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Multivariable Control Altitude Demonstration on the F100 Turbofan Engine

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The F100 Multivariable Control Synthesis Program was aimed at demonstrating the benefits of using linear quadratic regulator synthesis theory to design a multivariable turbofan 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. A control system designed for the F100 turbofan engine is described. Basic components of the control include: 1) a reference value generator for deriving desired equilibrium state and approximate control vectors, 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. The tests verified proper steady-state and transient control performance over a wide range of operating conditions. Engine responses are presented and the overall characteristics of multivariable engine control are explored.

Nomenclature

CI	= integral gain matrix
CIVV	= fan inlet guide vane angle, deg
CR	= linear quadratic regulator gain matrix
FTIT	= fan turbine inlet temperature, °F
$FTIT_{lim}$	= FTIT limit, °F
ΔFTIT	= $FTIT - FTIT_{lim}$, °F
N1	= fan speed, rpm
N2	= compressor speed, rpm
PB	= main burner pressure, psia
PLA	= power lever angle, deg
ΔP/P 2.5	= fan discharge Mach number parameter; fan discharge ΔP/P
$PS2.5_{core}$	= 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
P0	= 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, °F
TT2.5	= fan discharge temperature in duct, °F
u	= control vector
u_S	= scheduled control vector
WF	= main burner fuel flow, lb/h
WFC	= main burner fuel flow command, lb/h
x	= state vector
x_S	= scheduled state vector
y	= output vector
y_S	= scheduled output vector

Introduction

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 objective of the F100 Multivariable Control Synthesis (MVCS) Program was to demonstrate the benefits of using 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. In phase one, the multivariable control (MVC) logic was designed and evaluated on a digital simulation of the F100 engine. As a part of this phase, a set of linear operating point models was generated and control criteria were defined, upon which the LQR design could be based. In phase two, the multivariable logic was programmed on a control computer and evaluated in detail as it controlled a real time F100 hybrid simulation. In phase three, an actual F100 engine was controlled by the MVC logic in the NASA Lewis Propulsion

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Systems Laboratory (PSL) altitude facility. The results of phases one and two have been documented in Refs. 1-8. This paper describes the results of the phase three engine altitude tests in addition to reviewing the overall program.

There have been a number of past efforts to apply LQR theory in designing multivariable engine controls.[9-12] 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 presents a review of the MVCS program. It first discusses the F100 engine, the control design criteria and the MVC logic structure. Following that is 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 is covered followed by a brief review of the hybrid computer evaluation. Finally, representative steady-state and transient altitude tests results are presented and discussed.

F100 Multivariable Control Logic Design

The F100-PW-100 engine, used in the F100 MVCS program, is shown in Fig. 1. The engine is a twin-spool low-bypass-ratio afterburning turbofan. It has five controlled variables: main burner fuel flow, exhaust nozzle area, fan inlet guide vanes, compressor vane angles, and afterburner fuel flow. 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 are documented in 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 control criteria were translated into quadratic performance index specification for use in the LQR design process. The details of the design are contained in Ref. 2. The design process and resulting multivariable control structure will be briefly reviewed here. Linear state variable engine models were generated from the 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 was described in terms of its control, state, and output vectors. The control vector u for the F100 engine controlled in the MVCS program consisted of commanded fuel flow, exhaust nozzle area, compressor variable vane angle, fan inlet guide vane angle, and 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 fan and compressor speeds, main burner pressure, afterburner inlet pressure, and main burner fuel flow. The output vector y consisted of the variables which the five control inputs regulate to establish a steady-state engine operating point. They were: fan turbine inlet temperature, fan discharge Mach number parameter, fan speed, main burner pressure, compressor variable vane angle, fan inlet guide vane angle, and compressor exit bleed flow.

