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by James R. Mihaloew and Clint E. Hart
Lewis Research Center
Cleveland, Ohio 44135

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by James R. Mihaloew and Clint E. Hart

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

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ABSTRACT

In the past propulsion system simulations used in flight simulators have been extremely simple. This results in a loss of simulation realism, eliminates significant engine and aircraft interaction dynamics and prevents generation of important internal engine parameters. Reasonably detailed simulations will be necessary to permit system evaluations in a simulated flight environment. A real time digital simulation of a STOL propulsion system was developed which generates significant dynamics and internal variables needed to evaluate system performance and aircraft interactions using manned flight simulators. The simulation ran at a real-to-execution time ratio of 8.8. The model was used in a piloted NASA flight simulator program to evaluate the simulation technique and the propulsion system digital control. The simulation is described and results shown. Limited results of the flight simulation program are also presented.

INTRODUCTION

Cost considerations are becoming more important in planning experimental and flight programs. Simulation, with its inherent analytical flexibility, can be used effectively to develop aircraft and propulsion systems to a higher degree before hardware is built and tested. It also provides a safe means of studying failure modes and effects.

Studies using manned flight simulators to evaluate flight stability and engine-out performance have been made for STOL type aircraft (1, 2). Propulsion system models used in these simulation studies are extremely simple providing only a thrust signal. No concern was given to how the thrust was derived or what might be happening to the engine producing that thrust. For example, the engine simulation used in (1) and (2) was derived from a series of thrust transients from an early STOL engine hybrid computer model. The response was matched to a transfer function which gave a typical response.

Engine models were also kept simple because of the limited computation time available. Using these models resulted in a loss of simulation realism and eliminated significant engine and aircraft interaction dynamics. Also, important internal engine parameters were unavailable for analysis. To overcome these deficiencies, reasonably detailed real time propulsion system simulations must be developed. These will provide the capability to evaluate propulsion systems and their interaction with aircraft controls on a real time basis in a simulated flight environment.

The QCSEE (Quiet, Clean Short-haul Experimental Engine) Program was initated by NASA to develop and demonstrate propulsion system technology for an advanced commercial STOL aircraft. One of the specific technical objectives was to provide technology for digital electronic control of future commercial engines. An element of this technology development was to evaluate the digital control in a simulated flight environment.

To accomplish the QCSEE Program requirement an effort was initated whose overall purpose was to evaluate the QCSEE UTW (Under-the-Wing) digital control system over a range of conditions encountered in typical airport operations. The goal of the simulation effort was to derive a real time digital propulsion simulation which could be integrated into a multi-engine aircraft simulation.

This paper summarizes the accomplishments to date. It is divided into two parts. First, the simulation model and techniques are described and results presented. Second, the application of the propulsion system simulation to an aircraft simulation is presented. Limited results of the flight simulation test program are presented.

REAL TIME DIGITAL SIMULATION REQUIREMENTS

The nature of the digital computing process to perform real time digital simulation is one of efficient mathematical modeling to attain the desired detail with minimum computation time and maximum numerical stability within a specified time period. In this study we wish to model the propulsion system to a degree such that its internal engine and control system parameters will be available for analysis. For the level of steady state and dynamic complexity required to meet program objectives, steady state accuracy does not have to be compromised over detailed models. However, high frequency content may be reduced significantly. The initial improvement to the simulation comes from efficient programming to attain minimum calculation time. More rapid improvement occurs by maximizing numerical stability to permit long time steps.

The computer cannot meet real time requirements simply by repeating the calculations as rapidly as possible. The time needed to make the calculations bears no relation to the time step used to change the time variable. A means to schedule and account for computation time is essential to assure that the computations can be accomplished in the allotted time. Time available for computation of the propulsion system must be shared since it is only a part of a larger simulation. Real time, then, in the context of overall simulation implies that the propulsion system will have to be calculated faster than real time to be effective.

PROPULSION SYSTEM SIMULATION

In this part of the paper, the propulsion system is described and the development of the simulation is presented.

QCSEE Experimental Propulsion System

Engine. - The UTW engine is shown in figure 1. The engine uses an F101 core gas generator with a high bypass fan duct. The system features a high Mach inlet, a variable pitch fan, a variable geometry fan duct exhaust nozzle and a digital electronic control system combined with a hydromechanical fuel control. It is designed to provide 77395N (17400 lb) of installed thrust at takeoff on a 305.6 K (90 F) day.

The fan is a low pressure ratio, low tip speed configuration with variable pitch blades and is driven by a low pressure turbine through reduction gears. The fan is capable of blade pitch changes from forward to reverse thrust. The fan variable pitch actuation and control is designed to move the blades from forward to reverse position in less than one second.

The fan exhaust nozzle is a hydraulically actuated variable area design. It is capable of area change from takeoff to cruise as well as opening to a flare position to form an inlet in the reverse thrust mode.

Control. - The control system manipulates four variables to achieve rapid thrust response and noise suppression. Control of engine pressure ratio, fan speed and inlet Mach number is accomplished by manipulating fuel flow, fan blade pitch and exhaust nozzle area. Variable stator vanes are scheduled by core speed to attain optimum stall margin.

The structure of the control system is shown in figure 2. The digital control is the heart of the system and controls the output variables in response to commands from the aircraft. It generates all control laws and logic and most of the limiting functions as well as power management, condition monitoring and failure corrective action and indication. The hydromechanical control provides an electrohydraulic servo fuel valve which is used by the digital control for primary fuel control. It also provides backup fuel control through a core speed controller, acceleration and deceleration limits and primary control of the core compressor stators. The hydromechanical throttle is used as a mechanical enable or power limiter.

