F100 MULTIVARIABLE CONTROL SYNTHESIS PROGRAM: A REVIEW OF FULL-SCALE ENGINE ALTITUDE TESTS

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SUMMARY

The F100 Multivariable Control Synthesis (MVCS) program was conducted to demonstrate the benefits of linear quadratic regulator synthesis methods in designing a multivariable engine control capable of operating an engine throughout its flight envelope. The program, jointly sponsored by the Air Force Aero Propulsion Laboratory and the NASA Lewis Research Center, encompassed the design, real-time hybrid computer evaluation and full-scale engine testing of a multivariable control for an F100 engine.

This paper reviews the entire MVCS program, with particular emphasis on engine tests conducted in the NASA Lewis Propulsion Systems Laboratory altitude facility. The multivariable control has basically a proportional-plus-integral, model-following structure with gains scheduled as functions of flight condition. The multivariable control logic design is described, along with control computer implementation aspects.

Altitude tests demonstrated that the multivariable control logic could control an engine over a wide range of test conditions. Representative transient responses are presented to demonstrate engine behavior and the functioning of the control logic.

INTRODUCTION

The F100 Multivariable Control Synthesis (MVCS) program was jointly initiated by the Air Force Aero Propulsion Laboratory (AFAPL) and the NASA Lewis Research Center. 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 1 was to design the control logic based on a set of linear operating-point models and to evaluate the control on a digital F100 engine simulation. Systems Control, Inc. (Vt.) (SCI) and Pratt & 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 to evaluate it on a digital F100 simulation provided by P&W GPD. The goal of phase 2 was to evaluate the control by programming it on a control computer and controlling a real-time F100 hybrid simulation. It was NASA Lewis' responsibility to program the hybrid simulation facility. Assuming successful completion of phases 1 and 2, the goal of phase 3 was to demonstrate the multivariable control of an F100 engine in the NASA Lewis Propulsion Systems Laboratory (PSL) altitude facility.

All three phases have now been successfully completed. The results of phases 1 and 2 have been documented in references 1 to 8. This paper describes the results of the phase-3 engine altitude tests conducted by NASA Lewis.

F100 MULTIVARIABLE CONTROL LOGIC DESIGN

The Pratt & Whitney F100-PW-100 engine used in the F100 MVCS program is shown in figure 1. 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. Although it is 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 was 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 that minimum burner pressure limits be accommodated and that maximum and minimum airflow requirements be adhered to at certain flight conditions. The control must insure that 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 level angle inputs. Finally, it must control the engine accurately during flight maneuvers and accommodate disturbances such as afterburner lights.

These 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 the resulting multivariable control structure will be breifly 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 linear model is described in terms of its control, state, and output vectors. The variables used by the MVC are shown in figure 1.

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 output vector shown consists of the variables that the five control inputs regulate to establish the steady-state engine operating point.

Using this 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 states, outputs, and controls as functions of power level angle (PLA) and the 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 essentially the "model" that 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 by 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 by 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 the steady state. Selection of the outputs to be trimmed is performed by the engine protect logic and is described later. Contributions from the three control paths are finally summed to produce the five controller outputs. Because of 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 that 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 the fan turbine inlet temperature (FTIT) is slow. Figure 2 shows an FTIT estimator block that 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 that is used to limit fuel flow at intermediate power (PLA = 83^{o}).

Proper steady-state engine operation is obtained through the action of the integral trims. Fan-discharge $\Delta P/P$ (fan discharge Mach number parameter) is trimmed to its schedule to set the fan operating point. Also, rear compressor variable vanes (RCVV) and compressor inlet variable vanes (CIVV) are trimmed to be on their schedules, and the bleed integrator adjusts to close 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 in order to accommodate the limit. An FTIT limit takes priority over a burner pressure limit.

SYSTEM CONFIGURATION FOR ALTITUDE TESTS

Altitude testing of the F100 multivariable control logic was performed in the NASA Lewis PSL altitude facility. Figure 3 shows a system diagram describing the test setup. F100 engine XD11-8 was located in the PSL, but the SEL810B control computer had to be stationed some 1000 feet away in the hybrid computation center. A remote interface unit, located in the PSL control room, received five control command signals from the SEL and sent 24 sensed engine and ambient variables to the SEL. All signals were zero to 10 volts and were 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 had 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. 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 1 only) continued to be controlled normally by the standard F100 control.

The variables sensed by the 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.

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 the 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 television monitor facilitated communications.