A control was designed, using the above state-variable model description, having basically a proportional-plus-integral, model-following structure with 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 power lever angle (PLA) and ambient variables P0, 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

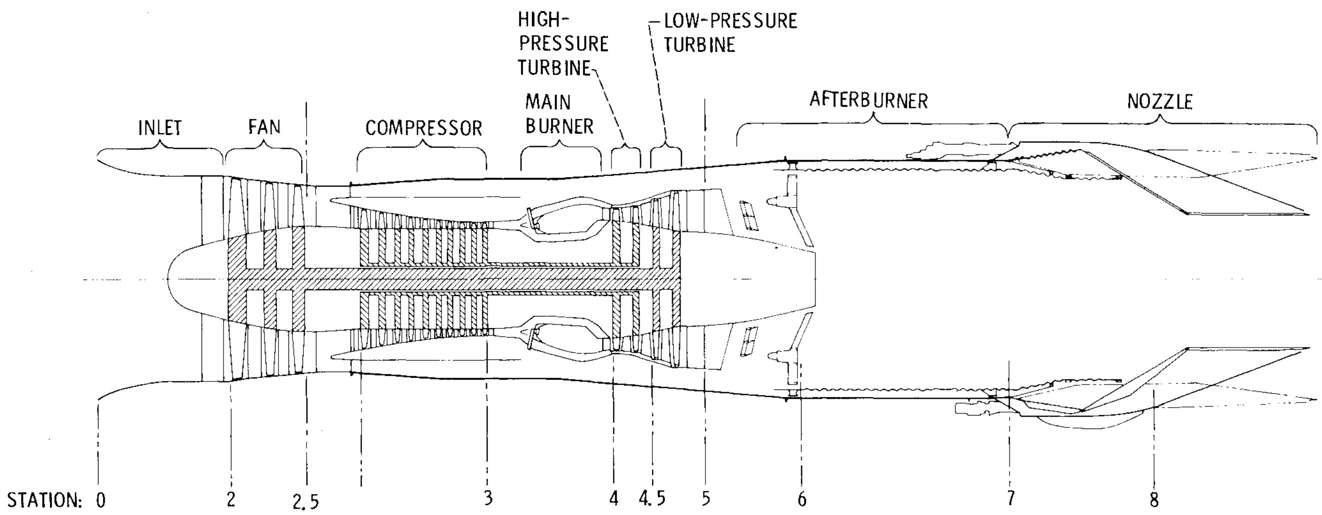

Fig. 1 Schematic representation of F100-PW-100 (3) augmented turbofan engine.

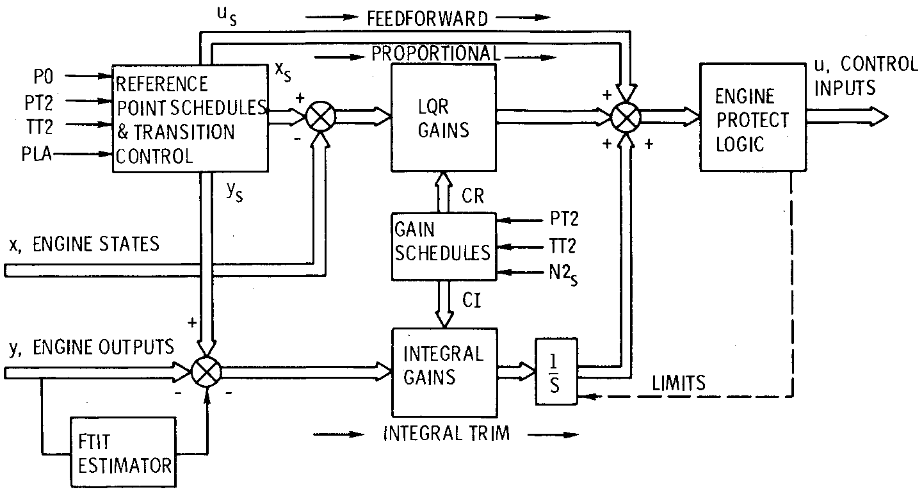

Fig. 2 Structure of F100 multivariable control (see Nomenclature for symbol definitions).

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 are scheduled as functions of engine face density and scheduled compressor speed.

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 fan turbine inlet temperature (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 deg).

