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Abstract

This paper covers the evaluation of a multivariable control design for the F100 turbofan engine. The evaluation was part of the F100 Multivariable Control Synthesis (MVCS) program. The MVCS program is a jointly sponsored, Air Force-NASA program, aimed at accomplishing the design, evaluation and testing of a multivariable, linear quadratic regulator control for the F100 engine. The evaluation utilized a real-time, hybrid computer simulation of the engine and a digital computer implementation of the control. Significant results of the evaluation are presented and recommendations concerning furture engine testing of the control are made.

Introduction

The F100 Multivariable Control Synthesis (MVCS) program has involved a 19-month Phase I effort covering the design and evaluation of a multivariable, linear quadratic regulator (LQR) control for the F100 turbofan engine. The MVCS program[1-3] is a jointly-sponsored, Air Force Aero-Propulsion Laboratory - NASA Lewis Research Center program, aimed at applying existing LQR technology to the design of a practical LQR control for a state-of-the-art turbofan engine. The MVCS program differs from previous studies in that it addresses the following issues: (1) the ability to accomplish large power excursions without exceeding engine or actuator limits, (2) the extension of the controller authority to the entire engine operating envelope, and (3) the consideration of sensor and actuator nonlinearities in the design process.

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Over the past several years, aircraft operational requirements have dictated the development of propulsion systems having increased performance over a wider operating envelope. To satisfy these performance requirements, variable geometry components have become an integral part of advanced aircraft engines. Future variable-cycle engines may incorporate variable fan, compressor, turbine and exhaust nozzle geometry to improve overall performance.[4] As a result, the engine control system will have to be capable of controlling engine fuel flows and the variable geometry in an "optimum" manner. This will necessitate the measurement of more engine variables. However, the multitude of variables to be manipulated and measurements to be utilized make it difficult to design controls for these advanced engines.

Classical control synthesis techniques, which involve the analysis and design of single-input, single-output control loops, have worked quite well for the older, simpler engines. Unfortunately, such techniques prove to be cumbersome and time-consuming when they are applied to the more complex, multivariable engines.

One approach to solving the engine control problem is the use of multivariable (optimal) control theory. The linear quadratic regulator (LQR) is one aspect of the theory that has been successfully developed and applied to a wide variety of linear multivariable control problems.[5] LQR designs result in feedback-type controllers which make use of inherent loop interactions to improve performance. The LQR control modes can also reduce the sensitivity to parameter variations and sensor inaccuracies.

There have been some initial research and development efforts made at applying LQR theory to the design of controls for the nonlinear, gas turbine engine process.[6-10] These efforts, however, have been limited to engine control over a narrow operating range (usually sea-level, static, standard-day conditions).

Systems Control Inc. (Vt.) has been contracted to design a multivariable control for the Pratt & Whitney F100-PW-100(3) turbofan engine, shown schematically in Fig. 1. The F100 engine was selected for the MVCS program due to the availability of detailed digital and hybrid computer simulations of that engine and the availability of an actual F100 engine for testing at NASA LeRC. The F100 engine represents the current state-of-the-art in aircraft gas turbine technology. Although not as complex as some of the advanced cycles being proposed, the F100 does provide a suitable test for the LQR technique. In addition to the main burner and afterburner fuel flows, the F100 has variable fan inlet guide vanes, variable compressor stator vanes and a variable convergent-divergent exhaust nozzle. Airflow bleed can be extracted at the compressor exit.

The evaluation of the multivariable control utilized a real-time, hybrid computer simulation of the F100 engine[11] and an implementation of the control logic on the NASA LeRC digital computer/controller.[12]

The evaluation effort constituted the most comprehensive test of an LQR engine control to date. In addition to steady-state control, the evaluation covered the simulated engine responses to: large and small amplitude throttle movements, cyclic throttle movements, afterburner ignition pulses, flight condition transitions and sensor failures. The hybrid tests were conducted at flight conditions covering the entire F100 operating envelope. To demonstrate the flexibility of the multivariable control structure, a "fast-acceleration" control design was also evaluated.

This paper describes the evaluation approach and presents the significant results of the hybrid evaluation. The value of the real-time engine simulation in providing a realistic "test-bed" for the control is also discussed. To aid in the interpretation of the results, the following sections provide brief descriptions of the multivariable control and its implementation.

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Multivariable Control

simplified block diagram of the F100 multivariable control system, designed by Systems Control Inc. (Vt.), is shown in Fig. 2. The control structure is applicable to many physical, nonlinear systems with state, control and output constraints. The nonlinear engine system and its control algorithm are given by:

Engine dynamics

$$\dot{x} = f(x,u,p) \qquad (1)$$

Engine outputs

$$y = h(x,u) \qquad (2)$$

Controller

$$u = u_s + C_x(x_s - x) + \int_0^t C_b\alpha(y_d - y)dt \qquad (3)$$

where

x = engine state vector (n x 1)

u = engine control vector (n x 1)

y = engine output vector (m x 1)

p = flight condition parameters

α = switching matrix (m x m)

x_s, u_s, y_d = reference point vectors

C_x = regulator gain matrix (n x n)

C_b = integral gain matrix (n x m)

All symbols are defined in the Symbol List.

The LQR and integral trim controls are designed to operate at or near specific operating points. Therefore, a practical multivariable control must provide for the calculation of the reference point values (x_s, u_s and y_d). The reference point schedules are functions of the throttle setting (PLA) and the flight condition (PT2, TT2 and MN) as shown in Fig. 2. The outputs of the reference point schedules are rate-limited in the transition control to prevent excessive deviations which could saturate the controls. The transition control provides a transient "model" for the linear regulator to follow.

The control mode is basically proportional-plus-integral with feed-forward action to provide rapid response. The proportional control action is provided by the LQR with the state feedback gains C_x able to affect changes in all of the available control variables to reduce deviations in all of the state variables (relative to the specified reference point x_s). The integral control provides steady-state trimming of the fan operating point (fan speed and fan discharge ΔP/P) and both variable vane schedules. The integral control gains C_b were designed to provide the desired steady-state trim action without affecting the LQR closed-loop response. For convenience of implementation, the LQR and integral control gains are combined in a single matrix structure as shown in Fig. 3.

Operation near engine limits,[1] such as the maximum allowable fan turbine inlet temperature (FTIT) or the minimum allowable burner pressure, will change the elements of the switching matrix α (Fig. 2) and cause the appropriate limit error to be substituted for the fan speed error in the integral control. During transients, the trim integrators are clamped except for the fuel flow integrator which continues to provide (if required) FTIT or burner pressure limiting.

