim for improved steady-state performance. In the future, increased demands on engine control system performance, weight, cost, and reliability dictate that control logic be implemented on an onboard digital computer. With the computer, it is then feasible to apply, for example, linear quadratic regulator (LQR) synthesis methods. This allows an integrated control action designed to meet both steady-state and transient requirements.

The F100 Multivariable Control Synthesis (MVCS) program, jointly initiated by the Air Force Aeropropulsion Laboratory and the NASA-Lewis Research Center, was aimed at demonstrating the benefits of LQR synthesis theory in the design of a multivariable engine control system for operation throughout the flight envelope. The advantages of such procedures include: (1) enhanced performance from cross-coupled controls, (2) maximum use of engine variable geometry, and (3) a systematic design procedure that can be applied efficiently to new engine systems.

The control system designed, under the MVCS program, for the Pratt & Whitney F100 turbofan engine is described. Basic components of the control include: (1) a reference value generator for deriving a desired equilibrium state and an approximate control vector, (2) a transition model to produce compatible reference point trajectories during gross transients, (3) gain schedules for producing feedback terms appropriate to the flight condition, and (4) integral switching logic to produce acceptable steady-state performance without engine operating limit exceedance. The design philosophy for each component is described and the details of the F100 implementation presented.

The engine altitude test phase of the MVCS program is described. A wide variety of test operating points and power transitions were made to test the functional behavior of the control logic. Engine responses are presented and the overall characteristics of multivariable engine control are explored.

INTRODUCTION

The F100 Multivariable Control Synthesis (MVCS) program was jointly initiated by the Air Force Aeropropulsion Laboratory (AFAPL) and the NASA-Lewis Research Center (NASA-LeRC). Its objective was to demonstrate the benefits of using Linear Quadratic Regulator (LQR) synthesis techniques in the design of a multivariable control system for operating a turbofan engine throughout its flight envelope.

The program was divided into three phases. The goal of phase one was to design the control logic based on a set of linear operating point models and evaluate the control on a digital F100 engine simulation. Systems Control Inc. (Vt)(SCI) and Pratt and Whitney Aircraft Group, Government Products Division (P&W GPD) were contracted by the Air Force to conduct this phase. P&W GPD generated the required linear models and defined a set of control criteria upon which the LQR design could be based. SCI's task was to produce the actual multivariable control (MVC) design and evaluate it on a digital F100 simulation provided by P&W GPD. The goal of phase two was to evaluate the control by programing it on a control computer and controlling a real-time F100 hybrid simulation. It was NASA-LeRC's responsibility to program the LQR logic on the control computer and conduct the evaluation in its hybrid simulation facility. Assuming successful completion of phases one and two, the goal of phase three was to demonstrate the multivariable control of an F100 engine in the NASA-LeRC PSL altitude facility.

All three phases have now been successfully completed. The results of phases one and two have been documented in references 1 through 8. This paper will describe the results of the phase three engine altitude tests conducted by NASA-LeRC in addition to reviewing the overall program.

There have been a number of past efforts to apply LQR theory to multivariable engine control designs (refs. 9 to 12). However, none of these investigations faced up to all the problems of extending what is basically a linear theory to the highly nonlinear engine problem. Significant contributions made by the MVCS program are in demonstrating how LQR theory can be adapted to handle such problems as the change of engine dynamic behavior with power level, accommodating engine and actuator limits, and operation over the complete engine flight envelope. In addition, program results have shown that the F100 MVCS control can be implemented on a control computer using a reasonable amount of storage and requiring a reasonable computer cycle time. Finally, the ability of the multivariable control algorithm to successfully operate an actual, full-scale engine has been proven by the recently completed altitude tests.

This paper will present a review of the MVCS program. It will first discuss the F100 engine, the control design criteria and the MVC logic structure. Following that will be a brief discussion of the procedures used to evaluate the control on the hybrid simulation and in the altitude tests. Next, the implementing of the control on a control computer will be covered followed by a brief review of the hybrid computer evaluation. Finally, representative steady-state and transient altitude test results will be presented and discussed.

F100 MULTIVARIABLE CONTROL LOGIC DESIGN

The P&W F100-PW-100 engine, used in the F100 MVCS program, is shown in figure 1. The engine is a twin spool, low bypass ratio afterburning turbofan. It has five controlled variables: main burner fuel flow, variable area exhaust nozzle, variable fan inlet guide vanes, variable compressor geometry and compressor exit bleed. While not as multivariable as variable cycle engines now under development, the F100 exhibits sufficient control complexity to test LQR theory. Since both digital and real-time hybrid F100 simulations exist and an engine was available for altitude testing, the F100 was selected for use in the MVCS program.

In addition to a system dynamic model, it is necessary to have a set of control criteria upon which to base an LQR design. The criteria for the F100 engine were formulated by P&W GPD (ref. 1) and can be summarized as follows. Primarily, the control must protect the engine against surge and keep the engine from exceeding speed, pressure or temperature limits. Airframe-engine-inlet compatibility considerations require minimum burner pressure limits be accommodated and maximum and minimum airflow requirements be adhered to at certain flight conditions. The control must insure engine thrust and fuel consumption are within tolerance for specified engine degradations and for installation effects. It is important that the control accelerate the engine safely, rapidly and repeatably with small overshoots in response to both large and small power lever angle inputs. Finally, it must control the engine accurately during flight maneuvers and accommodate disturbances such as afterburner lights.

The above controls criteria were translated by SCI into quadratic performance index specifications for use in the LQR design process. The details of the design are contained in reference 2. The design process and resulting multivariable control structure will be briefly reviewed here. Linear state variable engine models were generated from the P&W digital simulation at a large number of flight points and power conditions throughout the flight envelope. The engine models' structures were investigated and used to obtain reduced fifth-order linear models. Each model is described in terms of its control, state and output vectors. The control vector, u, for the F100 engine controlled in the MVCS program was:

- WFC - commanded fuel flow
- AJ - exhaust nozzle area
- RCVV - compressor variable vane angle
- CIVV - fan inlet guide vane angle
- BLC - compressor exit bleed command

Afterburner fuel flow was specifically not considered for control by the MVC; but compressor bleed, not controlled by the current F100 control, was used as an MVC control input. The fifth-order state vector x was comprised of:

- N1 - fan speed
- N2 - compressor speed
- PB - main burner pressure
- PT6 - afterburner inlet pressure
- WF - main burner fuel flow

The output vector y consists of the variables which the five control inputs regulate to establish the steady-state engine operating point. They are:

- FTIT - fan turbine inlet temperature
- ΔP/P2.5 - fan discharge Mach number parameter
- N1 - fan speed
- PB - main burner pressure
- RCVV - compressor variable vane angle
- CIVV - fan inlet guide vane angle
- BLD - compressor exit bleed flow

Using the above state-variable model description, SCI designed what is basically a proportional-plus-integral, model-following control having gain matrices scheduled as functions of flight conditions. Figure 2 shows the structure of the resulting MVC design. The Reference Point Schedules are based on the control schedules used by the current F100 control. They produce reference values for the states, outputs and controls as functions of PLA and ambient variables PO, PT2 and TT2. The Transition Control produces smooth, rate-limited transition values x_s, y_s, and u_s between desired reference values so that excessive control error buildup is prevented. The rates are functions of engine face density and power level. The Reference Point Schedules and Transition Control comprise essentially the "model" which the model-following control follows.

There are three paths through the control; the feedforward, u_s, the proportional path through the LQR Gains and the integral control path through the Integral Gains. The LQR Gain matrix was designed using standard LQR design techniques. The LQR Gains reduce the deviation between the five engine states and their scheduled values and thus alter engine transient response. The Integral Gain matrix was designed using a combination of LQR and decoupled pole-placement techniques. The integral trims serve to drive the errors between five selected outputs and their respective reference values to zero in steady-state. Selection of the outputs to be trimmed is performed by the Engine Protect Logic and will be described below. Contributions from the three control paths are finally summed to produce the five controller outputs. Due to engine nonlinearity, both LQR and integral gain matrices were scheduled as a function of engine face density and scheduled compressor speed, $N2_s$.