Analytical Model

The analytical model is derived from the real QCSEE UTW propulsion system. It represents mathematically the steady state and dynamic relations between the engine component representation and the control component representations. Engine dynamics are based on the dynamic form of the conservation equations and engine transient experience. Steady state engine performance is based on component representations derived from cycle model data and steady state forms of the conservation equations. The variable pitch fan and its ability to reverse duct flow impose unique engine modeling problems.

Engine representation. - A major initial assumption is to eliminate high frequency elements since they are not necessary to meet simulation objectives. As a result only rotor dynamics and compressor and turbine heat capacitances will be retained as true states due to their low frequency content. Also as a result of this assumption, certain iterative variables will be required. All other states in the engine are neglected and the component performance maps are manipulated functionally to accomodate these assumptions.

The form of the engine model and information flow follows the schematic shown in figure 3. All major engine components for the bypass duct and core are represented including the inlet throat and duct performance. These are important since the QCSEE UTW engine operates with a high Mach inlet.

Fan tip performance is represented using maps for pressure and temperature ratio as functions of corrected speed and weight flow. In this case the variable pitch angle is added as a parameter. The fan hub performance is assumed correlatable to the fan tip performance. Core inlet duct loss is also included. Fan inlet and discharge pressure are chosen as iterative variables. Fan duct pressure loss is derived from pressure loss relations as functions of duct airflow. The fan nozzle is represented by the nozzle flow equation for unchoked flow. Nozzle area is variable and constant discharge and velocity coefficients are assumed.

The compressor is represented by maps for pressure and temperature ratio. It is assumed that bleed flows are constant percentage of inlet flow and that the compressor operates with the variable stator vanes on schedule at all times. Compressor heat capacitance dynamics are derived from experimental correlations.

The combustor is represented by relations which include pressure drop and heat rise. Combustor dynamics are neglected. Combustor discharge pressure is chosen as a required iteration variable.

The high and low pressure turbine are represented by flow and enthalpy drop maps as functions of pressure ratio and corrected speed. Heat capacitances are derived from experimental experience.

The core nozzle is represented as the fan nozzle except that area is constant. The nozzle inlet pressure is a required iteration variable.

Control representation. - Since the control evaluation is a prime objective of the program a detailed control representation is essential especially for the control laws and switching logic.

The controls model includes representations for the digital and hydromechanical controls components. The digital portion contains detailed representations of the fan speed, inlet Mach number and engine pressure ratio (power) controls. The hydromechanical control includes the core speed, acceleration and deceleration controls.

The schematic of the control system is shown in figure 4. This diagram will not be discussed in detail since it is specific to the QCSEE engine. It is included to illustrate the extent of the control representation in the simulation. For further details see (3) and (4).

The resulting analytical model is sixteenth order and includes four engine states, four iterative loops, four control sensor states and four control actuator states. These do not include the digital controller states.

To meet the real time requirement, methods were required to generate the functional form of the component representations and to attain convergence in the iterative variables. These techniques are described next.

Function Representation

Examination of the function representations required in this model show that some are multivariable functions of two or three variables. To implement these representations in the simulation, two points must be considered. First, the functions must represent the performance of the engine components over a wide range of operation. Second, the computational method developed must be accurate and fast to meet the real time simulation requirement.

Function simplification. - A detailed QCSEE cycle model program was used to obtain data for the component function representations. Since the fan operates over a wider range of conditions than the compressor or turbines, various combinations of corrected fan speed, corrected weight flow and pitch angle were selected as inputs to the program. The outputs of the program consisted of the steady state values of most of the engine internal variables.

From this data the performance of each component was plotted according to the functional relations required in the model. In this way the operating range of each component in relation to the fan operating range was determined. A number of simplifications became evident. The most significant of these was that the core flow path was choked over the entire fan operating range. The compressor and high pressure turbine maps could thus be reduced to functions of a single variable.

Function generators. - Many generalized function generation routines for single and multivariable functions have been developed. These are based on table search and interpolation methods. Function generation routines described in (5) are convenient to use and calculationally efficient. These routines were used to program the function generation requirements of the simulation. Tests were made of the calculation time required for various tasks in the simulation. It was found that approximately 40 percent of the total calculation time was consumed in function generation. This indicated that calculation time could be decreased significantly if faster function generation methods could be found.

Curve fitting. - Another simple, direct means to accomplish function representations is curve fitting. Curves representing single or multivariable functions can be matched by equations containing polynomial, geometric or other analytical functions. Computer programs are available to carry out the details of various curve fitting techniques; however, much trial and error is involved. Higher order equations are used to improve accuracy but computation time increases. Higher accuracy can also be attained by dividing the curves into segments and matching each segment with lower order equations. The curve fitting technique was eventually adopted for this model development.

To illustrate this function generation method, curve fitting techniques are used here to develop the fan corrected flow map. The fan corrected flow map is a function of three variables: pressure ratio, corrected speed and blade pitch angle. It was assumed that the fan map could be represented by the functional relation shown in figure 5. This representation consists of a basic fan map which is a two-variable function based on data for zero-degree blade pitch angle. Modifying functions are applied to one input and the output of the basic fan map.

Using data obtained from the QCSEE cycle model program the functions were plotted to determine their functional form. The speed lines of the basic fan map could be represented by hyperbolas. The coefficients of the hyperbolas were functions of corrected speed calculated by third order polynomial equations. The pressure ratio function was found to be sensitive to both corrected speed and pitch angle. It was represented by a function of two variables derived from a multiple regression formula. The flow function was sensitive only to pitch angle. It was divided into four segments represented by two linear and two second order polynomial equations.