Because of the nonlinear nature of the engine process, a single set of LQR and integral control gains will not provide satisfactory closed-loop responses at all flight conditions. For this reason, the gains are scheduled (intropolated) as functions of the inlet air density and the scheduled compressor corrected speed. The gain-scheduling algorithm interpolates between gains, designed at each of four high-power conditions and two low-power conditions. Since the LQR and integral control gains are stored in a single matrix structure, they are scheduled by the same algorithm. It should be noted that the earlier LQR work[6-10] did not address the problems of reference point and regulator gain scheduling, associated with wide-range operation.

The current F100 control system uses lead compensation to correct for a slow FTIT sensor. The Systems Control Inc. (Vt.) design utilizes an FTIT "estimator" to predict whether the current fuel flow command, measured FTIT and scheduled FTIT will result in an overtemperature at a later point in a transient. The estimated FTIT is compared with the maximum allowable FTIT and, if an overtemperature is predicted, the engine is downtrimmed by the integral control.

Engine protection logic is included in the multivariable control design to provide absolute limiting of the control outputs to satisfy engine and actuator constraints. The engine protection logic, by means of the switching matrix α, clamps the appropriate integrators when individual controls become saturated.

Control Implementation

The F100 multivariable control logic was implemented on the NASA LeRC SEL810B digital computer/controller.[12] The salient features of that computer are listed in Table I. Although the SEL810B is not flight-qualified hardware, its memory, speed and word size are believed to be representative of the computers that will be used to control engines in the 1980's.

All of the SEL810B programming was performed in assembly language in order to reduce the core requirements and computation time. The multivariable control algorithm consumed approximately 7000 words of core storage. The total software package, including the control algorithm, matrix data, reference point schedule data and general-purpose I/O subroutines, consumed approximately 12 000 words of core storage. These core requirements are not a direct measure of the control complexity, however. While the schedules and matrix data would require the same amount of core on any 16-bit computer, the control algorithm requirements are highly dependent on the computer architecture, instruction set and the objectives of the programmer. In the MVCS program, one of the determining factors was a stated goal of achieving a 10 millisecond control update time since this would permit the design of the control on a continuous rather than discrete basis. To achieve the desired 10 millisecond update time, it was necessary to write the entire program using in-line code. This had the effect of eliminating the overhead associated with multi-level subroutine calls and indexing. While speeding up the computations, this required additional core storage. Other factors which contributed to the core storage and update time, such as the simulation of actuators and the sampling of transient data, are discussed in the following section.

Evaluation of the Multivariable Control

Prior to engine testing of the F100 multivariable control, it was necessary to evaluate the control logic and its implementation to ensure safe, stable engine operation throughout the F100 flight envelope. The following section describes the evaluation procedure.

Approach

The evaluation was accomplished using a real-time, hybrid computer simulation of the F100-PW-100(3) turbofan engine. It has been demonstrated that an engine simulation, running in real-time, provides a convenient and economical means of checking and "debugging" digital control hardware and software prior to engine testing.[13-14] This concept is illustrated in Fig. 4. The simulation represents, both statically and dynamically, all parts of the engine-control loop not available as hardware. In addition to the engine, these might include the sensors and actuators. By running in real-time, the simulation dynamics can realistically interact with the dynamics of the control system being evaluated.

The hybrid computer, because it includes both a digital and analog computer, is well suited for the engine simulation task. The digital portion of the hybrid computer can be used to perform the bivariate function generation[15] associated with modeling the performance of the engine's rotating components. The analog computer is then available for performing nonlinear calculations and integrations associated with the engine dynamics. The analog computer also provides an interface for continuous monitoring and recording of simulation data.

Figure 5 illustrates, schematically, how the various computers were configured for the MVCS evaluation. The hybrid computer provided the real-time engine simulation. The analog signals, representing the sensed engine variables, were trunked to a separate analog computer which provided real-time sensor simulations.

The simulated sensor outputs were digitized and processed in the SEL810B digital computer which performed the multivariable control calculation of the commands to the control actuators. Because of the full utilization of the hybrid and analog computers, the SEL810B was used to simulate, digitally, the actuators. The digital actuator outputs were converted to analog signals for input to the engine simulation.

The digital portion of the hybrid computer and the SEL810B provided digital listings of steady-state engine and control data, respectively. A total of 192 engine and control variables were listed at each evaluation operating point.

Strip-chart recorders and X-Y plotters were used to monitor transient data during the evaluation. Because of the vast amount of available transient data, however, a more convenient means of recording and processing transient data was desired. Therefore, the SEL810B was further utilized as a transient data sampler and storage device. A total of 72 variables were sampled and stored for each transient. These variables included engine variables, internal control variables, actuator commands and actuator outputs. Two hundred samples per variable per run were stored in the SEL810B. The sampling rate was adjusted to match the duration of each transient. For example, each of the 72 variables was sampled every 100 milliseconds (every 10th computer cycle) during a 20 second run. After the completion of each transient run, the stored data were transferred to a disk storage device for off-line processing.

Scope

The primary objective of the evaluation was to verify the multivariable control logic and its implementation prior to engine testing. A secondary objective was the quantative evaluation of the closed-loop performance of the control. The evaluation flight conditions (altitude/Mach number) and the types of tests conducted are listed in Table II. The flight conditions covered the engine operating envelope.

Steady-state tests were conducted at each flight condition to evaluate the reference point schedules, the linear quadratic regulator, the integral trim modes, etc. The range of flight conditions provided a test of the control's ability to track the various engine limits. Tests at most supersonic flight conditions were limited to the intermediate thrust setting (PLA = 83°) to satisfy inlet airflow requirements.[1] The multivariable control logic also restricted part-power operation at high altitude/low Mach number conditions to maintain minimum burner pressure levels. A total of 56 steady-state operating points were evaluated.

A total of 77 transient tests were also conducted to evaluate the transition control, the gain scheduling algorithm, the control mode switching and the engine protection logic. Both small and large amplitude throttle transients were run at all flight conditions where part-power operation was permitted. Cyclic movements of the throttle were also simulated to determine if the control could be "confused" by such maneuvers.

To test the regulating capabilities of the LQR, afterburner ignitions were simulated at each of the evaluated flight conditions. The ability of the regulator to suppress afterburner pressure pulses during the ignition was determined.

Inlet disturbances, representative of realistic aircraft maneuvers, were simulated at sea-level to determine the sensitivity of the control to changing fan inlet conditions. Transitions between other altitude conditions were also accomplished under multivariable control although the rates of change of the fan inlet conditions were not restricted or controlled in those cases.

The sensitivity of the control to various sensor failures was studied at the 9.14 km/0.9 (altitude/Mach number) condition. Although sensor failure accomodation was not a specified control requirement, it was felt that critical sensors should be identified prior to the engine tests so that the necessary sensor detection and accomodation logic could be developed.