The Engine Protect Logic contains schedules which place absolute limits on commanded control variables to assure safe engine operation in the test cell should a sensor or logic failure occur. Also, if an actuator saturates, the logic clamps the associated integrator and eliminates one column from the Integral Gain matrix to accommodate the loss in degrees of control freedom.

The sensor for engine output FTIT is slow. Figure 2 shows an FTIT Estimator block which was designed to produce an estimate of the true FTIT and thus compensate for the sensor lag. The FTIT estimate is an engine protection parameter, being used to limit fuel flow at intermediate power (PLA = 83^o).

The structures of the LQR and integral gain matrices are shown in figure 3. Figure 3(a) shows that many of the possible state-control couplings have been set to zero by using a sensitivity technique, resulting in a simplified control implementation. In addition, approximately half of the non-zero gains were constants. The integral gain matrix (fig. 3(b)) has eight columns. only five of which can be active at one time to set the steady-state match point of the engine. The first four columns are always used. Fan discharge $\Delta P/P$ is always trimmed to its schedule to set the fan operating point. Also, RCVV and CIVV are trimmed to be on their schedules and the bleed integrator adjusts to close the the bleed in steady-state. The other four columns are only used one at a time, depending on flight condition and power level. Usually, fan speed is trimmed to its schedule. However, if a maximum or minimum burner pressure is reached, fan speed is allowed to go off-schedule and the limit is accommodated by switching in the appropriate column. If an FTIT limit is reached, the FTIT column is switched in to allow the integrator to trim fuel flow and area to accommodate the limit. An FTIT limit takes priority over a PB limit.

The MVC logic was evaluated by SCI on a digital simulation of the F100 engine to determine its transient and steady-state performance. Having completed that evaluation, the MVC logic equations were transferred to NASA-LeRC and programed on a control computer for use in subsequent hybrid and engine tests.

COMPUTER IMPLEMENTATION AND EVALUATION PROCEDURES

The MVC logic shown in figure 2 was implemented on the LeRC SEL810B control minicomputer (ref. 13). The SEL810B has specifications representative of a flight-type computer, having 24K of 16 bit core memory, a 0.75 microsecond cycle time and a 50 microsecond digitizing rate. To achieve a desired 10 m/second update interval, fixed point assembly language programing was used. A feature on the 810B called INFORM (ref. 14) was used extensively for rapid man-computer communication. Using INFORM, steady-state and transient data were recorded while at the same time controlling the engine or simulation. The total core requirements for the MVC logic was about 7000 words. The version of the control used for engine tests incorporated logic to check for actuator or sensor failures. This added about 2500 words of memory and required increasing the update interval from 10 to 12 m/second.

Figure 4 is a plot of the various Mach number - altitude points selected at which the MVC was evaluated in both hybrid and altitude facility tests. The points were selected so as to explore the borders of the engine's flight envelope and also to conduct tests of transient performance in the center of the envelope. Due to altitude facility airflow limitations, the altitude test points don't encompass as wide a range as the hybrid test points.

Steady-state operating line data were taken at all test points. However, in certain ranges, airflow and/or burner pressure limits in the control limit the range of steady-state operation to near intermediate (PLA = 83°) operation. Transient control performance was evaluated by subjecting the control to small 3° PLA steps, to large PLA snaps and chops, to random, cyclic PLA motion and to zone-one afterburner lights. In addition, simulated flight maneuvers were performed, both on the hybrid and in engine tests.

SUMMARY OF REAL-TIME HYBRID EVALUATION

The configuration used for testing the MVC on the NASA-LeRC real-time F100 hybrid simulation (ref. 15) is shown in figure 5. Real-time capability is necessary to adequately check out control computer implementation aspects. The SEL810B digital computer, besides performing MVC logic calculations was used to simulate control actuators as shown. Also, the SEL recorded both transient and steady-state data which was transmitted to a disk unit for further off-line processing. This same data collecting capability was used for the altitude tests as well.

In all, 56 steady-state operating points were recorded and 77 transient tests were performed during the evaluation. The results were quite good. Proper steady-state performance was demonstrated at all points. The MVC was able to accommodate for the differences between the digital and hybrid simulations. Transient response specifications were satisfied, integral trim switching logic and gain scheduling functioned properly and regulator performance during A/B lights was proper. Certain control logic problems were corrected and programing errors eliminated prior to the engine altitude tests.

A number of issues specifically directed toward the altitude tests were also investigated. A sensor failure effects study was performed, which led to the implementation of sensor and actuator failure detection logic in the MVC version for use in the altitude tests. Hybrid tests also showed the MVC was stable for cycle times up to 250 m/second. Thus, the cycle time was safely increased from 10 to 12 m/second to ease programing problems in the altitude test version of the control. The simulation was also used to verify the safe operation of the system designed for transferring from MVC to backup control in the altitude facility. In summary, the hybrid evaluation was very instrumental in pinpointing and eliminating problems which could have occurred in subsequent altitude tests.

SYSTEM CONFIGURATION FOR ALTITUDE TESTS

Further testing of the F100 multivariable control logic was performed in the NASA-LeRC Propulsion Systems Laboratory (PSL) altitude facility. Figure 6 shows a system diagram describing the test setup. F100 engine number XD11-8 was located in PSL but the SEL810B control computer had to be stationed some 1000 feet away in the hybrid computation center. A remote interface unit was located in the PSL control room, receiving five control command signals from the SEL and sending 24 sensed engine and ambient variables to the SEL. All signals were zero to ten volts and transmitted over twisted pair lines with A/D and D/A conversion performed at the computer end.

Five research actuators having electrical inputs were required to be used in place of the standard F100 hydromechanical actuators. In addition, a backup control was required, both for control of the engine during startup and to take over control in the event of a computer, sensor or research actuator malfunction. The research actuators and their corresponding backups are described in Table I. Fuel flow and RCVV research actuators were modified F100 types, and backup control for each came from the standard F100 control. The research actuators for the other three controls were standard position servos. Nozzle area and bleed backups were simply fixed servo command signals. The electrical backup command for CIVV was generated on an analog computer function generator. In the research mode of operation, afterburner fuel flow (zone-one only) continued to be controlled normally by the standard F100 control.

Sensors used by the multivariable control are listed in Table II. Variables sensed were engine control, state and output variables as well as PO, PT2 and PLA. Temperature TT2.5 was also sensed, as the MVC used it in calculating the RCVV schedule.

The control of the engine's power lever angle remained in the PSL control room with an electrical PLA signal sent to the SEL computer. Switching of the control from backup to MVC was controlled in PSL by the test engineer who also controlled the abort-to-backup button in case of emergency. To aid the controls engineers located in the hybrid computation center, a cathode ray tube display of real-time engine parameters was provided along with panel meter displays of key engine variables. A two-way voice link and a one-way control room TV monitor facilitated communications.

The SEL810B control computer's main functions were the MVC logic calculations and sensor/actuator failure checks. But, it also performed pre-run line integrity checks and recorded and displayed steady-state and transient on-line data. In addition to outputting five actuator command voltages, the computer generated an abort signal in the event of a detected failure. It also sent logic signals to be displayed in the PSL control room which showed the MVC controls status (i.e., standby mode, run mode, integral trim on N1, etc.) on a panel display. A teletype unit was used for inputting commands to the SEL and for making program modifications. Also, upon request, steady-state data showing the values of the multivariable control's internal variables could be displayed. A floppy disk unit was used for storing the MVC program and associated subroutines. Steady-state and transient data were dumped out onto the floppy disk and after a test run, the disk data was read into an IBM 360 computer for further processing and plotting, as in the hybrid evaluation.