A comparison is shown in figure 6 for the basic fan map cycle model data and the generated function data. The comparison is excellent. The map generated at a constant corrected speed of 95 percent and various fan pitch angles is shown in figure 7. The accuracy is reasonably good for negative pitch angles along the constant 1.613 m^2 (2500 in^2) nozzle area line where most of the operation occurs. More accuracy could be attained but only at the cost of more complexity.

The method of function generation based on curve fitting techniques proved to be calculationally faster than the generalized method for all functions. The largest reduction in calculation time occurs for multi-variable functions. For the three variable fan map the calculation time per point was 85 μs using the curve fitting method. The generalized function generation method required 750 μs.

All component representation were correlated using this technique. It eliminates all generalized function generation and subroutine calls. Its main disadvantage at this point is its lack of general application and associated time consuming optimization using standard curve fitting routines.

Convergence Methods

At this point in the model development the functional relations have been determined and the states established. In addition to the states which require integration, the four iterative loops require a method to converge to a solution.

Iteration. - The initial convergence technique used was a simple iteration procedure. The equation formulation and solution order resulted in one double nested loop and two single loop iterations. The basic problem with iteration was that the time to converge was transient dependent; that is, cycle time varied proportionally to the rapidity of the transient. This is to be expected since larger nonsteady mismatches occur during transients than near steady state and more iterations are required to converge the difference. Simulation frame time must be based on the maximum calculation time in order to avoid missed intervals. Efficiency of this method is not good and was considered unacceptable in this model development.

Integration. - Integration is another method which may be used to provide approximate convergence in iterative loops. In this application the iteration differences which occur are integrated. A sketch of the process is shown in figure 8. The procedure is similar to using high gain integrators in analog computation to prevent algebraic loops. The previous "guessed" value, P_{GS}, is used to calculate the new required steady state value, P. The difference between these two values is integrated to generate an updated "guessed" value. The process shares the same integration algorithm used for the model states.

Integration algorithm evaluation. - To select a suitable integration method an evaluation of several one step direct algorithms was made using the model equations. The fourth order Runge-Kutta method was used as a standard measure of accuracy and stability. On the other end of the spectrum, simple Euler integration was also evaluated. No error analysis was made. Instead an empirical approach was used to determine performance based on a standard model transient.

Since four derivative evaluations are required per time step for the Runge-Kutta, accuracy and stability are high but calculation time is also high even though larger time steps are possible. On the other hand the Euler method had relatively large errors and stability was poor for the same time step range.

Two second order methods, the improved Euler (slope averaging) and the modified Euler (point averaging) methods were also evaluated and found to be comparable. The modified Euler had a slight advantage in programming efficiency. It also provided a compromise in that it computed in half the time of the Runge-Kutta but provided only slightly less stability. The algorithm proved to be stable over a wide range of transients. Because of these advantages the modified Euler algorithm was selected for use in the real time simulation.

Simulation Model

Using the functional correlations derived for the engine components, the state equations, the digital control algorithm and the integration convergence technique, a simulation model was assembled and programmed. The model resulted in a set of sixteen simultaneous first order nonlinear differential equations. These are solved as an initial value problem.

Every effort was made in programming to eliminate unnecessary calculations. Divide computations were minimized and exponentiation avoided. Extensive use of branching on condition was also used. The resulting computer program flow diagram is shown in figure 9.

The model programming and development was accomplished on a Univac 1100-40 computer using Fortran V. On this computer the flight segment of the model consumes 1.9 ms computation time per time increment. Cycle time was not transient sensitive. On the flight simulator computer, a Xerox Sigma 8, cycle time was 5.7 ms or three times slower. On both computers the simulation was found to be stable and accurate for integration time steps up to 50 ms. Thus the real time-to-execution time ratio was 26 for the Univac and 8.8 for the Xerox.

Simulation Results

Simulation verification. - No experimental transient data on the real engine and control system are available to verify the model results independently. Since the detailed cycle deck of the engine is the only source of independent steady state data, a comparison is made with it.

Figure 10 shows a comparison of cycle deck values and simulation model data for a number of selected parameters at operating points which were of primary importance for the control evaluation. These were: 100 percent takeoff power, 62.5 percent approach power and 100 percent reverse power at sea level standard day conditions. The comparison data were generated by setting simulation control values of percent corrected fan speed, fan pitch angle and fan exhaust nozzle area into the cycle deck. The cycle deck data, model data and percent error are shown. Parameters are defined according to the engine model schematic in figure 3.

The simulation data shows excellent agreement with the cycle deck for the two forward cases. Errors are generally less than one percent for the parameters listed. The reverse case is the least comparable with errors in the core path slightly over 5 percent. The model steady state accuracy is very acceptable.

Transient performance. - A number of transients were run which normally can be expected in a manned flight simulation program. These included normal as well as failed forward and reverse transients. A limited number are presented here to indicate the model's flexibility and to show the detail and extent to which engine variables are available.

Normal forward transient: One of the specific QCSEE program objectives was to develop a control which would insure a transient response of less than one second from 62.5 to 95 percent net thrust. This is accomplished primarily by maintaining a high fan speed with manipulation of the fan pitch. Fuel is manipulated to maintain a scheduled engine pressure ratio while the exhaust nozzle is open to a high area setting.

Figure 11 shows a typical approach waveoff transient from approach power at 62.5 percent to go-around power at 100 percent. Shown are a number of engine and control parameters as a function of time. Practically any engine or control parameter can be extracted from the model for display. These shown are only representative.

As shown in the figure the required thrust is achieved in about 0.6 seconds. As power is stepped the power control selects the turbine inlet temperature limit loop and then the acceleration limit and subsequently switches back to the engine pressure ratio control loop. The fan exhaust nozzle moves rapidly to an area slightly less than the takeoff value and then moves to control inlet Mach number for noise suppression. Likewise, the fan pitch is rapidly changed to maintain fan speed and, as shown in the fan speed transient, is a contributing factor in producing the rapid thrust increase.