Results and Discussion

Steady-State

The results of the steady-state evaluation are summarized in Table III. The reference point schedules appeared to accurately represent the performance of the engine simulation at most operating conditions. In spite of differences between the hybrid and baseline digital simulations,[11] the control provided good steady-state regulation of the operating point indicating that the control should be able to accomodate expected engine-to-engine variations. The linear quadratic regulator and integral trims provided good steady-state performance at all of the subsonic flight conditions. In particular, the fan speed-fan discharge $\Delta P/P$ trim mode resulted in good fan operating point control. Although thrust requirements were not specified for the supersonic flight conditions, the closed-loop performance at those conditions was also evaluated. Reference point scheduling errors at three of the supersonic conditions resulted in saturation of the integral trims. Authority limits had been placed on the trim integrators as protection against sensor failures, etc. In each case, saturation of the integral trims produced lower thrust values (by about 10 percent) than the baseline digital simulation. The control logic did maintain the engine operating point safely below the specified limits on FTIT, burner pressure and rotor speeds at all steady-state points. Similarly, the fan and compressor surge margins were maintained at acceptable levels. It is anticipated that minor modifications to the reference point schedules will produce the desired performance at the supersonic flight conditions.

In general, the results of the steady-state evaluation of the multivariable control indicated that the control logic and its implementation did satisfy the steady-state control requirements as specified by Pratt & Whitney.[1]

Transient

Power lever transients were run at those flight conditions where power settings below PLA = 83° are permitted (see Table II). To test the small perturbation response characteristics of the linear quadratic regulator designs, ±3° PLA snaps were run at several flight conditions. Initially, data were obtained at sea-level/static, 3.05 km/0.6 and 9.14 km/0.9 conditions. Those results indicated that the response characteristics were, in general, satisfactory. Response times (time to achieve 90 percent of the commanded thrust change) ranged from 0.5 second (at high altitude-high power) to 2.0 seconds (at sea-level/static - low power). However, an underdamped thrust response was observed in the 52° to 55° PLA range for all three of the evaluated flight conditions. The gain-scheduling breakpoints were subsequently shifted to a higher power condition. This, in effect, reduced the controller gains in the 52° to 55° PLA range. Small perturbation tests were then repeated with additional tests conducted at the 3.05 km/0.9, 13.5 km/0.9, sea-level/1.2 and 3.05 km/1.2 conditions. Figure 6 shows the responses of fan speed, burner pressure and net thrust to a PLA snap from 52° to 55° at the sea-level/1.2 condition. The results indicated that the underdamped thrust response had been corrected. Figure 6(c) shows that 90 percent of the thrust change was acheived in 0.6 second. The small perturbation response times are summarized in Table IV. A small perturbation response time requirement of 1.2 seconds was adopted due to a lack of specificity in the design requirements. The results of the evaluation were judged acceptable relative to that requirement.

Although LQR control of afterburner fuel flow was not a part of the multivariable control task, the requirements dictated that the control be tolerant of external disturbances such as afterburner ignition pulses. Pratt & Whitney specified the maximum allowable amplitudes of afterburner pressure pulses, based on current control performance.[1] It was hoped that the LQR would provide sufficient regulation based on the sensed afterburner pressure deviations.

Afterburner ignitions were simulated by a stepwise increase in the afterburner fuel flow. The amount of injected fuel matched the current control schedules. Figure 7 shows the results of the afterburner ignition tests. The results indicated that the LQR design, without the benefit of anticipatory nozzle opening, did provide pressure spike suppression at all flight conditions. The LQR utilized both the exhaust nozzle and the fan inlet guide vanes to reduce the after burner pressure deviations.

Large amplitude PLA transients were run at several flight conditions to evaluate the transition control, the gain-scheduling algorithm, the integral trim modes and the engine protection logic. Figure 8 shows the responses of fan speed, FTIT and net thrust to a PLA snap from 35° to 83° at the 3.05 km/0.9 condition. Ninety percent of the net thrust change was achieved in 2.1 seconds. Figure 8(b) shows that the FTIT peak, predicted by the estimator, exceeded the maximum allowable FTIT, resulting in a fuel flow downtrim which prevented the actual FTIT from exceeding the limit during the acceleration. Similar results were observed at the other evaluated conditions. Unsatisfactory response characteristics were noted at only one condition - oscillatory behavior was observed during a 50° to 70° PLA snap at the 3.05 km/0.9 condition. This was attributed to a high regulator gain relating fuel flow to the compressor speed deviation ($c_{1,2}$ in Fig. 3). As described in the Multivariable Control section, the LQR gains at this condition were dependent on the gain scheduling algorithm since none of the stored LQR gain matrices were designed at this flight condition. It is anticipated that this problem will be corrected prior to the engine tests.

Although the specified response time requirements were satisfied for most small and large amplitude transients, the results indicated that the potential existed for achieving faster thrust response. While fast thrust response was not a specific objective of the MVCS program, it was felt that achieving faster response, through a straightforward design iteration, would demonstrate the flexibility of the design approach and the resulting implementation.

The Systems Control Inc. (Vt.) approach to achieving faster response with the multivariable control was to redesign the transition control rate limit schedules. These rate limits define the transient model which the regulator attempts to follow. For the hybrid evaluation, the redesign was accomplished for the sea-level/static condition. The resulting rates were implemented in the SEL810B and were evaluated for PLA snaps from the idle to intermediate and from the 30 percent to intermediate thrust settings. The resulting transient data were compared with the corresponding normal-rate data. Figure 9 shows the results of the comparison for the idle-to-intermediate thrust transient. The responses of fan speed, FTIT and net thrust are presented. The faster acceleration was the result of increasing the fuel flow to the specified acceleration limit. No overshoots were observed, however. As shown in Fig. 9(b), the peak in the predicted FTIT produced a fuel flow downtrim and a resultant dip in the FTIT response. The faster thrust response was characterized by a 2.2 second response time as compared with the normal response time of 3.2 seconds. The faster response was achieved at the cost of about 0.012 in fan surge margin and 0.07 in compressor surge margin. Similar results were observed for the 30 percent-to-intermediate thrust transient. In that case, the response time was reduced from 2.2 to 1.4 seconds with no loss in fan surge margin and a loss of only 0.01 in compressor surge margin.