A typical altitude test of the multivariable control began with the engine being started on its backup control and the altitude facility adjusted to the appropriate values of P0, PT2 and TT2 for the flight condition desired.

The MVC was allowed to perform its control calculations with all integral trims set to zero, generating a set of five actuator commands. These commands were compared to the five sensed control signals. The integral trims were adjusted until the commanded controls equalled the sensed and then they were clamped. This allowed a smooth transfer from backup to multivariable control. Each of the five control variables were then sequentially switched from its backup to its research actuator. The integral trims were released and the engine was then on multivariable control. Engine control reverted to the backup mode if the computer detected a sensor or actuator failure. At the completion of MVC testing, an abort command initiated either by the SEL computer operator or by the engine operator put the engine control in backup mode in preparation for engine shutdown.

ALTITUDE TEST RESULTS

The purpose of the altitude tests (ref. 16) was to demonstrate the steady-state and transient performance of the multivariable control throughout the engine flight envelope. This section presents representative results obtained during those tests. The tests were run at six subsonic and four supersonic points, as shown in figure 4. At all points, 186 steady-state, control-related variables were recorded by the SEL control computer. These included actuator commands, sensed state and output variables and internal control logic variables. Forty-four of these variables were recorded by the SEL during transient tests. In addition, the standard altitude cell steady-state and transient data recording systems were used. They recorded steady-state data on over 300 sensed variables and transient data on 200 variables.

Prior to running the MVC tests, a number of baseline tests were run on the engine with standard F100 controls. They were conducted at the same flight conditions as were the MVC tests. In all, over 225 steady-state data points and 41 transients were recorded with standard F100 engine control. The main purpose in running these tests was to record reference point values which were scheduled by the standard control for engine XD11-8. These then were compared to the corresponding values scheduled by the multivariable control logic. Also, total and static pressure probe data at station 2.5 were recorded and used to synthesize the fan discharge $\Delta P/P$ parameter. These data were then compared to their values scheduled by the MVC logic. The MVC logic was run open loop during tests with the standard control so that MVC reference point schedule values could be generated for all control, state and outputs for subsequent comparison to the standard control's scheduled values. Also, MVC limit mode switching logic and failure detection logic were checked out prior to the MVC tests.

From the results of the baseline tests, it was found that the characteristics of engine XD11-8 differed from those of the nominal engine described by the P&W digital simulation. Since the reference point schedules in the MVC were designed based on the digital simulation values, some schedule adjustment was warranted before MVC testing. In particular, the corrected fan speed and the burner pressure schedules were biased down to allow the MVC to control the engine close to the values scheduled by the standard F100 control. The fan discharge $\Delta P/P$ schedule in the MVC was based on theoretical values from the deck. It was found that actual sensed $\Delta P/P2.5$ values were higher than theoretical for the same corrected airflow. Thus, the MVC $\Delta P/P2.5$ schedule was biased upward to provide proper fan airflow scheduling.

STEADY-STATE MULTIVARIABLE CONTROL PERFORMANCE

Steady-state operating lines were run with the multivariable control at the flight conditions shown in figure 4. In all, 309 individual steady-state points were taken. Overall, the MVC tracked the reference point schedules well. FTIT and burner pressure limits were accommodated where required. The RCVV's and CIVV's were held to their respective schedules through the integral trims. The two remaining scheduled variables which determine the steady-state operating point are fan speed and fan discharge $\Delta P/P$. They were made to track their schedules properly through use of integral trims on exhaust nozzle area and fuel flow. There were, however, some minor problems with area trim integrator saturation near mid-power at some flight conditions which could be corrected by further schedule refinements.

Figure 7(a) through (c) shows representative steady-state results for the F100 multivariable control. They are at intermediate power only but at all ten flight points. Three scheduled variables are shown. They are fan speed, FTIT and fan exit $\Delta P/P$. Fan speed is shown as a function of its scheduled value in figure 7(a). Fan speed was under integral control through the fuel flow integrator at intermediate at only three of the ten flight points. Dark symbols (indicating when on integral control) show fan speed was very close to schedule at these points (K, F and G′). At all other intermediate points, fan speed error was held to less than 250 rpm by the regulator, except for point L (10,000 ft., Mach 1.2). This larger-than-desired error in fan speed caused an increased fuel flow integrator downtrim at L to hold FTIT on its limit. A corrected fan speed schedule adjustment could have been made but wasn't, since transient behavior at L was quite good.

Figure 7(b) shows how well the multivariable control held FTIT on its scheduled limit. FTIT was not on a limit for the three points (K, F and G′) where fan speed was integrally controlled. But, FTIT was held on its limit for the remaining points. It can be seen that for TT2 above 56°F, the fuel flow integrator switched from fan speed to FTIT. Here, the fuel flow integrator zeroed the error between the FTIT limit and the output of the FTIT estimator. A predictable bias error exists for the estimator as a result of the design trade-off between fast estimator response and good steady-state accuracy. The bias mainly depends on the error between actual and commanded fuel flow. This bias error accounts for most of the deviations shown in figure 7(b), since the integral control generally held the error between FTIT and its estimate to less than 2°F. The FTIT estimate tended to be conservative so that FTIT tended to lie below its set limit. The FTIT values shown here are acceptable and in line with values observed in engine tests with the current F100 control.

Figure 7(c) shows the third primary scheduled variable, fan discharge $\Delta P/P$ plotted against its scheduled value. The parameter used for $\Delta P/P$ (ref. 6) was

$$\Delta P/P2.5 = 1/2\left(\frac{PT2.5_{core} - PS2.5_{core}}{PT2.5_{core}} + \frac{PT2.5_{duct} - PS2.5_{duct}}{PT2.5_{duct}}\right)$$

Each PT2.5 and PS2.5 was computed by electrically averaging four to six strain-gage type pressure transducer outputs. Individual total pressures were obtained from six 3-probe rakes. Three were installed in the engine fan duct and three in the core. Individual static pressures were obtained from taps located in the inner and outer duct and core walls. A preliminary analysis of $\Delta P/P2.5$ data taken in the MVC tests indicated that an adequate $\Delta P/P$ signal could have been obtained by using only one location for each of the four pressures. However, this was not done for the altitude tests. Integral control was used at all flight conditions to keep $\Delta P/P$ on schedule. Errors in figure 7(c) are generally less than one percent except for point G′ and point F. At G′, the exhaust nozzle was commanded to go to its minimum area but remained partly open due to hysteresis in the nozzle linkage. This caused $\Delta P/P$ to be higher than desired. At point F, the schedule requested a value about 3.5% lower than sensed, causing the nozzle to go to its minimum area. However, this was not a problem since the standard F100 control, upon which the $\Delta P/P$ schedules were based, commanded a minimum area here also.

In summary, steady-state performance of the F100 multivariable control was good at all points tested. Integral control held scheduled variables close to their schedules. Reference point schedule adjustments allowed schedule matching without controls saturating or engine variables exceeding allowable limits.

TRANSIENT MULTIVARIABLE CONTROL PERFORMANCE

Transient performance of the multivariable control was assessed at all flight points shown on figure 4. Large PLA transients (idle to 83°, 50° to 83°, 83° to idle, etc.) were run at all points were airflow schedules allowed PLA operation below 83°. Three degree PLA transients were run to check regulator performance and cyclic or random PLA sequences were run to verify correct gain scheduling logic operation. In all cases, PLA was changed at the rate of ±126°/second. Repeatable PLA transient inputs were assured by the use of a programable function generator to control PLA during transient tests. In all, 93 transients were run on multivariable control. In this paper, only three will be presented to demonstrate typical control performance in response to (1) a large PLA input at a low-altitude, subsonic condition, (2) an afterburner light at supersonic conditions and (3) a simulated flight maneuver.