In order to simplify the scheduling of the LQR and integral gains, many of the possible state-control couplings were set to zero by using a sensitivity technique. In addition, approximately half of the nonzero gains were constants. The integral trims are fed by the seven output errors, only five of which can be active at one time to set the steady-state match point of the engine. Four of the seven output errors are integrated at all times. Fan discharge Mach number ($\Delta P/P2.5$) is always trimmed to its schedule to set the fan operating point. Also, compressor variable vane angle (RCVV) and fan inlet guide vane angle (CIVV) are trimmed to be on their schedules and the bleed integrator adjusts to close the bleed in steady-state. The remaining three output errors 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 trimming on burner pressure error. Similarly, if an FTIT limit is reached, the FTIT error is switched in to allow the integrator to trim fuel flow and area to accommodate the temperature limit. An FTIT limit takes priority over a burner pressure limit.

The MVC logic was evaluated 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 then programmed on a control computer for use in subsequent hybrid and engine tests.

Computer Implementation and Evaluation Procedures

The MVC logic shown in Fig. 2 was implemented on an 810B control minicomputer.[13] The 810B has specifications representative of a flight-type computer, having 24K of 16-bit core memory, a 0.75 μs cycle time and a 50 μs digitizing rate. To achieve a desired 10 ms update interval, fixed-point assembly language programming was used. A feature on the 810B called INFORM[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 ms.

Figure 3 is a plot of the various Mach number vs 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 do not encompass as wide a range as the hybrid test points.

Steady-state operating line data were taken at all test points, from idle (PLA = 20 deg) to intermediate (PLA = 83 deg). However, in certain ranges, airflow and/or burner pressure limits in the control limit the range of steady-state operation to near intermediate operation. Transient control performance was evaluated by subjecting the control to small three degree PLA steps, to large PLA snaps and chops, to random, cyclic PLA motion and to afterburner lights. In addition, simulated flight maneuvers were performed, both on the hybrid and in engine tests.

Summary of Real-Time Hybrid Evaluation

The MVC logic was tested on a real-time F100 hybrid simulation.[15] Real-time capability was necessary to adequately check out control computer implementation aspects. The 810B digital computer, besides performing MVC logic calculations, was also used to simulate control actuators.

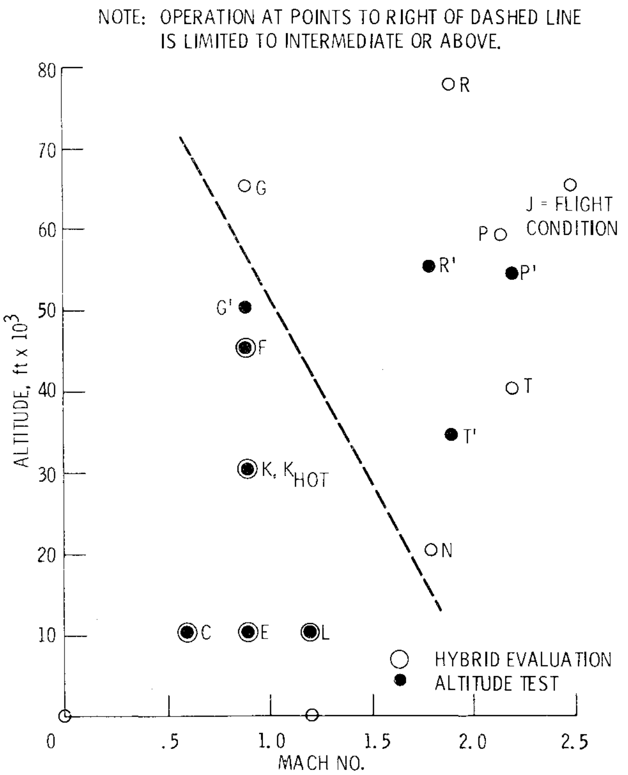

Fig. 3 F100 MVCS hybrid evaluation and altitude test conditions.