Sensor Failure

Since the SEL810B implementation did not include software provisions for accomodating sensor failures, hybrid tests were conducted to identify critical sensors in order that appropriate software could be developed prior to the engine tests. Various modes of sensor failure were studied at the 9.14 km/0.9 condition and an 83° PLA setting. Both full-scale (saturation) and sensor loss tests were conducted. The results of the failure study are summarized in Table V. The control structure with its engine protection logic provided safe downtrimming to part-power conditions for most sensor failures. Two critical sensor failures were identified, however. They were: saturation of the fan inlet total pressure (PT2) sensor and the loss of the fan speed sensor. The high PT2 signal resulted in a sudden increase in the scheduled values of fuel flow, burner pressure and afterburner pressure. The feed-forward path for the scheduled controls (see Fig. 2) drove the fuel flow command up while the downtrim limits prevented the integral control from tracking the engine limits on the rotor speeds and FTIT.

The loss of the fan speed sensor resulted in increased fuel flow and nozzle area uptrims from the regulator. The fuel flow integrator was also driven to its uptrim limit by the false fan speed deviation. This resulted in overspeeds and an overtemperature. Based on these results, it was concluded that some form of sensor failure detection and accomodation logic should be incorporated in the multivariable control prior to engine testing.

Conclusions

The primary objective of the hybrid evaluation was to verify the multivariable control logic and its implementation to ensure safe and stable operation of the F100 engine during subsequent altitude tests. The results of the evaluation indicated that the control logic and its implementation will be capable of controlling the engine throughout its operating range. The specified engine limits were not violated during normal steady-state and transient operation.

The multivariable control matched baseline, steady-state performance for all but a few supersonic test conditions. The degraded supersonic performance was attributed to reference point scheduling errors at those conditions. Minor modifications to the reference point schedules will produce satisfactory steady-state performance at all flight conditions. The proportional (LQR) plus integral control structure provided good fan operating point control and when required, tracked the engine limits.

The LQR and transition control produced satisfactory transient responses at most operating conditions. The specified response time requirements were satisfied for all small and large amplitude transients with the exception of the small (+3°) PLA snaps at the sea-level/static, idle condition. A 1.2 second response time requirement for the small perturbations was adopted due to a lack of specificity in the design criteria.

The flexibility of the control structure and design methods was demonstrated by implementing a fast-acceleration set of rate limits in the transition control. The resulting sea-level/static acceleration from idle to intermediate thrust showed a reduction in the response time from 3.2 to 2.2 seconds.

The results of the sensor failure study at the 9.14 km/0.9 condition indicated that most sensor failures would result in a safe, downtrimming to a part-power condition. The saturation of the PT2 sensor or the loss of the fan speed sensor, however, resulted in a catastrophic overspeed and overtemperature condition. Therefore, it is recommended that some form of sensor failure detection and accomodation logic be implemented in the multivariable control prior to the engine tests.

Considering the fact that, in approximately 10 months, a control design for the F100 engine was accomplished, it must be concluded that the computer-aided LQR approach to designing multivariable controls is a practical solution to the engine control problem. The results of the hybrid evaluation demonstrated that the Systems Control Inc. (Vt.) design can control the nonlinear F100 engine throughout its operating envelope. The implementation of the control logic on the SEL810B digital computer showed that a practical LQR control could be programmed on a computer having many of the characteristics of flight-qualified hardware. The core requirements (7.1 K) and the update time (10 milliseconds) are comparable to the requirements of flight-qualified, full-authority digital controls such as the IPCS control.[16]

The evaluation of the F100 multivariable control has demonstrated the value of real-time engine simulations for digital control development. A timely, comprehensive evaluation of the steady-state and transient performance of digital control hardware and software was accomplished prior to full-scale engine testing.

Symbol List

C_b	integral gain matrix (n x n)
C_x	regulator gain matrix (n x m)
$c_{i,j}$	gain matrix element, i = 1-5, j = 1-15
CIVV	fan inlet guide vane angle, deg
FTIT	low-pressure (fan) turbine inlet temperature, K
f	engine state function
h	engine output function
MN	Mach number
N1	fan rotor speed, rpm
N2	compressor rotor speed, rpm
$N2_s$	scheduled compressor rotor speed, rpm
PB	burner pressure, $N\text{-}cm^{-2}$
PLA	power lever angle, deg
ΔPLA	power lever angle change, deg
ΔP/P	fan discharge Mach number parameter
PT2	fan inlet total pressure, $N\text{-}cm^2$
PT6	afterburner inlet total pressure, $N\text{-}cm^{-2}$
p	flight condition parameters
RCVV	compressor stator vane angle, deg
TT2	fan inlet temperature, K
u	engine control vector (n x 1)
u_s	scheduled engine control vector (n x 1)
x	engine state vector (n x 1)
x_s	scheduled engine state vector (n x 1)
y	engine output vector (m x 1)
y_d	desired engine output vector (m x 1)
α	switching matrix (m x m)

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TABLE I. - SEL810B DIGITAL

COMPUTER FEATURES

Two 16-bit accumulators

Memory specifications

- 24 K Magnetic core
- 0.75 Microsecond cycle time

Fixed-point multiply and divide

- 1.5 Microsecond add
- 4.5 Microsecond multiply
- 8.25 Microsecond divide

Double precision arithmetic

Infinite indirecting and indexing

Direct memory access

66 Total instructions

Two 64-channel multiplexors

50 Microsecond/sample digitizing rate

26 Digital-to-analog channels

Tektronix 4010A peripheral system

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TABLE II. - F100 MULTIVARIABLE CONTROL EVALUATION TESTS

Alt(km)/MN	Steady-state		Transient					Sensor failure
			ΔPLA			Disturbance		
	PLA = 83	PLA < 83	Small	Large	Cyclic	A-B	Maneuv.	PLA = 83
0.0/0.0	●	●	●	●	●	●	●	
3.05/0.6	●	●	●	●	●	●		
3.05/0.9	●	●	●	●	●	●		
9.14/0.9	●	●	●	●	●	●		●
13.7/0.9	●	●	●	●	●	●		
19.8/0.9	●					●		
0.0/1.2	●	●	●	●		●		
3.05/1.2	●	●	●	●		●		
6.10/1.8	●					●		
22.9/1.8	●					●		
17.8/2.15	●					●		
12.2/2.2	●					●		
19.8/2.5	●					●		

TABLE III. - STEADY-STATE RESULTS

Reference point schedules match hybrid simulation at most operating points

Good steady-state performance at all subsonic conditions

Reference point schedules in error at supersonic conditions resulting in trim saturation

All engine limits maintained

Control logic and implementation verified

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TABLE IV. - SMALL PERTURBATION RESPONSE TIMES

Alt(km)/MN	Thrust response times (sec) PLA (DEG)			
	20 - 23	30 - 33	52 - 55	80 - 83
0.0/0.0	2.0	1.4	0.8	0.7
3.05/0.6	1.2	1.0	.6	.6
3.05/0.9	1.0	1.0	.8	.5
9.14/0.9	---	.7	.5	.5
13.7/0.9	---	---	.4	.4
0.0/1.2	---	---	.6	.5
3.05/1.2	---	---	.75	.6