Figures 8(a) and (b) shows the response of the engine under multivariable control to a PLA snap from 50° to 83° at flight point C (10,000 ft., Mach 0.6). Engine dynamic characteristics here are quite similar to those at sea level static conditions. This transient exercised a number of multivariable control logic functions: transfer from fan speed trim to FTIT trim, regulator and integrator gain scheduling as a function of compressor speed, FTIT estimation of FTIT and trimming of nozzle area to set fan exit $\Delta P/P$. In figure 8(a), it can be seen that before the PLA snap occurred at 0.5 seconds, fan speed was on schedule. After PLA moved, the transition control generated request values of the state variables (fan and compressor speed and burner and afterburner pressure). Differences between the sensed and scheduled values fed through the regulator to cause the sensed values to track the schedules. The states responded in a stable, controlled fashion, with little or no overshoot. In the bottom of figure 8(a), FTIT estimate can be seen to reach the FTIT limit shortly before time equals one second. At this point, the fuel flow integrator input error was switched from fan speed to FTIT, and consequently, fan speed fell below its scheduled value in steady-state.

In figure 8(b), fuel flow and the three components which, added together, produced its command are plotted: the scheduled value, the LQR output and the fuel flow integrator output. Fuel flow remained close to its scheduled value. The LQR contribution initially increased to reduce negative errors in the state variables. Fuel flow integrator uptrim was inhibited until the FTIT estimate reached the limit. At this point, it can be seen that the integrator introduced downtrim which reduced fuel flow down and away from the scheduled value. This moved the FTIT estimate down to the limit so that in the steady-state FTIT was at its limit.

The nozzle area moved both to trim fan exit $\Delta P/P$ to its schedule and to reduce state variable errors during the transient. Figure 8(b) shows that before the PLA snap, nozzle area was on a scheduled maximum area limit; consequently, $\Delta P/P$ was lower than its scheduled value. This area limit was introduced during the hybrid evaluation to insure stability for PLA's below about 50°. After the snap began, the LQR nozzle contribution initially increased nozzle area, primarily in response to a negative fan speed error and then at about 1.5 seconds decreased nozzle area to null out a negative error in afterburner pressure. The area integrator trim reduced to close the nozzle and cause $\Delta P/P$ to be on schedule at PLA = 83°. The last two traces in figure 8(b) show the RCVV's, which held quite closely to schedule, and the CIVV's. CIVV's lagged behind the CIVV schedule due to a contribution from the LQR which cambered the CIVV's in order to reduce the magnitude of fan speed error. In steady-state, however, the CIVV integrator overrode any LQR contribution to position CIVV's on schedule. Large transient responses for other flight points were qualitatively similar to the responses shown in figure 8. Exceptions were at high altitude, low Mach number points (45,000 and 50,000 ft., Mach 0.9) where responses were more underdamped than desired. This is possibly due to the effects of unsteady test-cell conditions. Also, a slower than normal burner pressure transducer caused the multivariable control responses to be slower than desired for certain large PLA transients. This slow signal caused the standard F100 WF/PB schedule programed at part of the Engine Protect Logic (see fig. 2) to inadvertently limit fuel flow during these accels.

Afterburner lights were performed at all flight points to test the ability of the multivariable control to attenuate external disturbances. Feedforward logic such as is used in the standard F100 control was not used to aid in reducing the effect of the afterburner ignition pulse. Control of the afterburner was specifically excluded from the MVC design. Hence, the afterburner pulse acted as a disturbance to the system. Figure 9 shows the results of an afterburner light at a high altitude supersonic condition (55,000 ft., Mach 1.8). The control rapidly responded to attenuate the afterburner pressure pulse resulting from the light. The results also verify the correct scheduling of LQR and integral gains and reference point schedules at this supersonic, high inlet temperature point. The light occurred at times equals 0.5 second as shown by the rise in A/B fuel supply pressure in the top trace. The effect of the light was to cause afterburner pressure to increase and fan speed to drop. Compressor speed remained essentially constant. The FTIT estimate followed the sensed value with an offset of about eight degrees. During the light, the estimate was held close to the limit through integral trim on fuel flow, thus causing the sensed value of FTIT to remain below the limit.

Figure 9(b) shows that fan speed error (and to some extent A/B pressure error) acted through the LQR area output to initially open the nozzle. At the same time, fan discharge $\Delta P/P$ dropped below schedule and caused the area to open until $\Delta P/P$ was back on schedule. The net result was that A/B pressure was attenuated as desired. There was also some slight control activity on fuel flow as the fuel flow integrator trimmed to keep FTIT below its limit. The multivariable control successfully attenuated afterburner pressure pulses at all other flight points except for 45,000 and 50,000 feet, Mach 0.9. Here, sensed fan discharge $\Delta P/P$ did not change sufficiently to allow nozzle trim control to suppress the disturbance. Further analysis of sensed $\Delta P/P$ data in this region is being undertaken.

A total of nine simulated flight maneuvers were performed to test, in particular, gain scheduling and FTIT estimator performance with varying PLA and ambient conditions. Maneuvers included combinations of climbs, dives, accels and decels and the multivariable control performed well in all tests. Figure 10 shows one representative maneuver, an accel at a constant 10,000 foot altitude. Actual pressure altitude varied from about 8,500 to 11,000 feet during the transient and Mach number increased from 0.6 to 0.9 in about 15 seconds. Inlet temperature couldn't be changed so that the initial condition was standard day and the final condition was 40°F colder than standard day. The PLA was increased manually from 65° to 83° in about five seconds. Figure 10(a) shows compressor speed making a controlled transition with a slight overshoot. Fan speed tracked its schedule with a slight overshoot. Figure 10(b) shows that at about four seconds, the FTIT estimator reached the limit and the fuel flow integrator ceased trimming on fan speed error and downtrimmed fuel to keep FTIT below its limit. In steady-state, FTIT held to the limit within 5°F. Finally, figure 10(b) shows that the exhaust nozzle area closed down to keep fan discharge $\Delta P/P$ on schedule as desired. In summary, the multivariable control produced a well-controlled transition of engine power setting with varying ambient conditions.

TESTS OF ALTERNATE TRIM MODES AND FAILURE DETECT LOGIC

A number of other topics were explored during altitude testing and will be briefly mentioned here. As mentioned before, a backup control and sensor/actuator failure logic were used to allow safe test cell operation with nonflight-qualified sensors and actuators. The failure logic performed well and was exercised a number of times. Experience gained with this type of logic will prove useful in designing flight-qualified engine controls which must be able to both detect and accommodate failures. To demonstrate the flexibility of the F100 multivariable control structure, two control logic changes were tested. One was the so-called EPR-N1 trim mode. Here, fan discharge $\Delta P/P$ was replaced by engine pressure ratio as the variable which determines the fan operating line. The control structure made control mode changing simple, requiring only new regulator and integrator gain matrices to be entered. The EPR-N1 mode functioned properly in limited testing. The other logic change implemented was the so-called "fast-accel control." Its performance had been verified in the hybrid evaluation and was further tested at two altitude flight points. A more rapid than normal engine response was obtained by increasing all rates in the transition control. The modular structure of the multivariable control allowed this change to be made without having to change regulator gains, integral gains or reference point schedules.

CONCLUSIONS

The objective of the F100 Multivariable Control Synthesis Program was to demonstrate that a control could be designed using linear quadratic regulator (LQR) design methods that would operate a modern turbofan engine over its entire flight envelope. The LQR design methods were used to develop feedback gains for a series of operating points. Reference schedules were used to translate pilot and ambient inputs to reference point specifications. A transition controller was used to produce smooth and rapid transitions from one operating point to another. A variable structure integral trim control was designed to produce specified steady-state performance and to accommodate limits. The performance of the multivariable control was evaluated on a real-time simulation of the P&W F100 turbofan engine with the control logic programmed on a digital computer. Use of the real-time simulation allowed program debugging and verification of proper control logic functioning prior to engine tests in an altitude facility. Sensor and actuator failure detection logic was developed and checked out by simulating transfers from multivariable to a backup control.