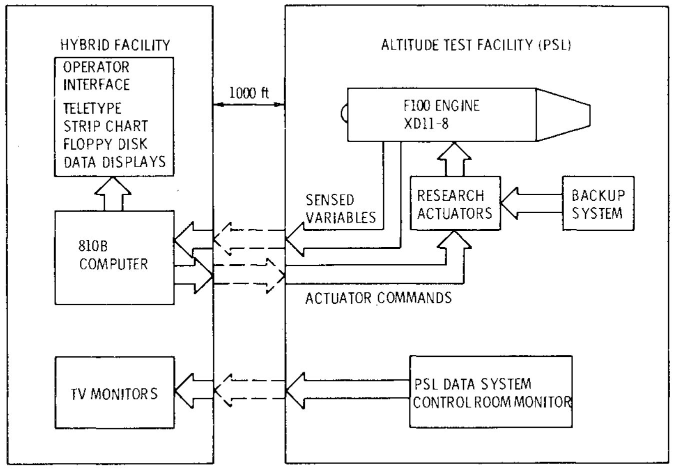

Fig. 4 Control system schematic for altitude tests.

In addition, the computer recorded both transient and steady-state data which were 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 afterburner lights was proper. Certain control logic problems were corrected and programming 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 ms. Thus, the cycle time was safely increased from 10 to 12 ms to ease programming 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 Lewis PSL altitude facility. Figure 4 shows a system diagram describing the test setup. F100 engine number XD11-8 was located in PSL but the 810B computer had to be stationed some 1000 ft away in the hybrid computation center. A remote interface unit was located in the PSL control room, receiving five control command signals from the 810B and sending back 24 sensed engine and ambient variables. All signals were 0-10 V and transmitted over twisted pair lines with analog-to-digital and digital-to-analog conversion performed at the computer end.

Five research actuators having electrical inputs were 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. 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.

Variables sensed for multivariable control were engine control, state and output variables as well as P0, PT2 and PLA. Temperature TT2.5 was also sensed, as the MVC used it in calculating the RCVV schedule.

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 was 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 was 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 810B computer operator or by the engine operator put the engine control in the backup mode in preparation for engine shutdown.

Altitude Test Results

The purpose of the altitude tests 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 Fig. 3. At all points, 186 steady-state control-related variables were recorded by the 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 810B 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 test, 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 MVC logic. Also, total and static pressure probe data at station 2.5 were recorded and used to synthesize ΔP/P2.5. The MVC logic was run open loop during these tests 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 mode switching 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 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 ΔP/P2.5 schedule in the MVC was based on theoretical values from the deck. It was found that actual sensed ΔP/P2.5 values were higher than theoretical for the same corrected airflow. Thus, the MVC ΔP/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 all flight conditions. 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 ΔP/P2.5. 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. This could be corrected by further schedule refinements.

Figure 5 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: fan speed, FTIT, and ΔP/P2.5. Fan speed is shown as a function of its scheduled value in Fig. 5a. 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 was not, since transient behavior at L was quite good.

Figure 5b 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

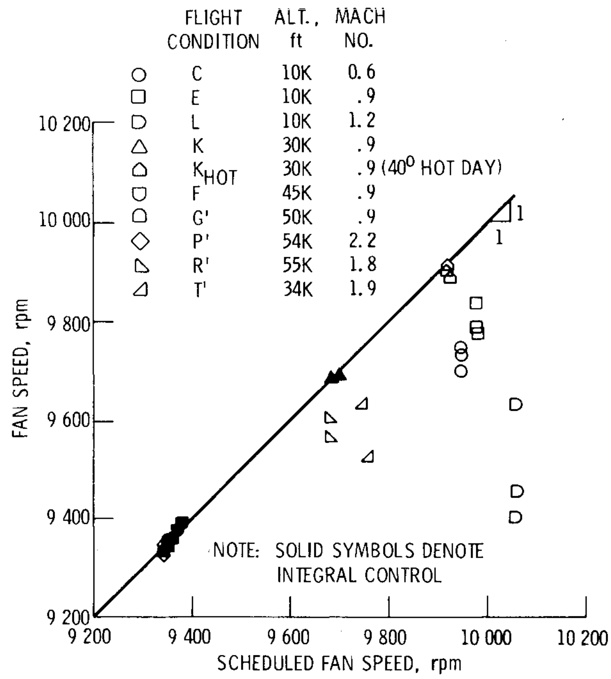

Fig. 5a Fan speed vs scheduled fan speed.