TABLE V. - RESULTS OF HARD SENSOR FAILURES;

9.14 km/0.9; PLA = 83 deg		
Sensor	Failure mode	Result
MN	Loss	None
	Saturation	Slight downtrim
PT2	Loss	Downtrim to 38 percent thrust
	Saturation	*Overtemperature and overspeed
TT2	Loss	None
	Saturation	Downtrim to 63 percent thrust
N1	Loss	*Overtemperature and overspeed
	Saturation	Downtrim to 60 percent thrust
N2	Loss	Downtrim to 34 percent thrust
	Saturation	Downtrim to 58 percent thrust
PB	Loss	Downtrim to idle
	Saturation	None
PT6	Loss	None
	Saturation	Downtrim to 74 percent thrust
ΔP/P	Loss	Slight downtrim
	Saturation	None

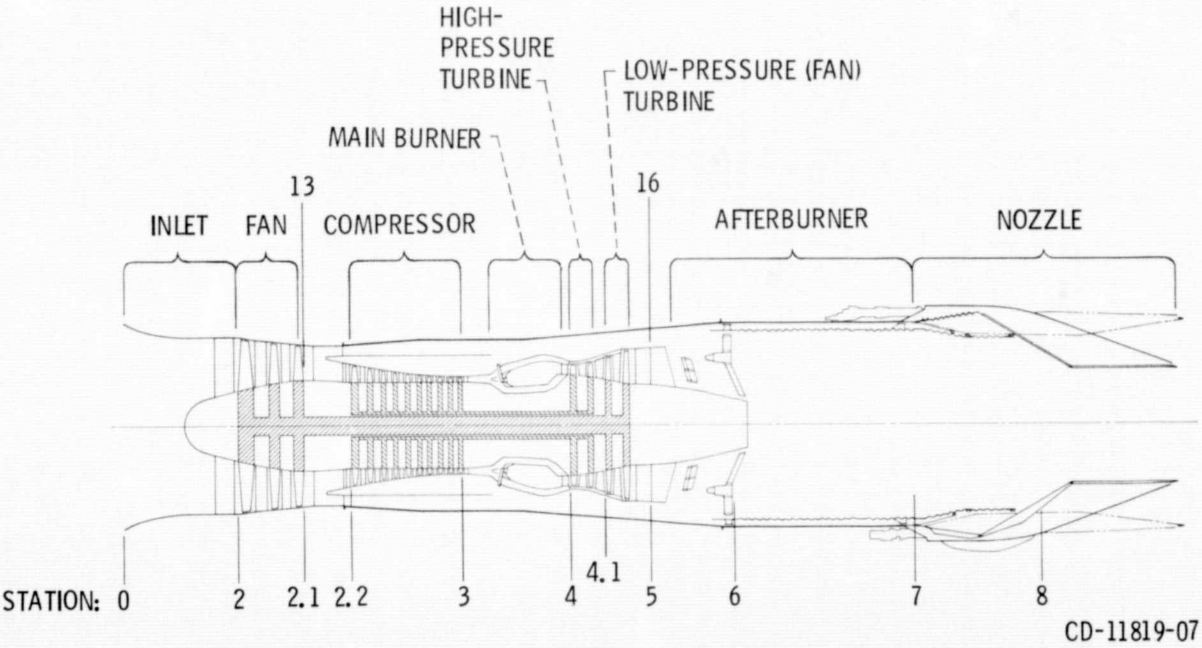

Figure 1. - Schematic representation of the F100 turbofan engine.