The multivariable control was tested while controlling an F100 engine at ten flight points in an altitude facility. The control exhibited good steady-state performance, the ability to hold engine trim variables on schedule at all flight points. Tests of the engine with the standard F100 control prior to multivariable control tests provided data which were used to adjust some of the reference point schedules. This allowed tracking of reference point schedules without trim saturation and matching of engine operating lines obtained with the standard F100 control.

Good transient performance was demonstrated at almost all flight points. However, underdamped behavior was noted at high altitude subsonic points, possibly due to sensitivity to varying ambient conditions. The integral trims successfully accommodated FTIT limits and low burner pressure limits where required. The control attenuated afterburner pressure pulses occurring during afterburner lights at all but two flight points. At supersonic points, where operation was permitted only at intermediate and above, excellent suppression of afterburner disturbances was observed. The multivariable control successfully operated the engine for random PLA excursions, thereby verifying the correct functioning of regulator gain schedules and transition logic. A number of flight maneuvers were performed to check the control's performance with simultaneously varying PLA and ambient conditions. The control tracked reference point schedules well and accommodated all limits.

Programing flexibility which exists due to the modular structure of the multivariable control was demonstrated by testing two alternate control modes. A fast acceleration set of transition control rates was implemented which allowed more rapid engine accelerations. Also, the integral trim structure was changed to use engine pressure ratio instead of the fan discharge Mach number parameter normally used with the multivariable control. The new trim structure worked satisfactorily, requiring only a change of gain matrices to implement it.

Sensor and actuator failure detection logic was incorporated into the control for altitude tests and functioned well in conjunction with a backup control. All of the control logic was programed in 9.5K of core, using a 12 m/second computer cycle time. These computer requirements are within the capabilities of present generation computers envisioned for use as engine-mounted digital controls.

It is concluded that LQR-based control design techniques can be successfully used to design digital engine controls. Its systematic, structured approach has much to offer in the design of controls for new-generation airbreathing engines.

SYMBOL LIST

BLC	compressor exit bleed command, percent of compressor exit flow
BLD	compressor exit bleed flow, percent of compressor exit flow
CI	integral gain matrix
CIVV	fan inlet guide vane angle, deg.
CR	LQR gain matrix
FTIT	fan turbine inlet temperature, ^{o}F
$FTIT_{est}$	estimated value of FTIT, ^{o}F
N1	fan speed, rpm
N2	compressor speed, rpm
PB	main burner pressure, psia
PLA	power lever angle, deg.
$\Delta P/P2.5$	fan discharge Mach number parameter
$PS2.5_{core}$	average fan discharge static pressure in core, psia
$PS2.5_{duct}$	average fan discharge static pressure in duct, psia
$PT2.5_{core}$	average fan discharge total pressure in core, psia
$PT2.5_{duct}$	average fan discharge total pressure in duct, psia
PO	ambient (static) pressure, psia
PT2	fan inlet total pressure, psia
PT6	afterburner inlet total pressure, psia
RCVV	compressor variable vane angle, deg.
TT2	fan inlet total temperature, ^{o}F
TT2.5	fan discharge temperature in duct, ^{o}F
u	control vector
u_s	scheduled control vector

WF	main burner fuel flow, lb/hr
WFC	main burner fuel flow command, lb/hr
x	state vector
x_s	scheduled state vector
y	output vector
y_s	scheduled output vector

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TABLE I - F100 MULTIVARIABLE CONTROL ACTUATORS AND BACKUP CONTROL

Control input	Research control actuator	Backup control
(1) Fuel flow	Fuel-hydraulic servovalve positions area of modified F100 BOM metering valve; ΔP across valve maintained constant by engine fuel pump	Research metering valve is bypassed and BOM control controls fuel flow
(2) RCVV	Fuel-hydraulic servovalve controls modified BOM RCVV actuator	Servovalve supply shutoff and BOM RCVV command pressures ported to research actuator
(3) Nozzle area	Electrohydraulic servo piston positions area control cable	Research servo input switched to fixed voltage, preselected to give proper nominal area for flight point
(4) CIVV	Electrohydraulic position servo controls modified BOM CIVV actuator	Research servo input switched to analog-computer-generated BOM CIVV schedule
(5) Bleed	Servo-actuated valve connected to bleed port	Servo command voltage switched in to close valve

TABLE II - F100 MULTIVARIABLE CONTROL SENSORS

VARIABLE	SENSOR/SIGNAL CONDITIONER
Ambient	
PO	Strain-gage-type transducer
PT2	Strain-gage-type transducer
TT2	Average of four thermocouples
Controls	
WF	Turbine meter and frequency-to-dc converter
AJ	Potentiometer
CIVV	Potentiometer
RCVV	Potentiometer
BLC	Potentiometer
States	
N1	Magnetic pickup on fan and frequency-to-dc converter
N2	Voltage from alternator and frequency-to-dc converter
PB	Strain-gage-type transducer
PT6	Two-probe pneumatic average for each of duct and core sides; each to strain-gage transducer
Outputs	
FTIT	Average of seven thermocouples using BOM probes
$\Delta P/P2.5$	Electrical average of 24 strain-gage-type transducers
Other	
PLA	Potentiometer
TT2.5	Average of six thermocouples on duct side

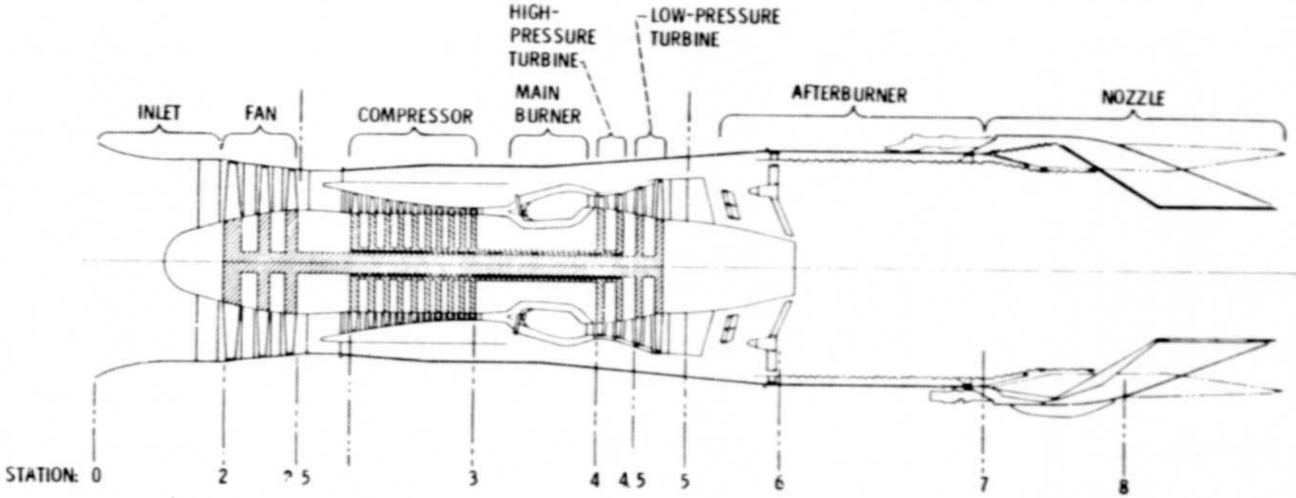

Figure 1. - Schematic representation of F100-PW-100 (3) augmented turbofan engine.