Normal reverse transient: Another of the specific program objectives of QCSEE is to provide for a fast thrust reversal capability. A key factor here is in the design and evaluation of the control system logic. The thrust reversal must be achieved in less than 1.5 seconds while maintaining safe engine operation. The variable pitch is used to reverse direction of the fan duct airflow. In this model, reversal occurs by rotating the blades through stall.

Figure 12 shows the transient response of a simulated takeoff abort-to-reverse sequence. As shown in the transients, thrust decays rapidly to a reverse level. The small thrust increase at reverse initiation is due to a flow increase produced by the fan pitch opening before the fan speed responds. The flat segment at zero thrust is an effect simulating flow reattachment as the fan blades go through stall. The same effects occur in coming out of reverse. A steady state reverse thrust level is approached in about 1.5 seconds.

Computer failure transient: Figure 13 indicates the transient which occurs when a simulated computer failure is imposed. The failure is simulated by setting the digital computer servovalve torque motor currents to zero. In this condition the nozzle goes to a wide open position, the fan blade pitch fails fixed due to a fail-fixed servovalve and fuel control is assumed by the hydromechanical core speed control. The core speed schedule is set to 10 percent above that which would occur during normal steady state operation.

The initial power is at 62.5 percent. This is followed by a step increase in power to 90 percent. The computer failure occurs at 5 seconds. As shown, net thrust increases as well as fan and core speed. Control is still maintained through the power setting input.

Other transients: Other normal and failed transients were run including takeoff rolls to altitude, constant throttle climb to altitude, inadvertent reverse on takeoff and approach, and various servovalve failure modes. It is important to investigate every conceivable condition that may be encountered in a simulated flight evaluation primarily to insure safe flight simulator operation and to determine model operational limits.

FLIGHT SIMULATOR APPLICATION

This section describes the application of the propulsion simulation to a flight simulator program used to evaluate the simulation techniques and the propulsion system control. The simulation program used the NASA Ames Flight Simulator for Advanced Aircraft (FSAA) facility. The QCSEE UTW simulation developed previously was interfaced with the Externally Blown Flap (EBF) airframe (6). The model integration, interfacing and evaluation program are described and typical prelimi-nary results are presented.

Flight Simulator Description

The FSAA is a general purpose aircraft simulator designed for transport aircraft research. It uses a two-man simulator cockpit operating in six degrees of motion with lateral motion up to 100 feet. It is supported by a central computing facility and a terrain subsystem for visual effects. A brief description of the facility is given here. For a more detailed description and user's guide see (7). A composite photo of the system is shown in figure 14.

Computer. - The real time simulation facility includes a digital computer with links to all peripheral equipment relevant to real time simulations. The heart is the digital computer. It is a Xerox Sigma 8 with a 128 K word core using 32 bits per word. It has a cycle time of 2.5 μs.

Software. - Real time simulation of virtually any aircraft model can be implemented by way of a subroutine system. These functions include all common kinematic and aerodynamic relations as well as environmental and motion relations. These subroutines are partitioned with respect to frequency content into time loops for multirate com-putation.

The engine simulation is a user supplied subroutine. Program inputs include throttle positions, failure switches, aircraft states and atmospheric properties. Program outputs include the aircraft axis components of the applied torque and forces acting on the aircraft due to the propulsion system and parameters to drive engine instruments in the cab.

Visual display. - Visual display includes terrain models which have several runway complexes including a STOL strip. Graphics are generated from the terrain models using a moving base camera com-manded by the digital computer.

Aircraft and Control System Description

Aircraft. - The aircraft simulation used in this study was a high wing four engine externally blown flap (EBF) civil STOL transport simulation developed for previous programs. The aircraft was designed for use with high bypass turbofan engines such as the QCSEE UTW engine. A complete description including the aerodynamic model is given in (1) and (6).

Control system. - The aircraft control system used is described in (1) and (6). In addition to the basic aircraft control system, engine failure or thrust loss compensation controls were incorporated. These include a programmed thrust and roll trim compensation system, a thrust command regulated thrust controller and a flight path stabilization controller. Characteristics of these control concepts are described in (2).

Model Integration

The propulsion system model described in the first part of this paper was integrated into the EBF STOL airframe simulation.

Looping structure. - Normally an aircraft simulation on the FSAA is partitioned into three time loops with a 1:2:4 frame time ratio. The engine subroutines are also normally called from the slow or low frequency loop. Frame times for this loop are usually greater than 60 ms so that the QCSEE models were precluded from being called in that loop. Additionally, the engine model required more computational time than the frame time of the fast loop would permit. Therefore the QCSEE engine was called from the medium speed loop. To save additional computational time all fast loop subroutines were also called from the medium speed loop along with the engine. In addition the slow loop was updated only one-third as often as the medium loop. The resulting loop structure is shown in figure 15. Using this three-to-one two loop structure, enough computation time was available to provide two complete propulsion system simulations. The entire simulation ran in real time on the Sigma 8 with a basic frame time of 50 ms with the simulation period at 150 ms maximum.

Multiengine simulation. - Only two complete engine simulations were included in the aircraft simulation. Since the aircraft required four engines a scheme was devised whereby one simulation was used for the normal or unfailed engine and the other was used for either normal or failed operation. A logic subroutine, shown in figure 16, enabled selecting the engine position at which the programmed failure was to occur and placed the failure model at that position and assigned the proper throttle to it. Control panel discrete signals were used to initiate failures at any time during the flight. The unfailed engine model was assigned to the remaining positions with their throttles ganged together for either forward or reverse thrust operation.