During a typical altitude test of the multivariable control, the engine was 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 and generated 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 the integrators 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 SEL computer operator or by the engine operator put the engine control in backup mode in preparation for engine shutdown.

COMPUTER IMPLEMENTATION

The MVC logic shown in figure 2 was implemented on the Lewis SEL810B control minicomputer. The SEL810B has specifications representing a current flight-type computer with a 24K 16-bit core memory and a 0.75-microsecond cycle time. Other characteristics of the machine are as follows:

(1) Two 16-bit accumulators
(2) Memory specifications -
    24K magnetic core
    0.75-μsec cycle time
    Expandable to 32K
(3) Two's-complement, fixed-point multiply and divide -
    1.5-μsec add time
    4.5-μsec multiply time
    8.25-μsec divide time
(4) Double-precision arithmetic
(5) Infinite indirect addressing
(6) Infinite indexing
(7) Direct memory access
(8) 28-Levels of vectored priority interrupt
(9) 66 Total instructions

Shown in figure 4 is a control timing diagram of the MVC logic used in the PSL tests. In the 12-millisecond update time of the control, the computer performs the control-algorithm control sequencing, sensor-actuator-output failure checks, and research data input and output. The control algorithm and the control sequencing operation were discussed previously.

The sensor failure checks performed by the SEL810B consist of a simple min-max limit check on all sensors and either a delta check or a set-point deviation check. The delta check compares the present value of the sensor to the past value in order to detect erratic signal behavior. The set-point deviation check uses the multivariable control's own set-point schedules and transition logic to generate a modeled value for the sensor. This modeled value is compared with the actual sensed value to determine if the sensor is behaving in an abnormal manner. The actuator checks are made by doing nonlinear simulations for the actuator dynamics in the control computer. The outputs of the simulations are compared with the actuator feedback signals to verify that the actuators are behaving within normal bounds. For the sensor and actuator checks the failure must be present during four consecutive update intervals for the signal to be declared bad. The output checks verify that the difference between the current output and the past output is within some specified tolerance. This allows detection of a possible failure in the arithmetic unit, undetected shift overflows, etc. This check had to be invalid for only one update interval in order to be considered a failure.

The research data input and output functions are performed during the computer's spare time. This spare time occurs when the control is waiting for the interval timer interrupt after it has finished calculating the update of the control and during the time that the digitizer is sampling the input data. In this spare time an input-output program called INFORM (ref. 9) is run to generate necessary research data. These data can be either transient or steady state. The steady-state data are output in engineering units to a floppy disk. or to the teletype. The transient data can also be output to the disk for later processing or to brush recorders for dynamic real-time data evaluation and debugging. The data output to the floppy disk can be transmitted to a central computer for further processing, plotting, etc.

Table I shows the control's memory requirements. The total amount of software necessary to perform the MVC algorithm is 7787 words. This includes 4091 words of code and 2488 words of schedule and matrix data. The sensor-actuator-output checks add another 1743 words. Therefore a total of approximately 9500 words is necessary to the complete MVC task for the F100 engine. Furthermore the general-purpose input-output and debug package (INFORM) adds 5694 words to the total controls package.

ALTITUDE TEST RESULTS

Transient and steady-state performance of the MVC was demonstrated by testing at six subsonic and four supersonic points. These points were selected to represent the operating envelope of the F100 engine. Steady-state operating line data were taken at all points. In certain regions, airflow and/or burner pressure limits restricted the range of steady-state operation to be close to intermediate (PLA = 83°). A total of 309 individual steady-state data 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 that 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 midpower at some flight conditions, but these could be corrected by further schedule refinements.

Transient performance of the multivariable control was assessed at all flight points. Large PLA transients (idle to 83°, 50° to 83°, 83° to idle, etc.) were run at all points where 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 degrees per second. 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 5 shows the response of the engine under multivariable control to a PLA snap from 50° to 83° at 10 000 feet, 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-discharge $\Delta P/P$. It can be seen that, before the PLA snap occurred at 0.5 second, 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 were 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. The FTIT estimate reached the FTIT limit shortly before 1 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.

Fuel flow and the three components that, added together, produced its command are also plotted in figure 5: 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 the integrator introduced downtrim, which reduced fuel flow below its scheduled value. This caused the FTIT estimate to decrease so that in the steady state FTIT was at 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 5 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 5 show the RCVV's, which held quite closely to schedule, and the CIVV's. CIVV's lagged behind the CIVV schedule because of a contribution from the LQR that 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 5. Exceptions were at high-altitude, low-Mach-number points (45 000 and 50 000 ft at 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 programmed as part of the engine protect logic (fig. 2) to inadvertently limit fuel flow during these accelerations.