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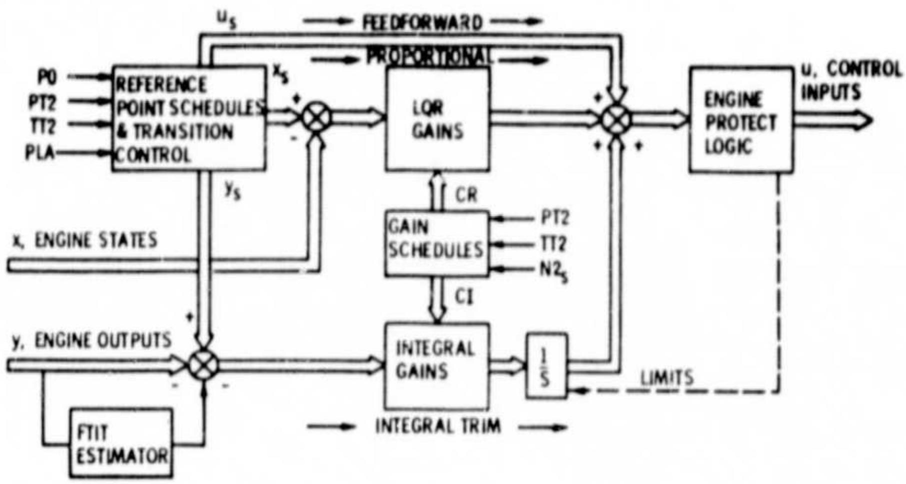


Figure 2. - Structure of F100 multivariable control.

CONTROLS	STATE DEVIATIONS: FAN SPEED	COMPRESSOR SPEED	AFTERBURNER PRESSURE	MAIN BURNER FUEL FLOW	BURNER PRESSURE
MAIN BURNER FUEL FLOW	X	X	X	X	X
EXHAUST NOZZLE AREA	X	X	X	0	0
CIVV	X	0	X	0	0
RCVV	X	X	X	0	0
COMPRESSOR DISCHARGE BLEED FLOW	X	X	0	0	X

X - INDICATES NON-ZERO GAIN.

(a) LQR GAIN MATRIX, CR.

CONTROLS	OUTPUT DEVIATIONS: FAN DISCHARGE ΔP/P	CIVV	RCVV	COMPRESSOR DISCHARGE BLEED FLOW	FAN SPEED	MAX FTIT	MIN PB	MAX PB
MAIN BURNER FUEL FLOW	X	0	0	0	X	X	X	X
EXHAUST NOZZLE AREA	X	0	0	0	X	X	X	X
CIVV	X	X	0	0	X	0	0	0
RCVV	0	0	X	0	0	0	0	0
COMPRESSOR DISCHARGE BLEED FLOW	0	0	0	X	0	0	0	0

UNSWITCHED GAINS SWITCHED GAINS

(b) INTEGRAL CONTROL GAIN MATRIX, CI.

Figure 3. - F100 multivariable control gain matrices.

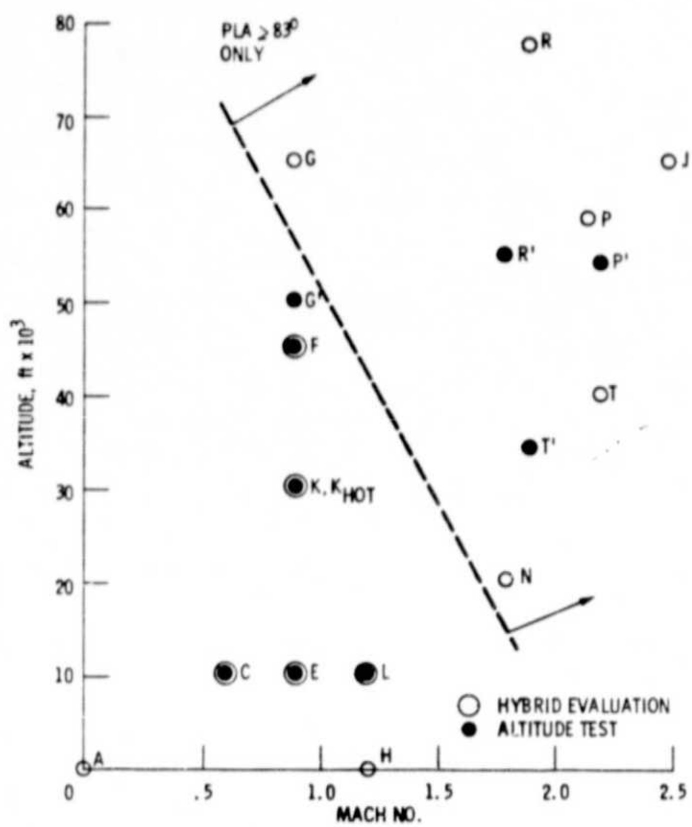


Figure 4. - F100 MVCS hybrid evaluation and altitude test conditions.

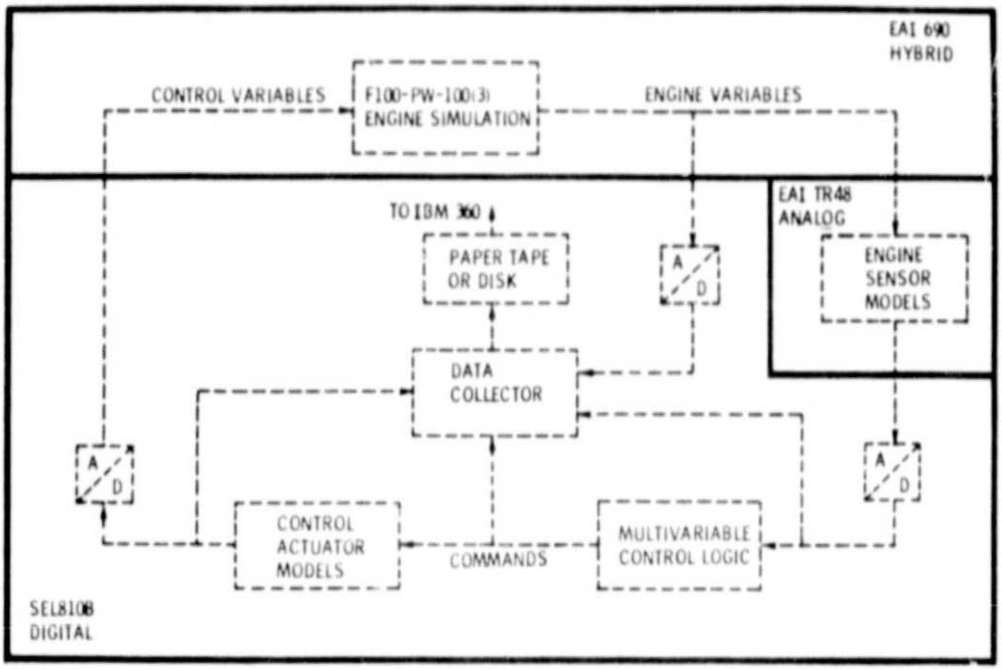


Figure 5. - Real-time hybrid computer evaluation of F100 MVCS control logic.