In addition a simple engine model, as described and used in (1) and (2), was programmed to provide a rapid, simple method of trimming the aircraft prior to a flight since the complex models had no fast initialization capability. The simple model was matched in steady state thrust, ram drag and engine speed to data from the complex model. The simple engine could interface with the EBF airframe in the same manner as the complex engine models.

Test Plan

The simulation was exercised in a test program in which environment, aircraft control configuration, propulsion system mode and flight mode were varied.

Environmental variables included wind velocity and direction and turbulence magnitude. Aircraft control configurations included uncompensated, thrust command and flight path stabilization versions of the basic aircraft control. Propulsion system modes included normal, abort and failure modes. Flight modes included takeoff, cruise, approach, landing and reverse with and without braking action. Failures were prescreened and limited to those types that caused pilot concern if they occurred in flight.

In addition to the broad objectives stated earlier, a number of specific objectives were established in the test program. These were related generally to engine and control performance and pilot reaction. As regards performance these included turbine life consumption, thrust linearity, fan blade pitch modulation, reverse control logic and effect of gusts and turbulence on inlet Mach number control. Pilot reaction items include thrust response, engine and control failure response and automatic control sequencing.

Preliminary Results

Data was recorded in the form of time histories for over 100 flights with various NASA experimental test pilots. Data recorded include engine performance variables, control system parameters and aircraft status. Output was in the form of multiplexed (two variables per channel) strip charts for selected variables on both engine models. In addition, the complete data set of engine, control, environmental and control input variables were recorded on tape for each time interval. Also, a printout was obtained of selected variables for initial and final conditions, minimum-maximum values and statistical variations including mean and standard deviations.

Simulation operational limits. - Results of the simulation technique evaluation are based primarily on observable restrictions to model operation during the integration and flight test phases.

Although the propulsion system model was exercised over the expected flight operation range, operational conditions and engine manipulations were encountered in the flight program which were not preexamined. These, in general, led to operational limits which were imposed on the model.

Power range was limited at the low end to 30 percent in forward and 40 percent in reverse. These limits were needed to avoid run time errors caused by a model instability related to the lead-lag representation used in the turbine heat soak model. The instability was initiated by large rapid throttle decreases which usually occurred after aircraft touchdown. The only restriction to the flight program was the requirement to start at a higher thrust level than that of ground idle at takeoff.

Another limitation imposed was the restriction to the flight Mach number to a maximum of 0.4. The thrust parameter used in the QCSEE power control is engine pressure ratio. It is insensitive to flight Mach number below about 0.4. Above that, however, nonlinear corrections to the thrust management schedule must be made to maintain a flat rated thrust rating and linear power-to-throttle demand. This omission in the existing QCSEE control led to the restriction on flight Mach number.

Within the limitations imposed there were no run time errors or missed intervals due to the engine simulation during the flight simulation program.

Failure effects evaluation. - A preliminary evaluation of all failure modes programmed into the engine simulation was made to determine which failures produced effects of consequence to the aircraft. The purpose was primarily one of safety but also to advise the pilots of possible effects on aircraft stability so that compensatory changes to the aircraft control could be anticipated. Failures simulated included: engine out, digital computer failure, inadvertent reverse; nozzle, fan pitch and fuel servovalve failures in open, closed and fixed positions; and nozzle, fan pitch and fuel valve position and engine pressure ratio sensor loss.

All failures except those involving the nozzle required significant pilot action. The engine out, inadvertent reverse, failed close fan pitch and failed closed fuel servovalve failures (in general, failures resulting in thrust loss) required roll trim compensation. This was provided through a commanded differential position of outboard flap in the lateral stability and augmentation system. Normally, this trim is actuated by the pilot. However, if a digital control contains failure detection and indication logic, an important aspect of digitial control capability, aircraft control compensation can be programmed to occur automatically when a failure signal is received at the flight control computer. This control integration feature was assumed in all flights.

Flight control compensation effects. - Normal pilot recognition delays and reaction to engine failures are of significant concern in powered lift aircraft. Cueing by visual means to alert the pilot to engine thrust loss is one potential solution. An alternate approach is for automatic thrust loss compensation provided by a thrust command or regulated thrust control (3). Thrust loss compensation controls such as these were evaluated in the flight simulation program.

Thrust command control: A thrust control concept is shown in figure 17. In this concept total engine thrust is compared to the commanded thrust. After an engine failure the error generated would cause the thrust control to advance the power inputs until the demanded level is achieved. For normal operation the pilot can select thrust level separately or together for all engines.

Typical flights: Representative time histories of two flights without and with the thrust command control during an engine failure are shown in figure 18 (without) and figure 19 (with). The loss of the right outboard engine is simulated during an approach maneuver with subsequent landing and reverse. Wind is ahead at 15 knots with 0.91 mps (3.0 fps) rms turbulence. Each channel in figures 18 and 19 is multiplexed to show two variables. Except for the aircraft status data, unfailed engine data is contained in the "short side" traces while failed engine data is in the "long side" traces.

Performance without compensation: Turbine inlet temperature variations, figure 18, due to pilot throttle movement during the unfailed engine approach segment, are small. They were comparable to other similar approach flights without engine failure. Variations to 111^{o} K (200^{o} R) without substantial peaking were typical.

The outboard engine failure occurs at 263 meters (863 feet) altitude. There is a 1.25 second delay in pilot response to initiate a power compensation adjustment for the power loss and 4.0 seconds to accomplish the adjustment. Roll trim was automatically inserted into the lateral-directional stability and command augmentation system at the point of failure. As shown on the runway position history, the aircraft yaws left on the approach strip.

Performance with compensation: Unfailed operation with the thrust command control in the throttle loop, figure 19, shows that throttle movements to adjust thrust on approach tends to produce peaking in the fuel flow and turbine inlet temperature. This peaking is not observed to the same degree in uncompensated flights.