Afterburner lights were performed at all flight points to test the ability of the multivariable control to attenuate external disturbances. Feedforward logic is used in the standard F100 control in order to reduce the effect of an afterburner ignition pulse. Control of the afterburner was specifically excluded from the MVC design. Feedforward logic was not used by the MVC; hence the afterburner pulse acted as a disturbance to the system. Figure 6 shows the results of an afterburner light at a high-altitude supersonic condition (55 000 ft at 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 0.5 second, 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. The FTIT estimate followed the sensed value with an offset of about 8 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 6 also 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 samt 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 afterburner 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 at 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, accelerations, and decelerations; and the multivariable control performed well in all tests. Figure 7 shows one representative maneuver, an acceleration at a constant 10 000-foot altitude. Actual pressure altitude varied from about 8500 to 11 000 feet during the transient, and Mach number increased from 0.6 to 0.9 in about 15 seconds. Inlet temperature could not be changed, so the initial condition was standard day and the final condition was 40 degrees F colder than standard day. The PLA was increased manually from 65° to 83° in about 5 seconds. Figure 7 shows compressor speed making a controlled transition with a slight overshoot. Fan speed tracked its schedule with a slight overshoot. Figure 7(b) shows that at about 4 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 degrees F. Finally, figure 7(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.

CONCLUSIONS

The objective of the F100 Multivariable Control Synthesis program was to demonstrate that a control that would operate a modern turbofan engine over its flight envelope could be designed by using linear quadratic regulator (LQR) design methods.

The multivariable control was tested while controlling an F100 engine at 10 flight points in an altitude facility. The control exhibited good steady-state performance, that is, the ability to hold engine trim variables on schedule at all flight points.

Good transient performance was demonstrated at almost all flight points. 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. 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.

Sensor and actuator failure detection logic was incorporated into the control for altitude tests and functioned well in conjunction with a backup control. All the control logic was programmed in 9.5K of core, using a 12-millisecond 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. The systematic, structured approach used in the F100 MVC design has much to offer in the design of controls for next-generation airbreathing engines.

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TABLE 1. - CORE REQUIREMENTS FOR MVC PROGRAM

MVC Control Algorithm:	
FTIT Estimator	309
Set Point Schedules	618
Gain Control	834
Transition Control	632
Integral Control	783
LQR Control	347
Engine Protection	198
Function Generation	370
Total	4091
Block Data:	
Schedules	1752
Matrices	736
Total	2488
Failure Detection Logic:	
Sensor Checks	1169
Actuator and Output Checks	574
Total	1743
Control Executive	1208
Grand Total	9530
General-Purpose Input-Output and Debug	5694

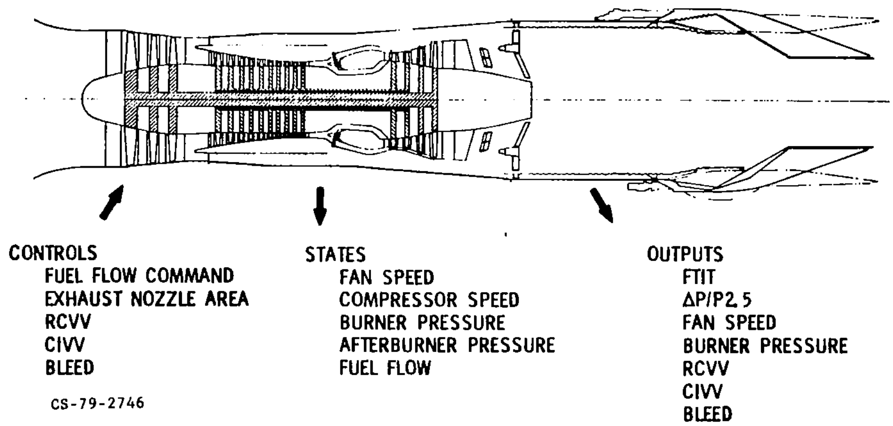

Figure 1. - F100 engine variables used for multivariable control.