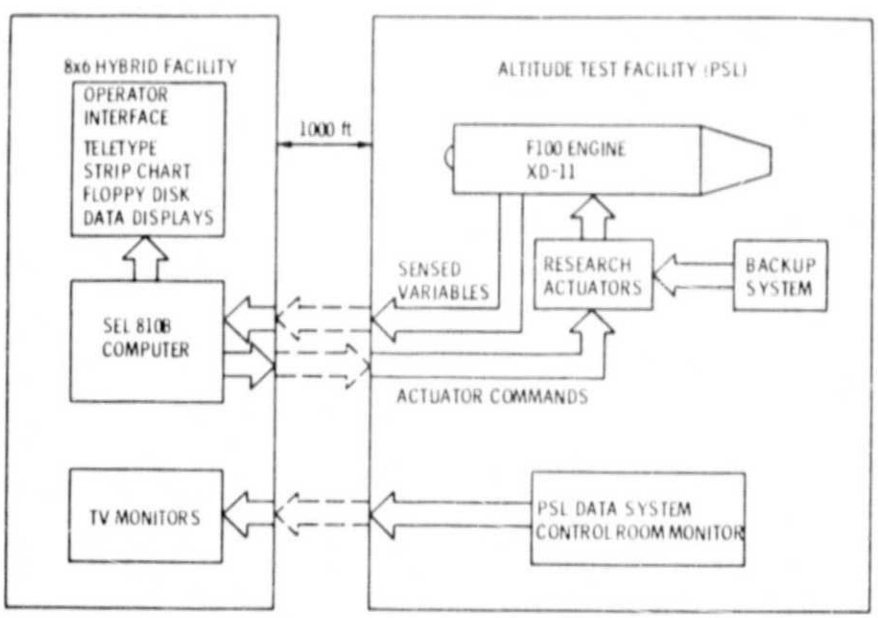
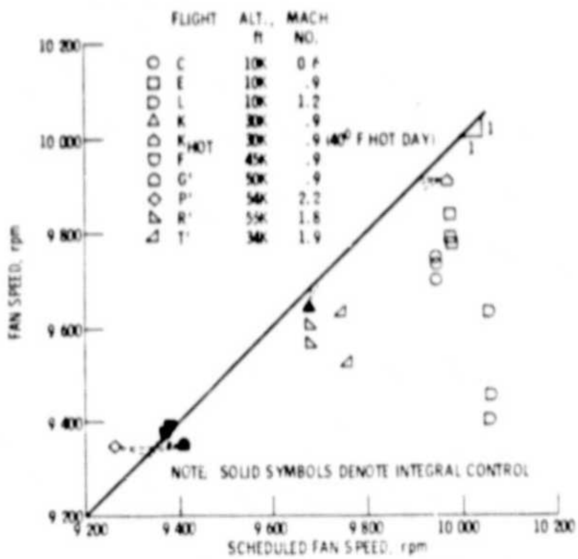
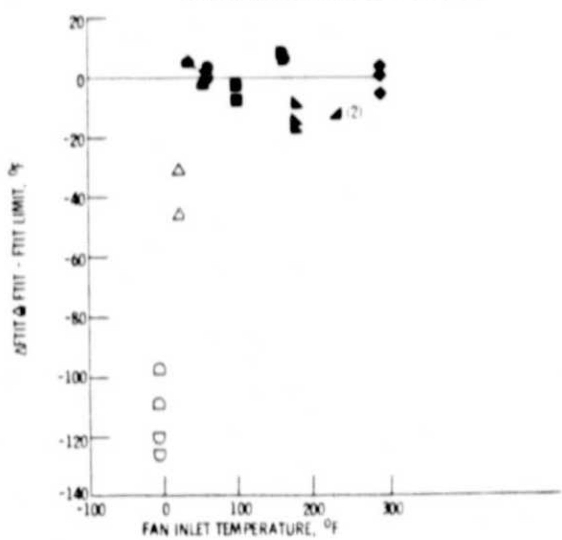


Figure 6. - Control system schematic for altitude tests.

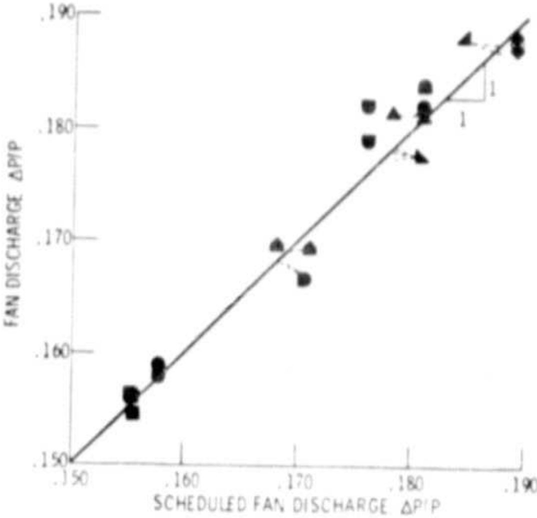


(a) FAN SPEED VS SCHEDULED FAN SPEED.



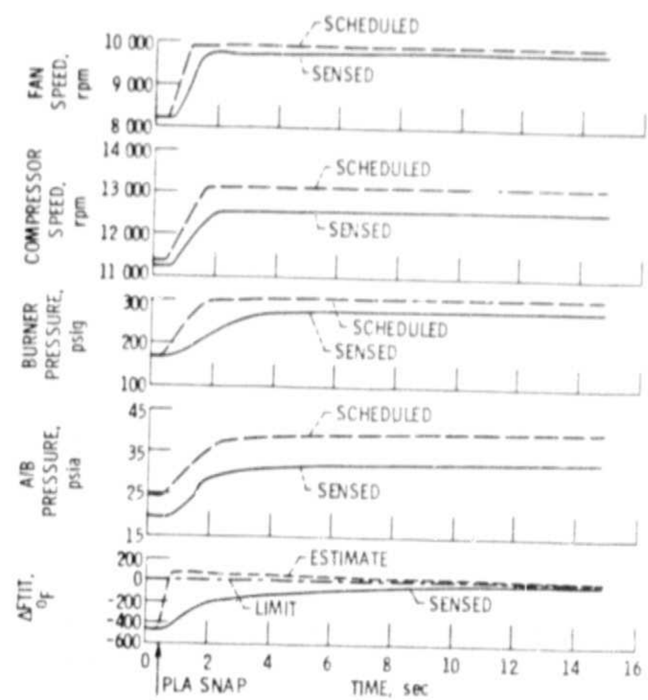
(b) DIFFERENCE BETWEEN FTIT AND FTIT LIMIT VALUE.

Figure 7. - Steady-state performance of F100 multivariable control at intermediate power.



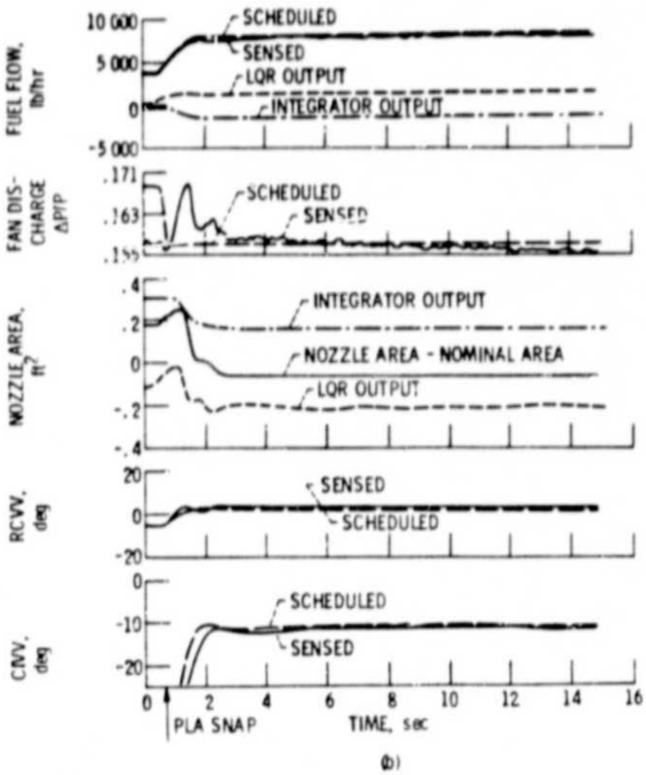
(c) FAN DISCHARGE ΔP/P VS SCHEDULED FAN DISCHARGE ΔP/P.

Figure 7. - Concluded.