The outboard engine failure occurs at approximately 100 meters (325 feet) altitude. Because of the disparity in failure altitudes it is not possible to draw conclusions regarding thrust command control effects on touchdown and landing performance. At engine failure there is no delay due to pilot reaction. The rapid automatic compensation for thrust loss eliminates the need for pilot corrective action on thrust and improves throttle response. The controller corrected the power inputs in 3.0 seconds which is about 57 percent of the total time in the uncompensated case. Roll trim was again automatically engaged. Although no judgement can be made in the basis of a single flight, in this case the aircraft yaw was reduced substantially from the previous flight. The performance of the unfailed engine after the failure is very similar to normal uncompensated flights including the reverse sequence.

With the automatic thrust command control, peaking occurs in the turbine inlet temperature which may be detrimental to engine life. This peaking is due to the thrust command control which effectively modifies the power demand dynamically even without an engine failure. Off-line runs with the command system simulated verify this point. The thrust command control is not optimized for the system. However, it is obviously interacting with the engine control. This points up the requirement for an integrated aircraft propulsion system approach particularly for high response, close coupled powered lift systems.

CONCLUDING REMARKS

Flight simulation provides a safer and relatively inexpensive approach to propulsion system evaluation compared to flight testing. This is especially true for failure modes and effects analysis. And, depending on the level of detail, it permits observation of internal system parameters which could otherwise be difficult or impossible to measure in flight.

The real time digital propulsion system simulation effort under the QCSEE Program has generated valuable simulation technology and flight simulator operational experience. It has yielded a technically feasible real time digital simulation approach which is faster and has much higher real-to-execution time ratios than previous models. The techniques developed have been effective in permitting an excellent level of detail within real time constraints. In addition, the application of this model to a flight simulator has indicated the need for an integrated aircraft-propulsion system approach to powered lift systems.

Interest in real time digital simulation has grown and appears to have widespread application beyond flight simulators. These include the use of the present QCSEE model in various controls analyses and application of model techniques developed in this study to other controls analysis models.

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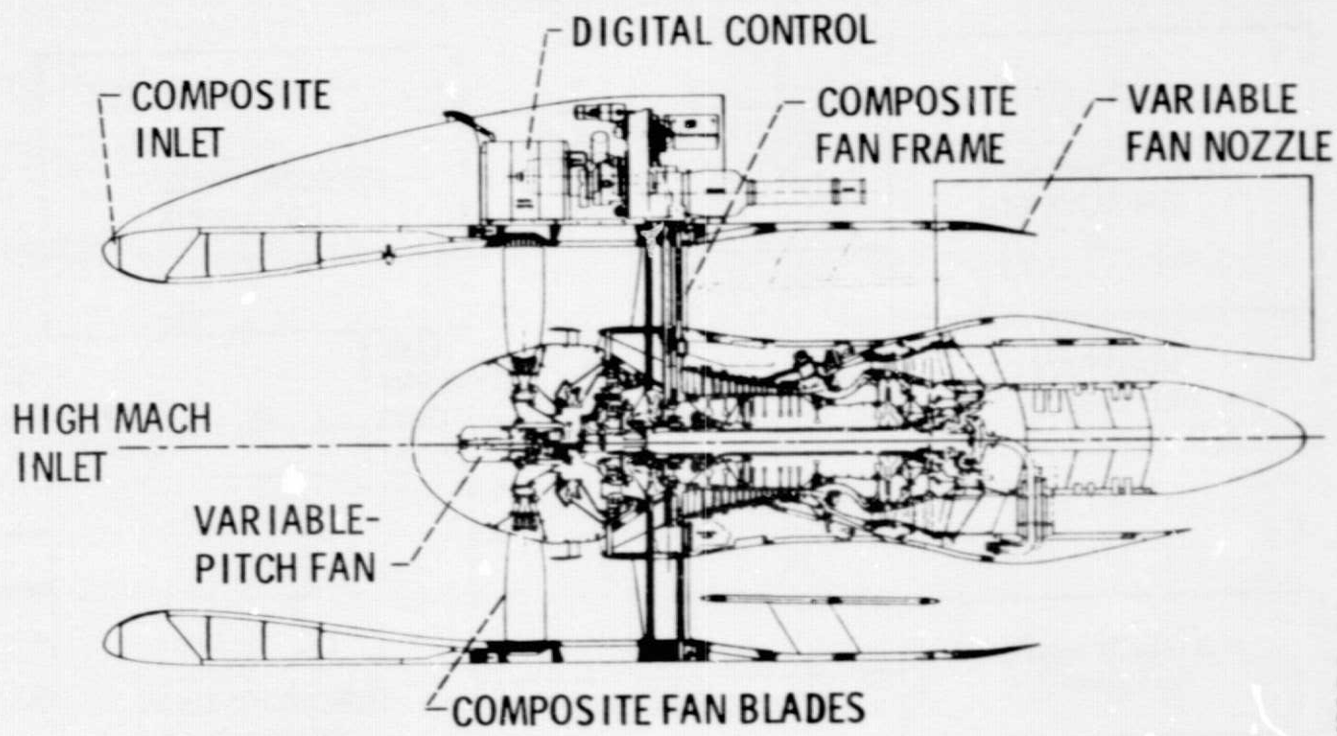

Figure 1. - QCSEE UTW experimental propulsion system.