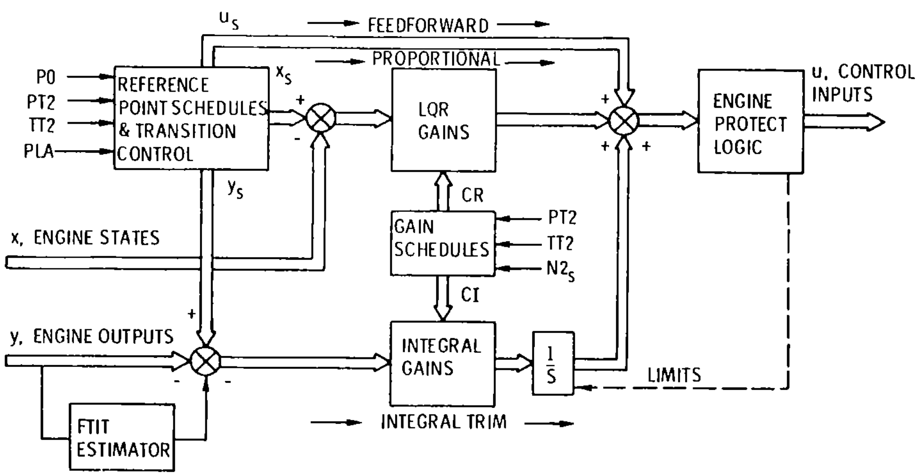

Figure 2. - Structure of F100 multivariable control.

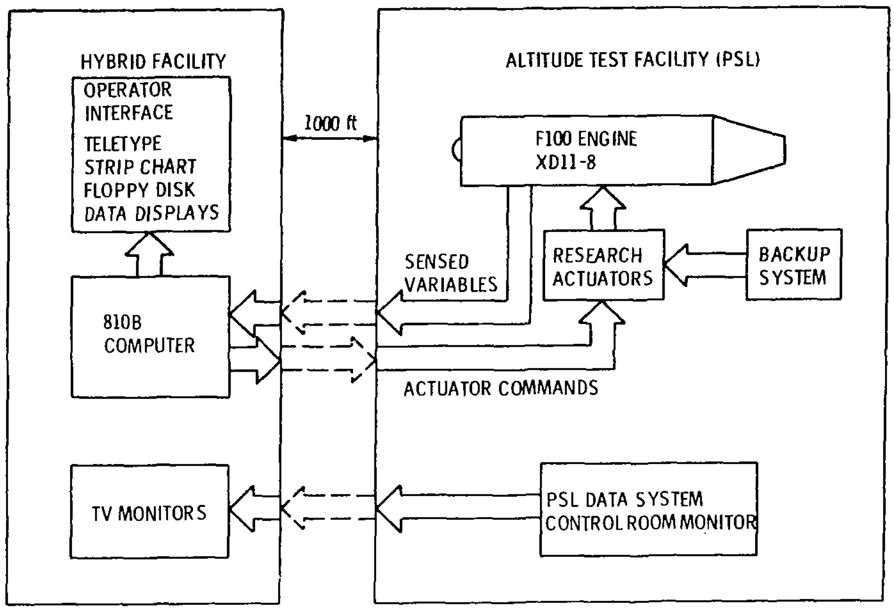

Figure 3. - Control system schematic for altitude tests.

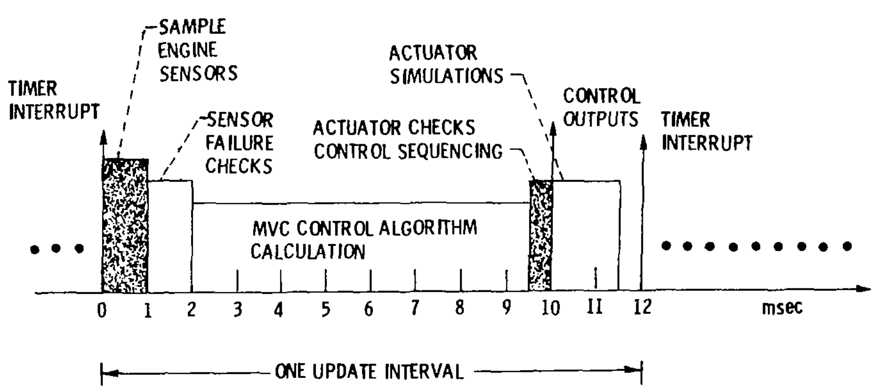

Figure 4. - MVC control timing diagram.