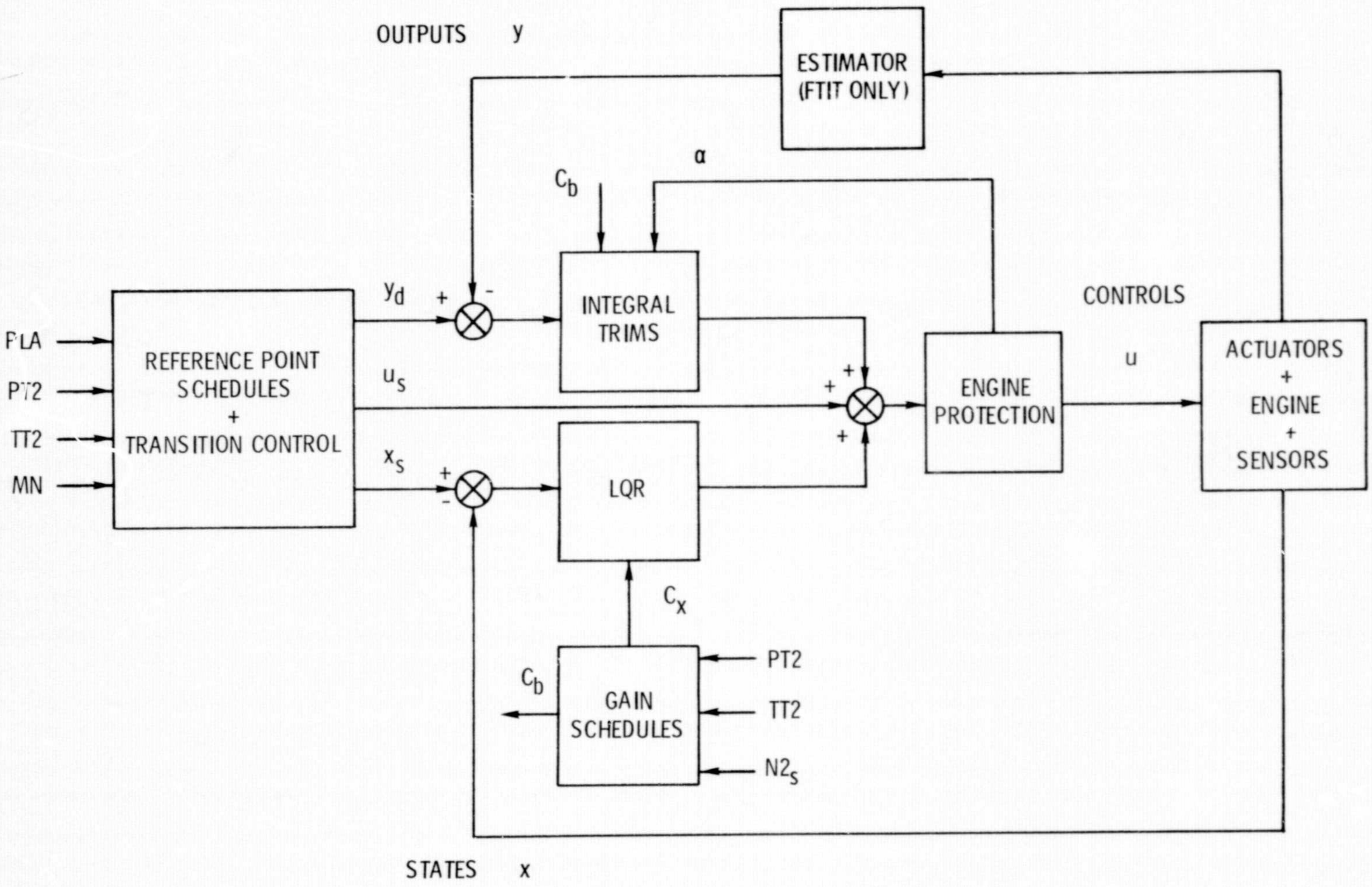

Figure 2. - Block diagram representation of the F100 multivariable control.

CONTROLS	STATE DEVIATIONS: FAN SPEED	COMPRESSOR SPEED	AFTERBURNER PRESSURE	MAIN BURNER FUEL FLOW	BURNER PRESSURE	SPARES	SPARES	OUTPUT DEVIATIONS: FAN DISCHARGE ΔP/P	CIVV	RCVV	COMPRESSOR DISCHARGE BLEED FLOW	FAN SPEED	MAX FTIT	MIN PB	MAX PB
MAIN BURNER FUEL FLOW	$c_{1,1}$	$c_{1,2}$	$c_{1,3}$	$c_{1,4}$	$c_{1,5}$	0	0	$c_{1,8}$	0	0	0	$c_{1,12}$	$c_{1,13}$	$c_{1,14}$	$c_{1,15}$
EXHAUST NOZZLE AREA	$c_{2,1}$	$c_{2,2}$	$c_{2,3}$	0	0	0	0	$c_{2,8}$	0	0	0	$c_{2,12}$	$c_{2,13}$	$c_{2,14}$	$c_{2,15}$
CIVV	$c_{3,1}$	0	$c_{3,3}$	0	0	0	0	$c_{3,8}$	$c_{3,9}$	0	0	$c_{3,12}$	0	0	0
RCVV	$c_{4,1}$	$c_{4,2}$	$c_{4,3}$	0	0	0	0	0	0	$c_{4,10}$	0	0	0	0	0
COMPRESSOR DISCHARGE BLEED FLOW	$c_{5,1}$	$c_{5,2}$	0	0	$c_{5,5}$	0	0	0	0	0	$c_{5,11}$	0	0	0	0

Figure 3. - Multivariable control gain matrix structure.

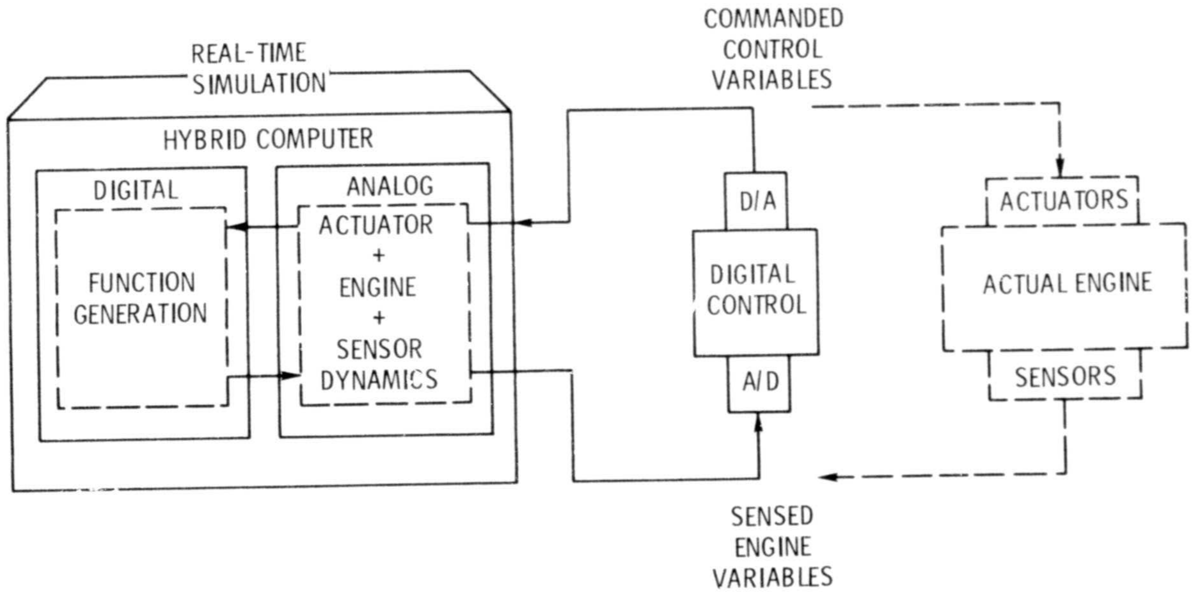

Figure 4. - Use of real-time, hybrid computer simulations for digital control development.