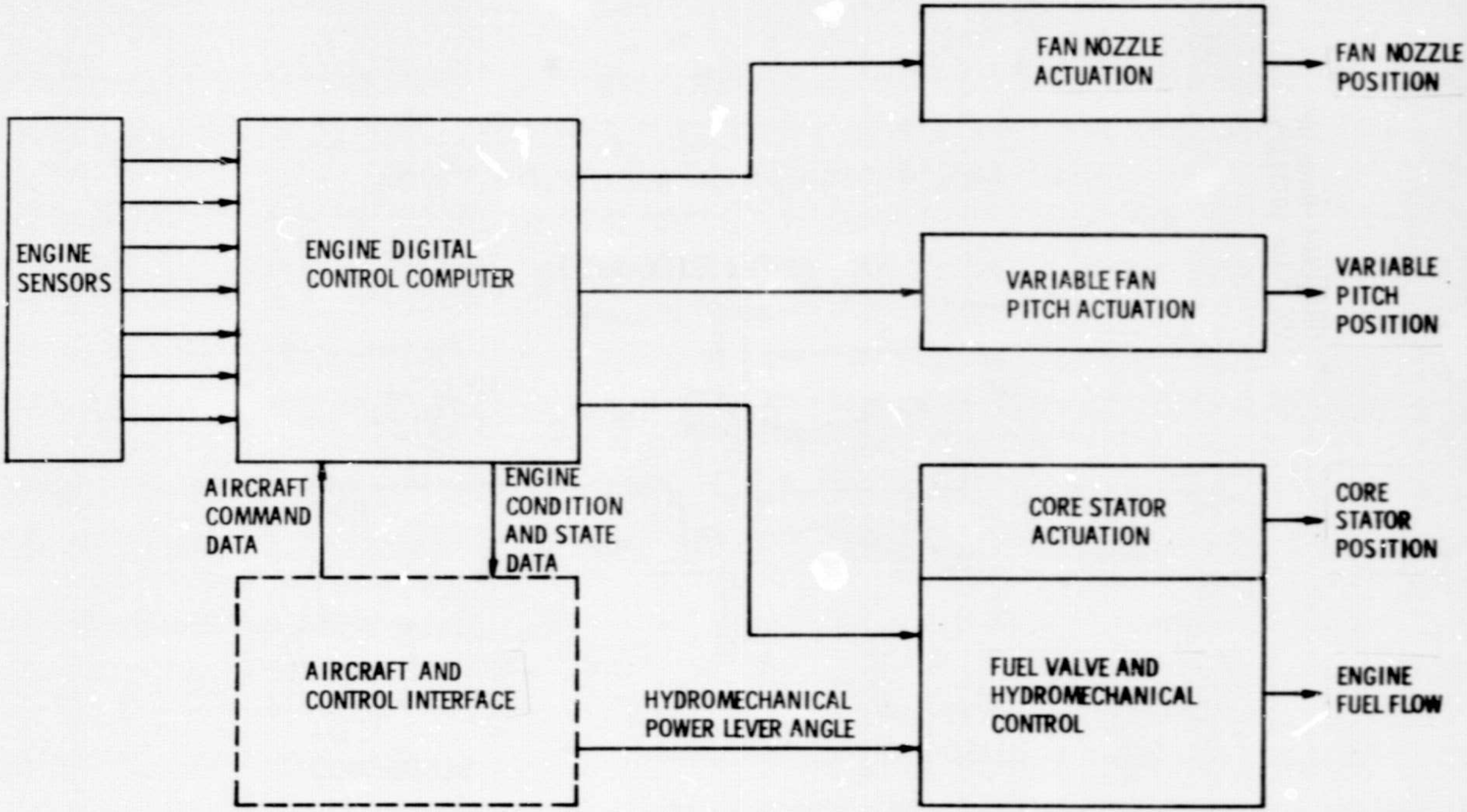

Figure 2. - QCSEE UTW control system schematic.