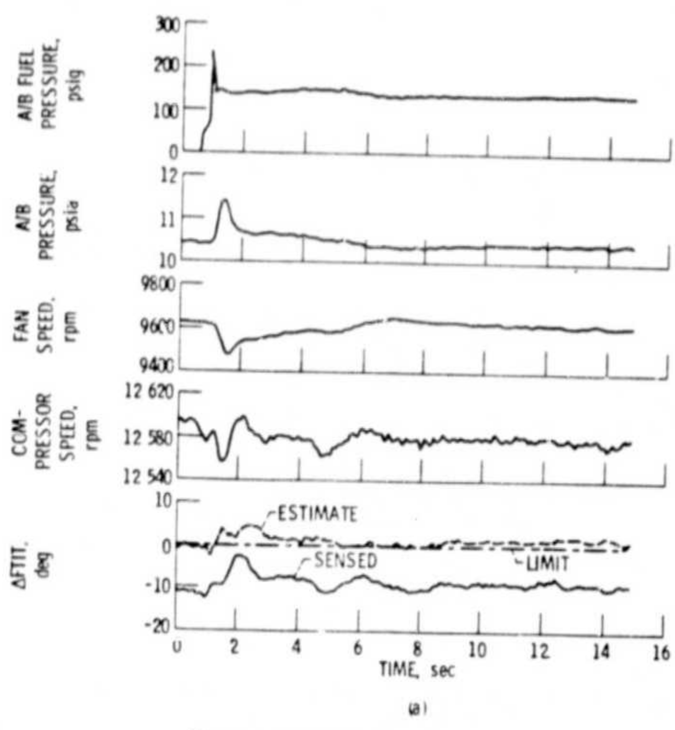
(a)

Figure 8. - Typical F100 multivariable control performance in large PLA transient, altitude = 10 000 ft, Mach 0.6, 50° to 83° PLA snap.



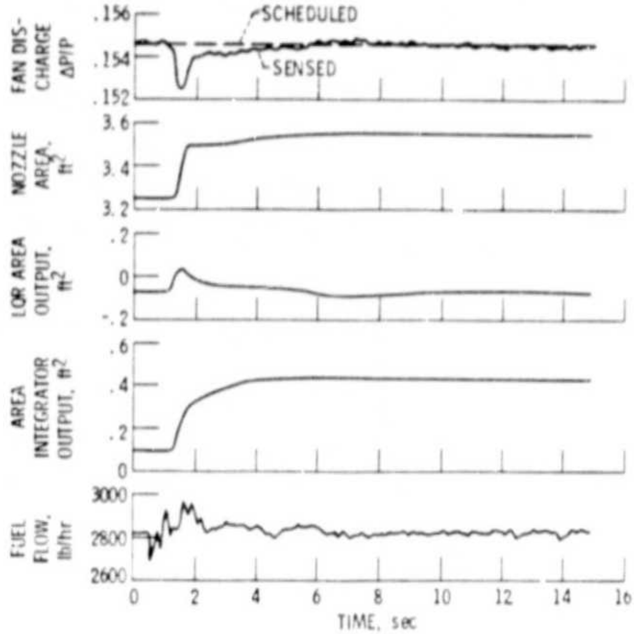
(b)

Figure 8. - Concluded.



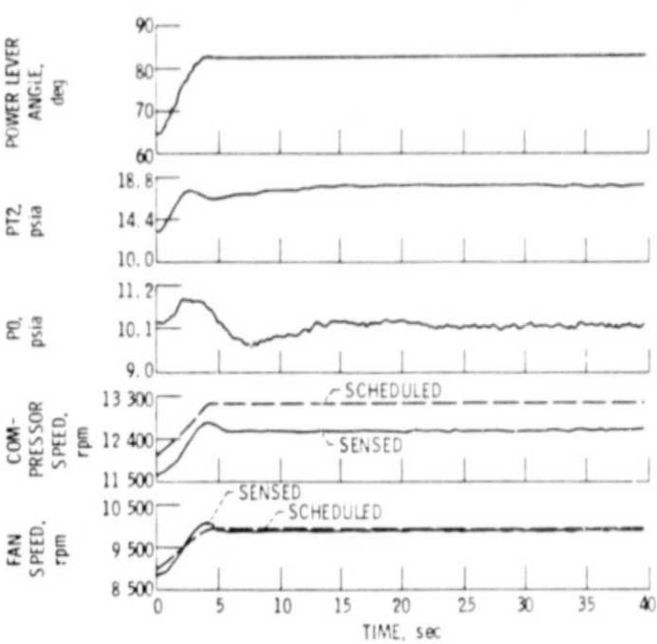
(a)

Figure 9. - Typical afterburner transient at supersonic conditions, altitude = 55 000 ft, Mach 1.8.



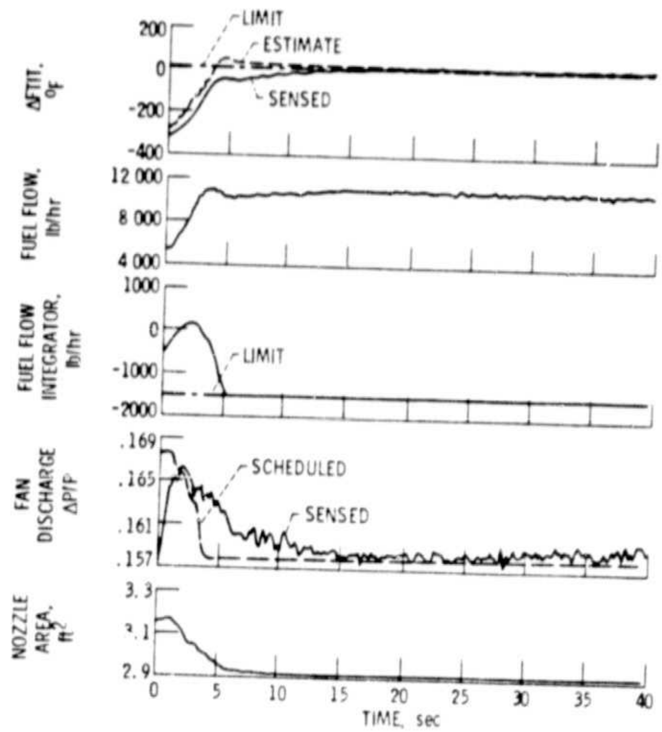
(b)

Figure 9. - Concluded.



(a)

Figure 10. - F100 flight maneuver simulated in altitude facility, altitude = 10 000 ft, initial MN = 0.6, final MN = 0.9, initial TT2 = std. day, final TT2 = 40° F cold day cond.



(b)

Figure 10. - Concluded.

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15. Supplementary Notes

16. Abstract

The F100 Multivariable Control Synthesis (MVCS) program, jointly initiated by the Air Force Aeropropulsion Laboratory and the NASA-Lewis Research Center, was aimed at demonstrating the benefits of LQR synthesis theory in the design of a multivariable engine control system for operation throughout the flight envelope. The advantages of such procedures include: (1) enhanced performance from cross-coupled controls, (2) maximum use of engine variable geometry, and (3) a systematic design procedure that can be applied efficiently to new engine systems. The control system designed, under the MVCS program, for the Pratt & Whitney F100 turbofan engine is described. Basic components of the control include: (1) a reference value generator for deriving a desired equilibrium state and an approximate control vector, (2) a transition model to produce compatible reference point trajectories during gross transients, (3) gain schedules for producing feedback terms appropriate to the flight condition, and (4) integral switching logic to produce acceptable steady-state performance without engine operating limit exceedance. The design philosophy for each component is described and the details of the F100 implementation presented. The engine altitude test phase of the MVCS program is described. A wide variety of test operating points and power transitions were made to test the functional behavior of the control logic. Engine responses are presented and the overall characteristics of multivariable engine control are explored.

17. Key Words (Suggested by Author(s)) Turbofan engines; Airbreathing propulsion; Feedback control; Digital control; Engine testing; Optimal control	18. Distribution Statement Unclassified - unlimited STAR Category 07

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