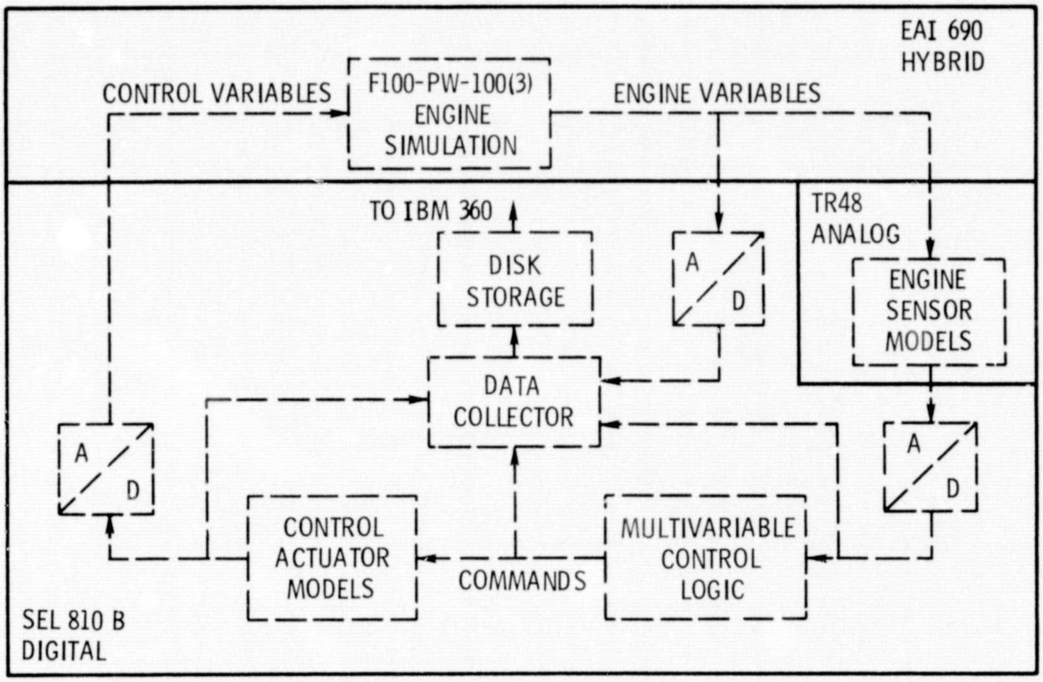

Figure 5. - Schematic representation of the multivariable control evaluation configuration.

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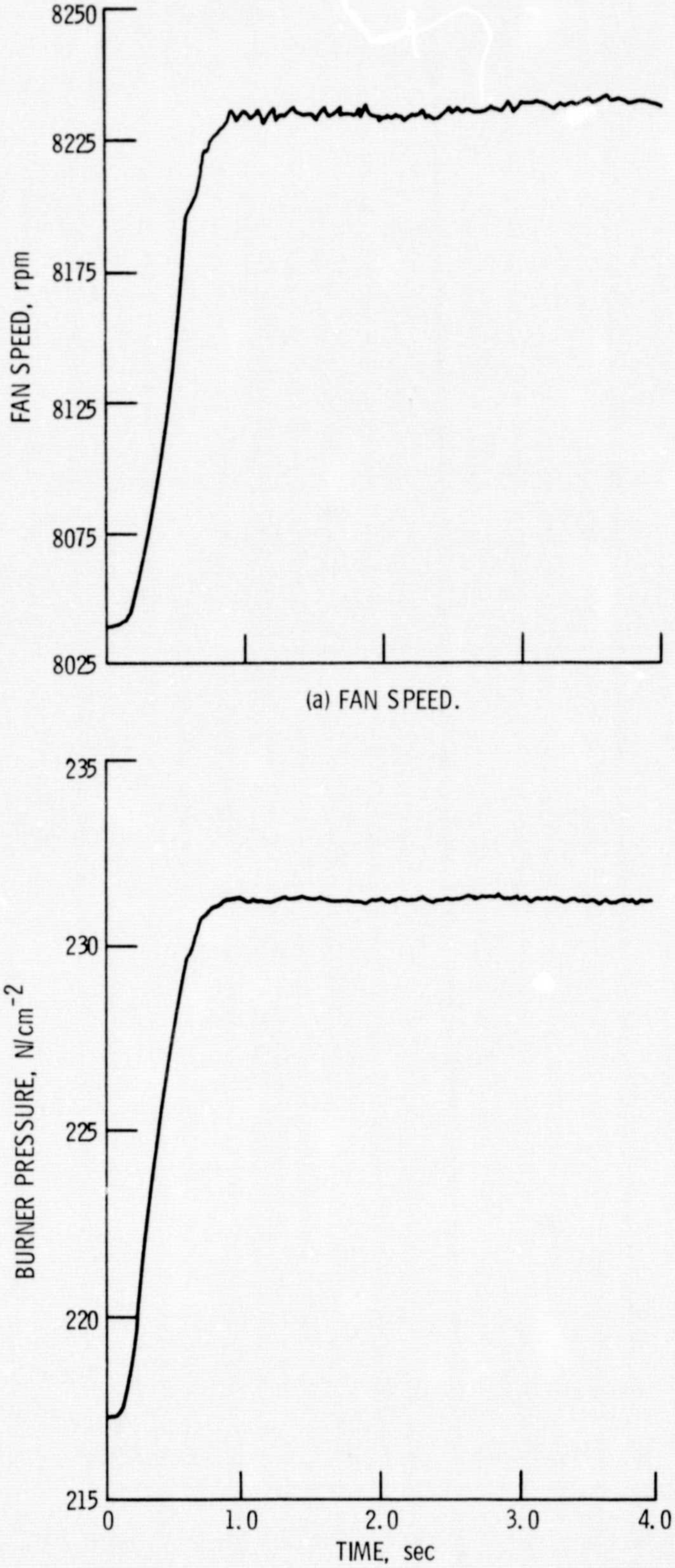
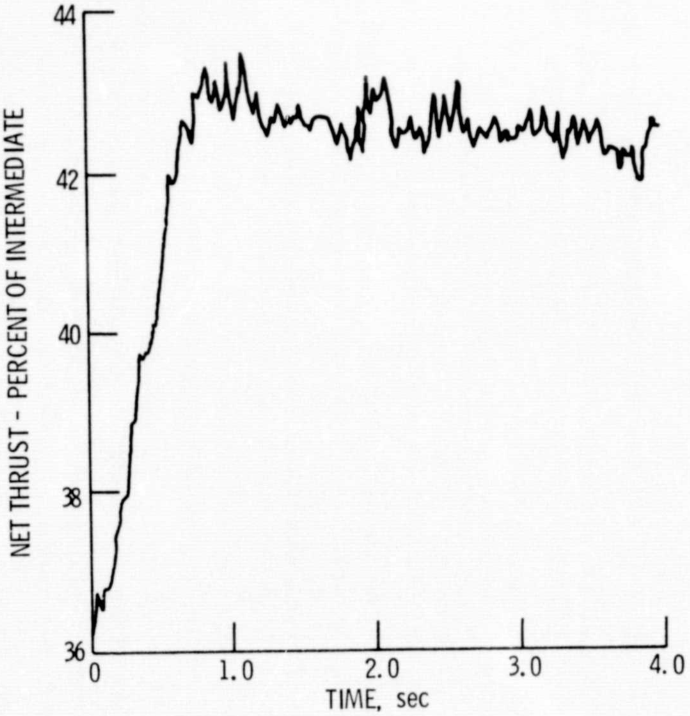


Figure 6. - Simulated F100 response to a 52 to 55 degree PLA snap at sea-level, Mach 1.2; multivariable control.



(c) NET THRUST.

Figure 6. - Concluded.