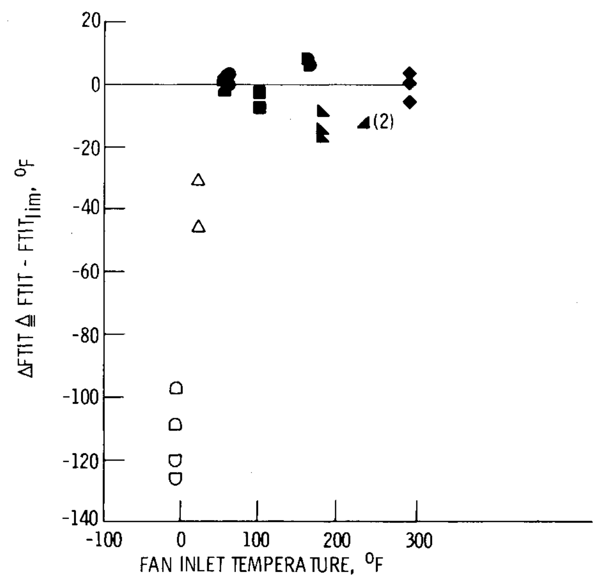

Fig. 5b Difference between FTIT and FTIT limit value.

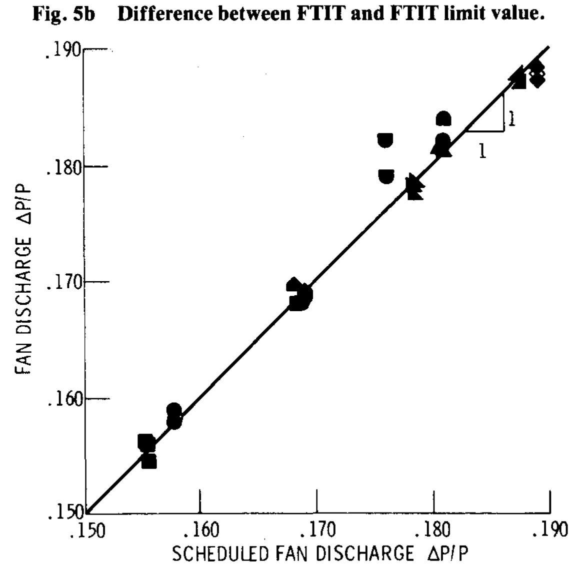

Fig. 5c Fan discharge ΔP/P vs scheduled fan discharge ΔP/P.

Fig. 5 Steady-state performance of F100 multivariable control at intermediate power.

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 tradeoff 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 Fig. 5b, 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 standard F100 control.

Figure 5c shows the third primary scheduled variable, $\Delta P/P2.5$, plotted against its scheduled value. The parameter $\Delta P/P2.5$ was computed using the equation

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

Each total and static pressure 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 $\Delta P/P2.5$ 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 $\Delta P/P2.5$ on schedule. Errors in Fig. 5c are generally less than 1% except for point G′ and point F. At G′, the exhaust nozzle was commanded to its minimum area but remained partly open due to hysteresis in the nozzle linkage. This caused $\Delta P/P2.5$ 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 $\Delta P/P2.5$ 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 Fig. 3. Large PLA transients (idle to 83 deg 50 to 83 deg, 83 deg to idle, etc.) were run at all points where airflow schedules allowed PLA operation below 83 deg. 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 deg/s. Repeatable PLA transient inputs were assured by the use of a programmable 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.

Figure 6 shows the response of the engine under multivariable control to a PLA snap from 50 to 83 deg 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