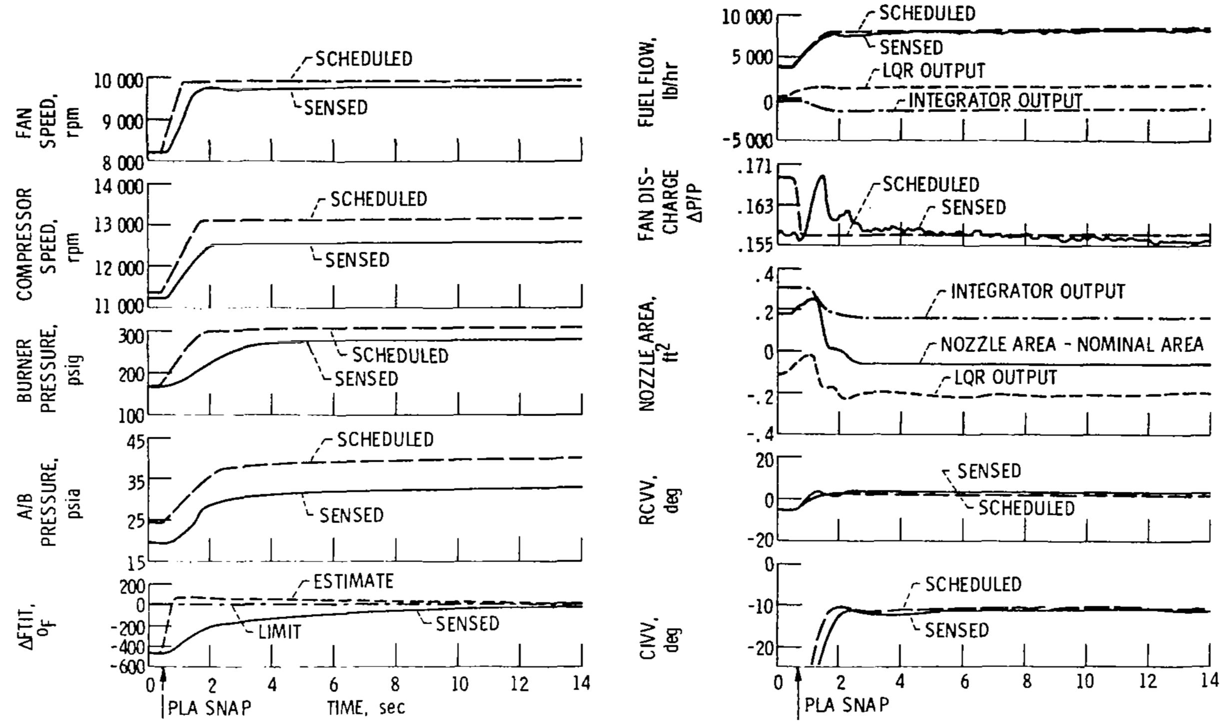

Figure 5. - Typical F100 multivariable control performance in large PLA transient. Altitude, 10 000 ft; Mach number, 0.6; 50° to 83° PLA snap.