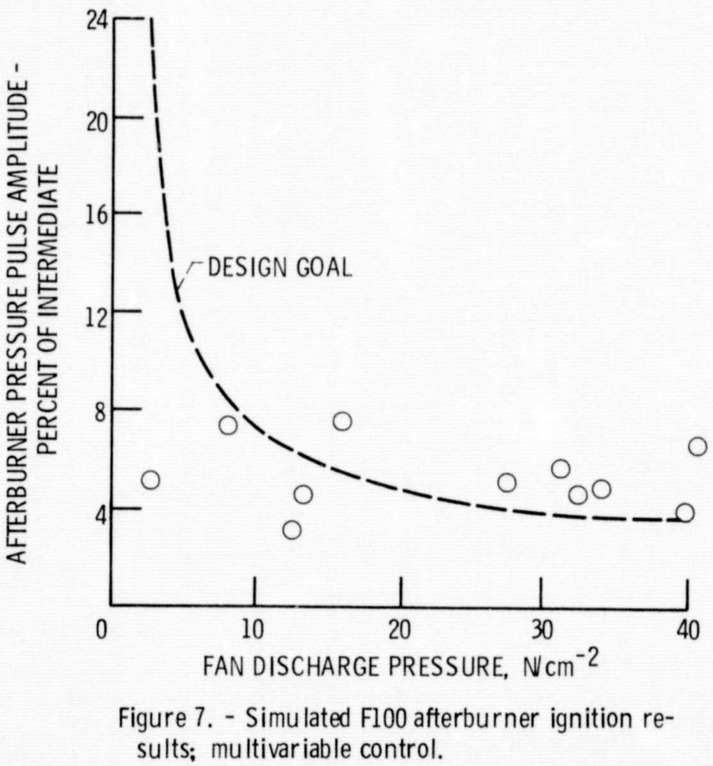


Figure 7. - Simulated F100 afterburner ignition results; multivariable control.

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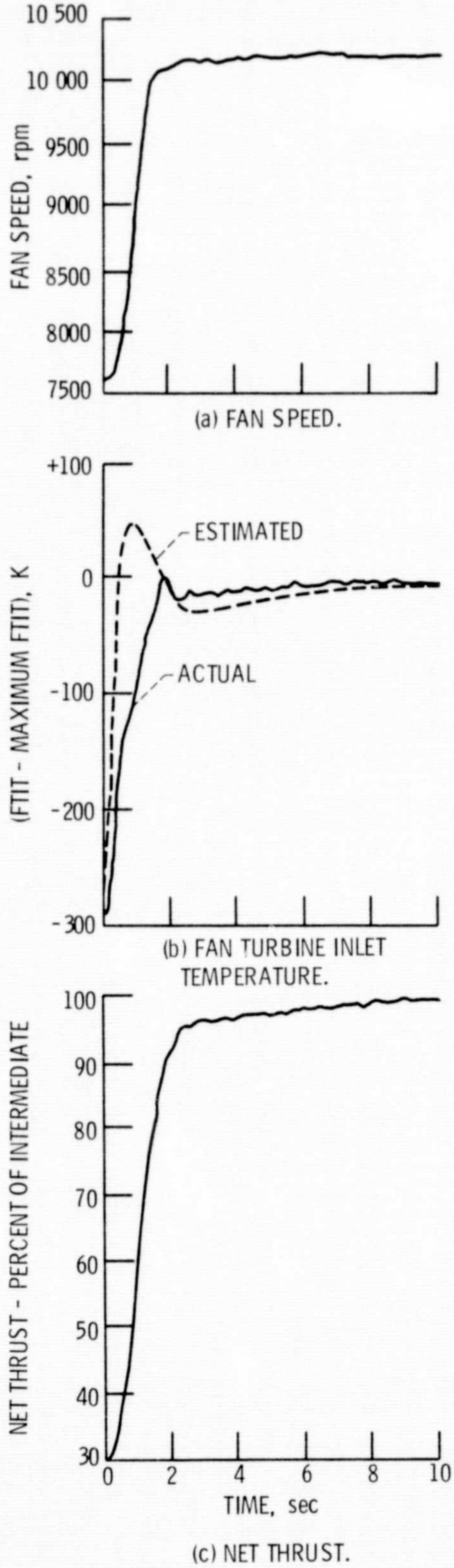

Figure 8. - Simulated F100 response to a 35 to 83 degree PLA snap at 3.05 km, Mach 0.9; multivariable control.

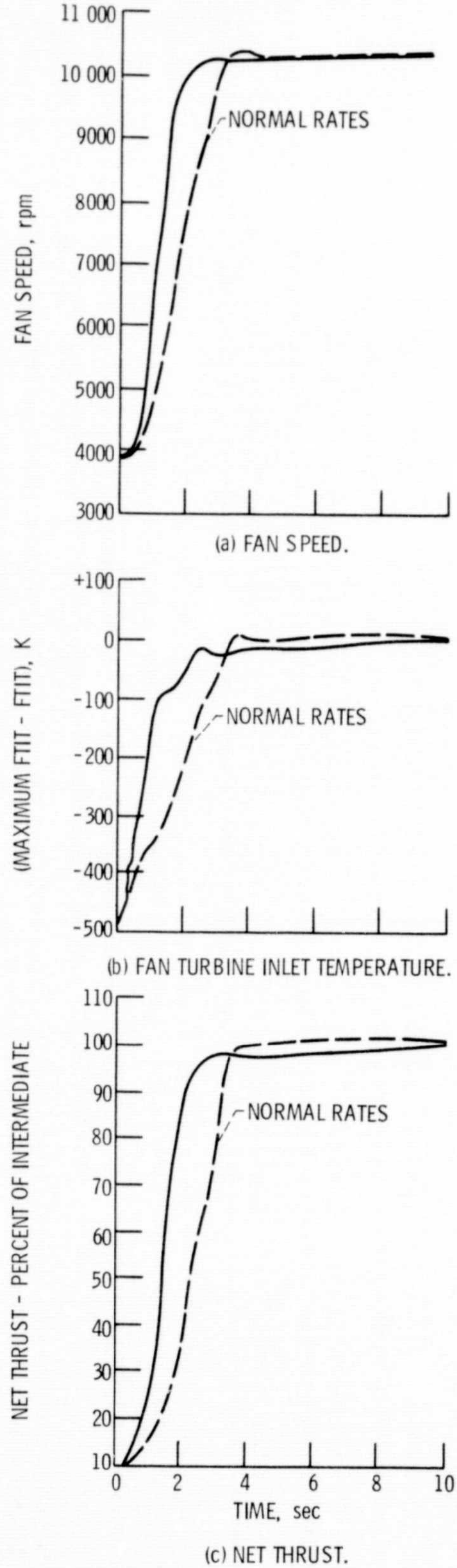

Figure 9. - Comparison of normal and fast F100 simulation responses to a 20 to 83 degree PLA snap at sea-level, static; multivariable control.