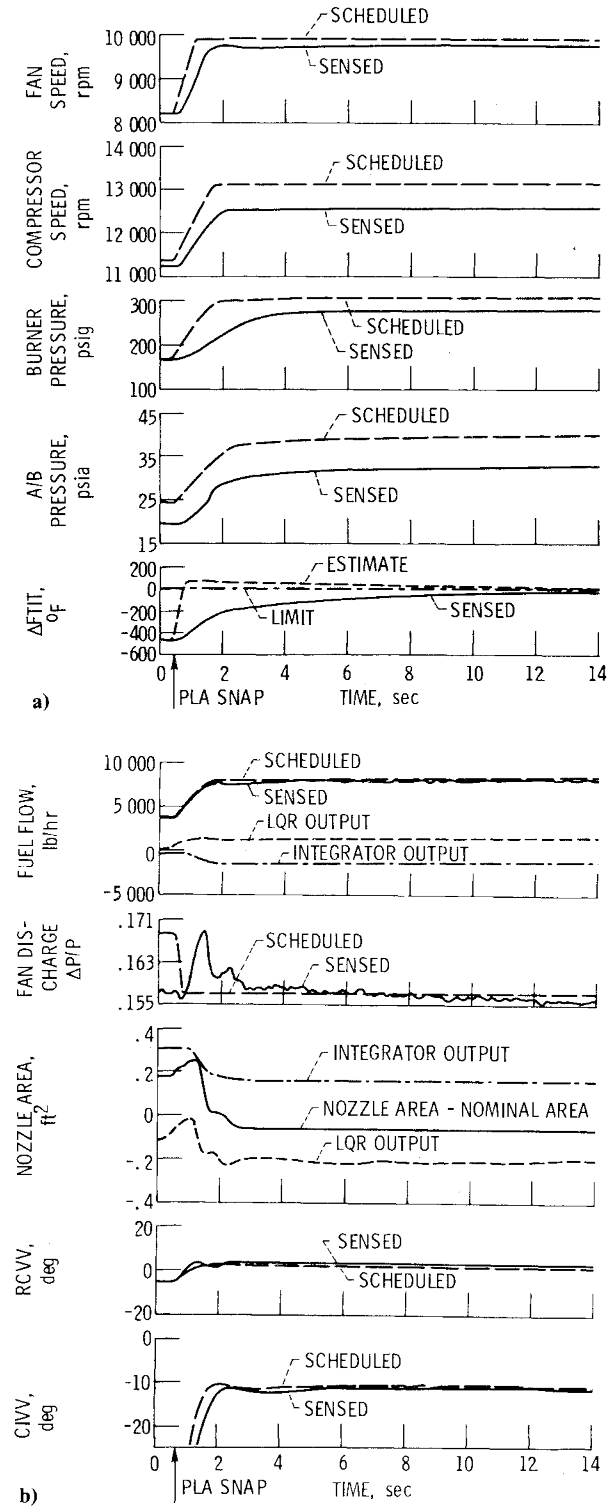

Fig. 6 Typical F100 multivariable control performance in large PLA transient: altitude = 10,000 ft, Mach 0.6, 50-83 deg PLA snap.

trim, regulator and integrator gain scheduling as a function of compressor speed, estimation of FTIT and trimming of nozzle area to set $\Delta P/P2.5$. In Fig. 6a, it can be seen that before the PLA snap occurred at 0.5 s, 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 Fig. 6a, the FTIT estimate can be seen to reach the FTIT