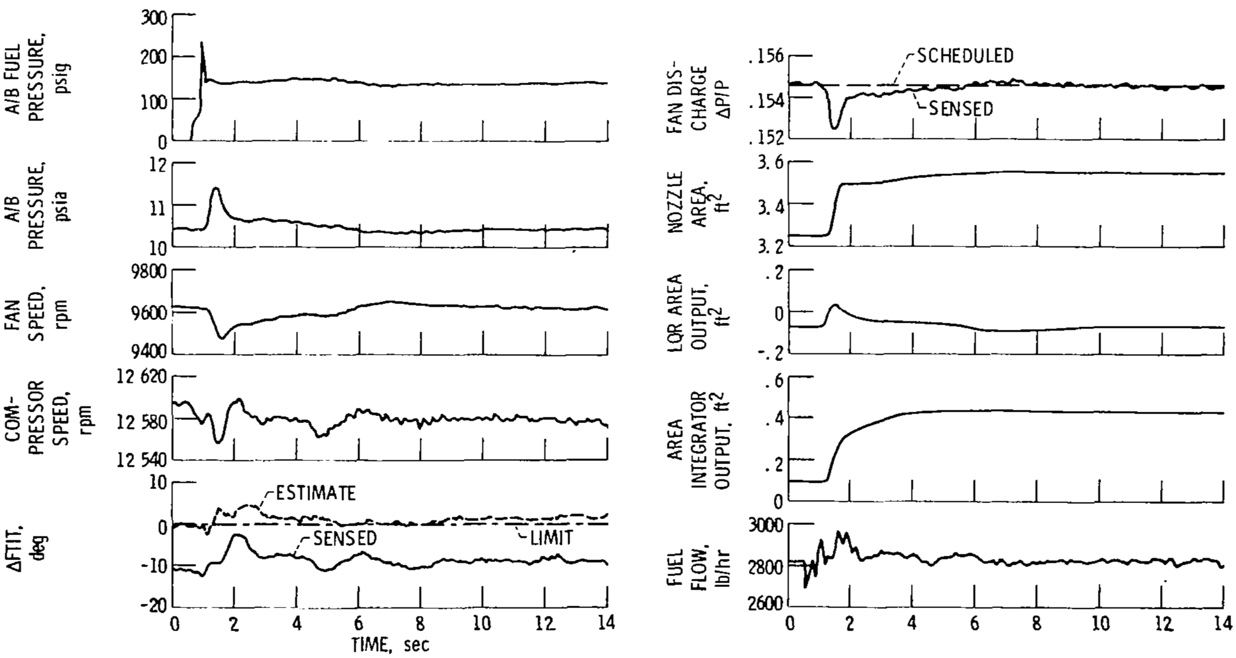

Figure 6. - Typical afterburner transient at supersonic conditions. Altitude, 55 000 ft; Mach number, 1.8.

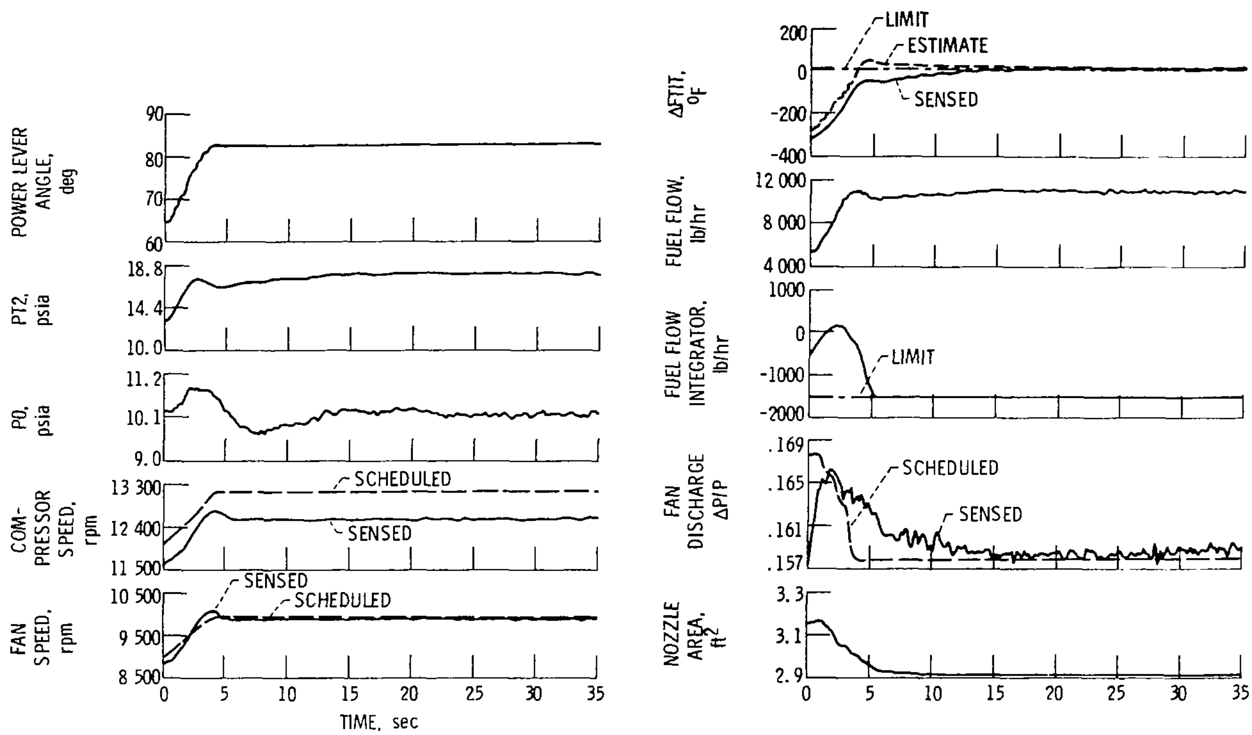

Figure 7. - F100 flight maneuver simulated in altitude facility. Altitude, 10 000 ft; initial Mach number, 0.6; final Mach number, 0.9; initial inlet temperature, standard day; final inlet temperature, 40° F (cold-day conditions).