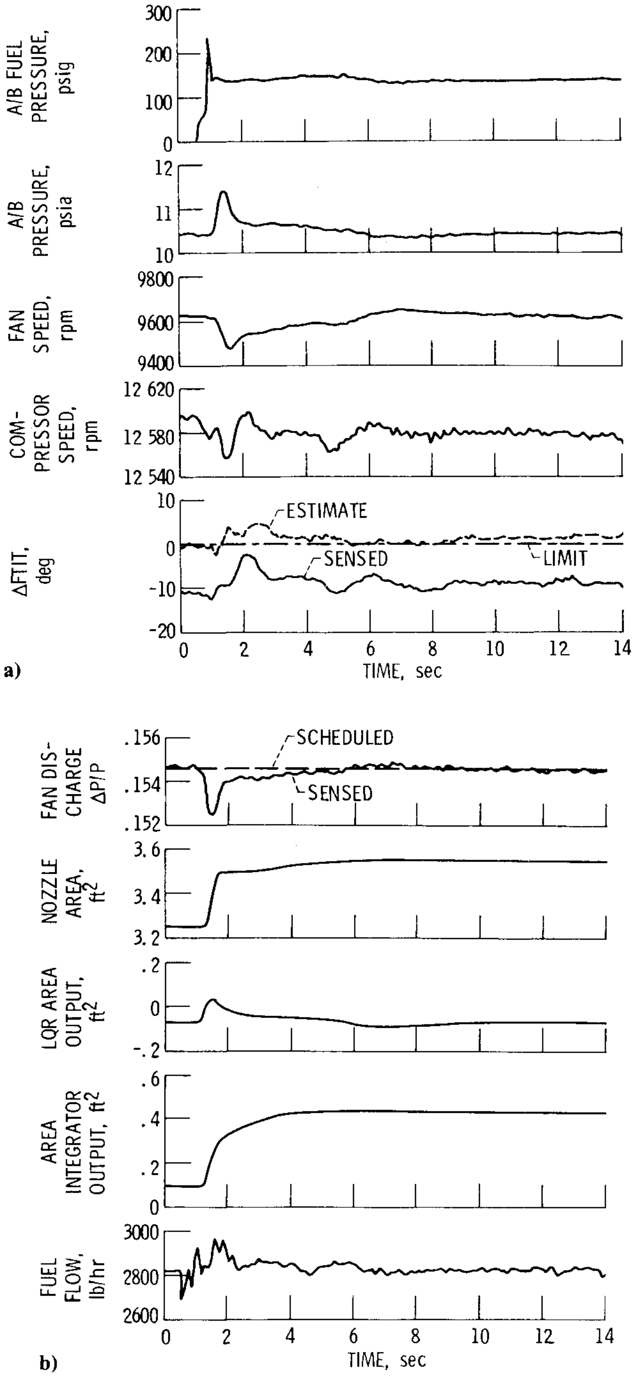

Fig. 7 Typical afterburner transient at supersonic conditions: altitude = 50,000 ft., Mach 1.8.

limit shortly before time equals 1 s. At this point, the fuel flow integrator input error was switched from fan speed to FTIT, and consequently, fan speed fell about 100 rpm below its scheduled value in steady-state.

In Fig. 6b, 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 within 500 lb/h of 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 about 1500 lb/h downtrim which reduced fuel flow down and away from its scheduled value. This caused FTIT and its estimate to decrease so that, in the steady-state, FTIT was on its limit.

The nozzle area moved both to trim fan discharge $\Delta P/P$ to its schedule and to reduce state variable errors during the transient. Figure 6b shows that before the PLA snap, nozzle area was on a scheduled maximum area limit; consequently, $\Delta P/P2.5$ was lower than its scheduled value. This area limit was introduced during the hybrid evalution to insure stability for PLA's below about 50 deg. 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 s decreased nozzle area to null out a negative error in afterburner pressure. The area integrator trim reduced to close the nozzle and cause $\Delta P/P2.5$ to be on schedule at PLA = 83 deg. The last two traces in Fig. 6b 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 the CIVV's on schedule. Large transient responses for other flight points were qualitatively similar to the responses shown in Fig. 6. 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 a WF/PB schedule programmed as part of the engine protect logic (see Fig. 2) to inadvertently limit fuel flow during these transients.

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. Hence, the afterburner pulse acted as a disturbance to the system. Figure 7 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 time equals 0.5 s as shown by the rise in afterburner 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 (± 20 rpm). The FTIT estimate followed the sensed value with an offest of about 8 deg. During the light, the estimate was held within 4 deg of the limit through integral trim on fuel flow, thus causing the sensed value of FTIT to remain below the limit.

Figure 7b shows that fan speed error (and to some extent afterburner 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, thus bringing $\Delta P/P$ back on schedule within 3 s. The net result was that afterburner pressure was attenuated as desired within about 3 s. 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 ft, Mach 0.9. Here, the sensed value of $\Delta P/P2.5$ did not change sufficiently to allow nozzle trim control to suppress the disturbance. Further analysis of sensed $\Delta P/P2.5$ data in this region is warranted.

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, accelerations, and decelerations and the multivariable control performed well in all tests. Figure 8 shows one representative maneuver, an acceleration at a constant 10,000 ft altitude. Actual pressure altitude varied from 8500 to 11,000 ft during

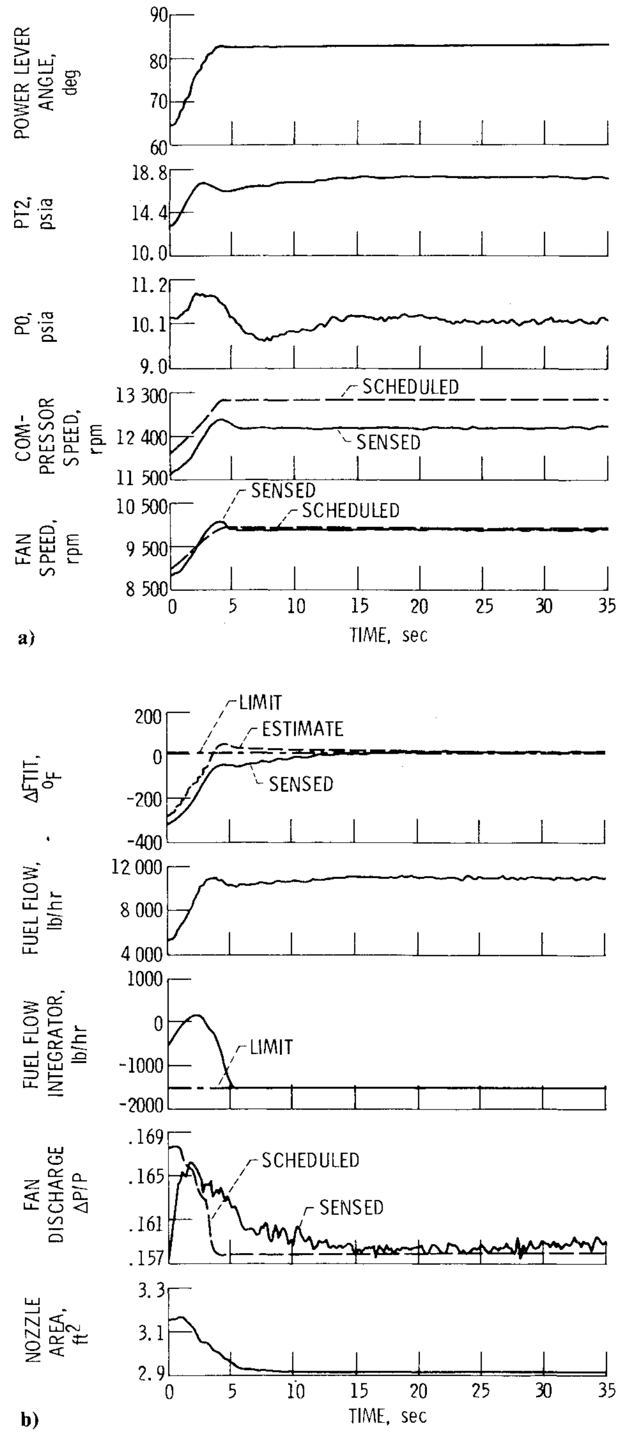

Fig. 8 F100 flight maneuver simulated in altitude facility: altitude = 10,000 ft, initial Mach number = 0.6, final Mach number = 0.9, initial TT2 = standard day, final TT2 = 40°F cold day conditions.

the transient and Mach number increased from 0.6 to 0.9 in about 15 s. Inlet temperature could not 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 deg in about 5 s. Figure 8a shows compressor speed making a controlled transition with a slight 300 rpm overshoot. Fan speed tracked its schedule with acceptable overshoot of about 200 rpm. Figure 8b shows that at about 4 s, 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, Fig. 8b 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 MVC 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 EPR (engine pressure ratio) as the variable which determines the fan operating line. The multivariable control's 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. With this control, 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

A control system has been designed for a turbofan engine using design methods based on a linear quadratic regulator. The control logic was implemented on a digital computer, evaluated on digital and hybrid engine simulations, and finally used to successfully control an F100 engine in an altitude test facility. Based on these results, it is concluded that the linear quadratic regulator design approach has much to offer in the design of controls for next-generation air-breathing engines.

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