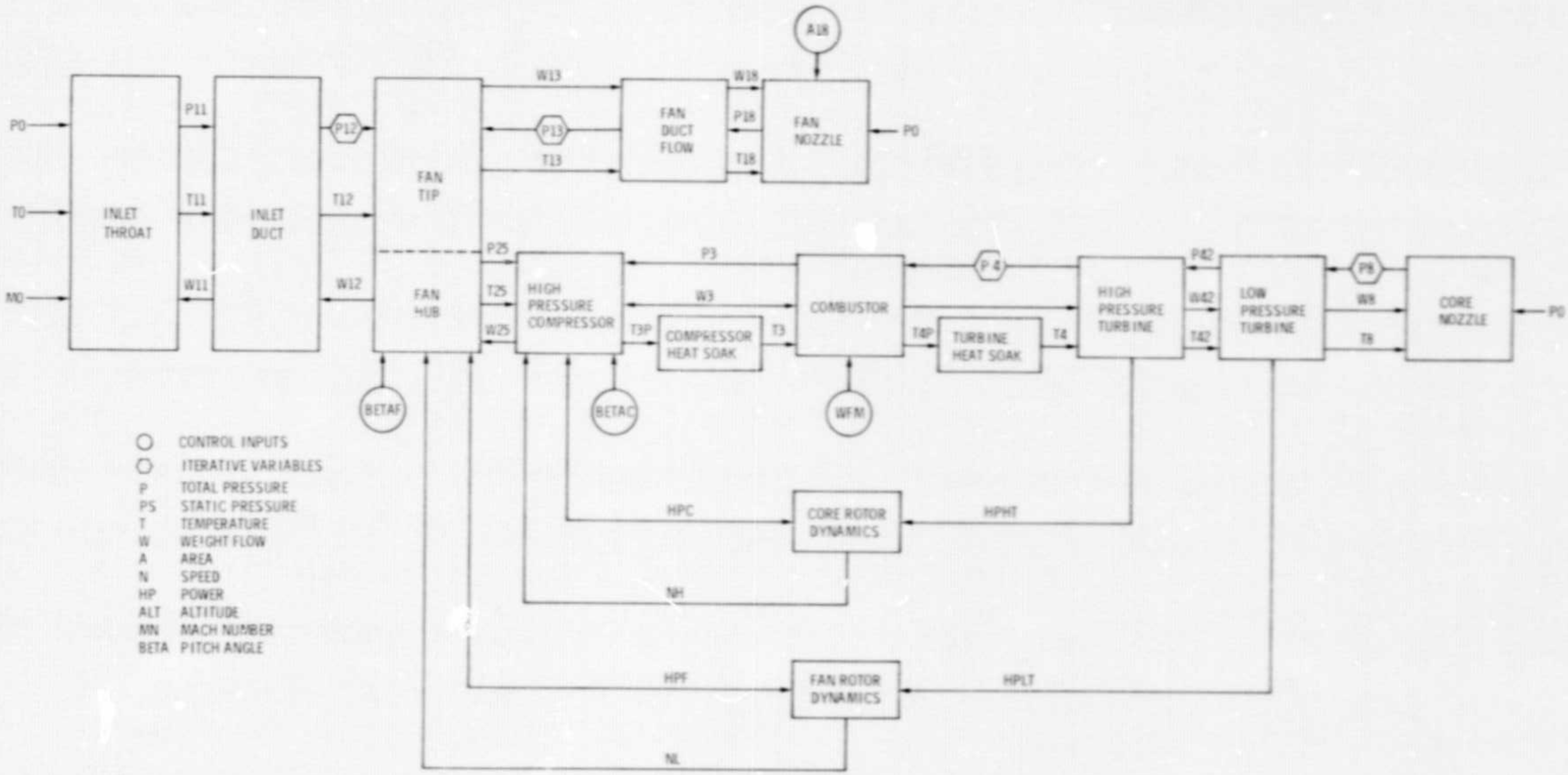

Figure 3. - QCSEE engine model schematic and information flow diagram.

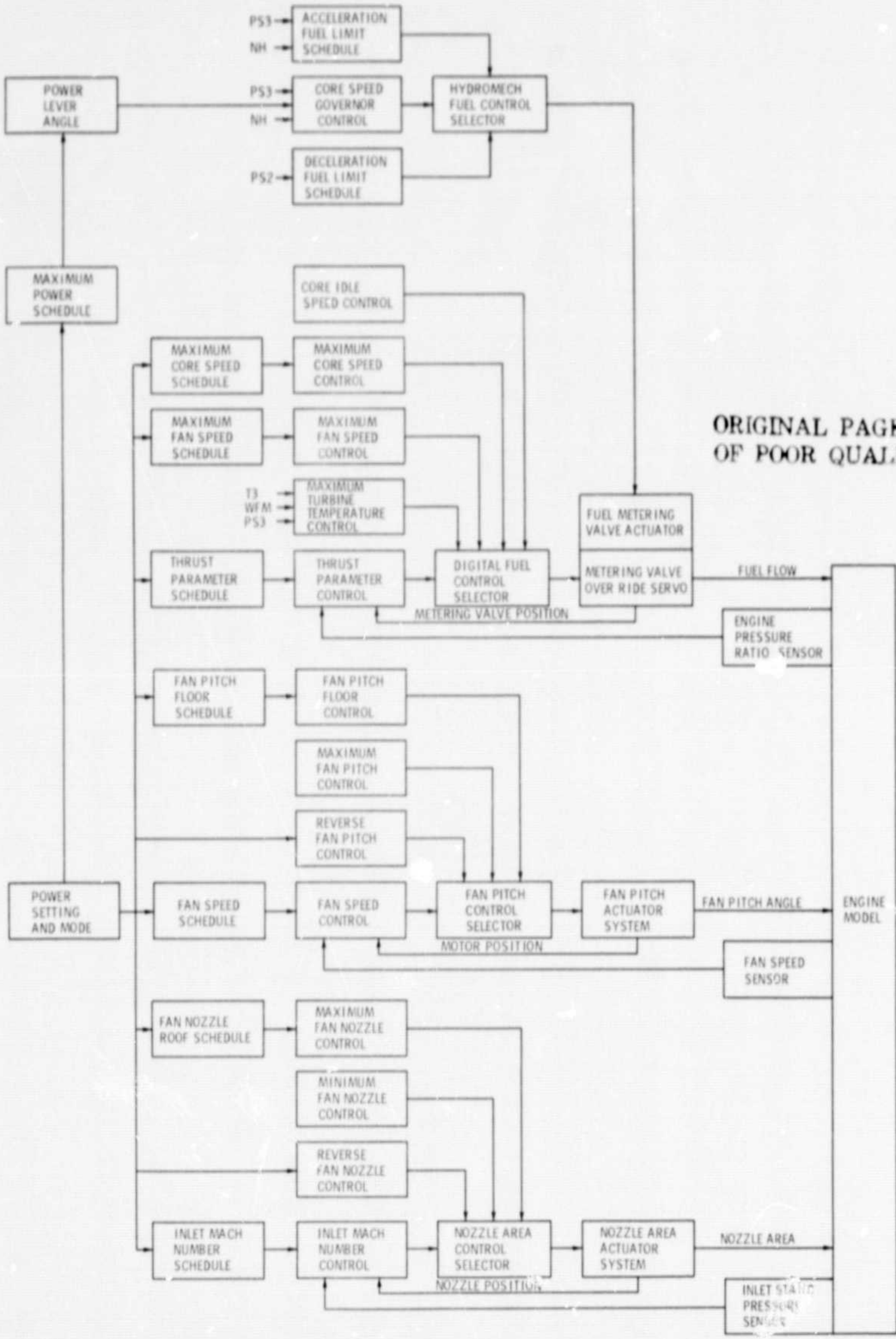

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Figure 4. - QCSEE control model schematic.

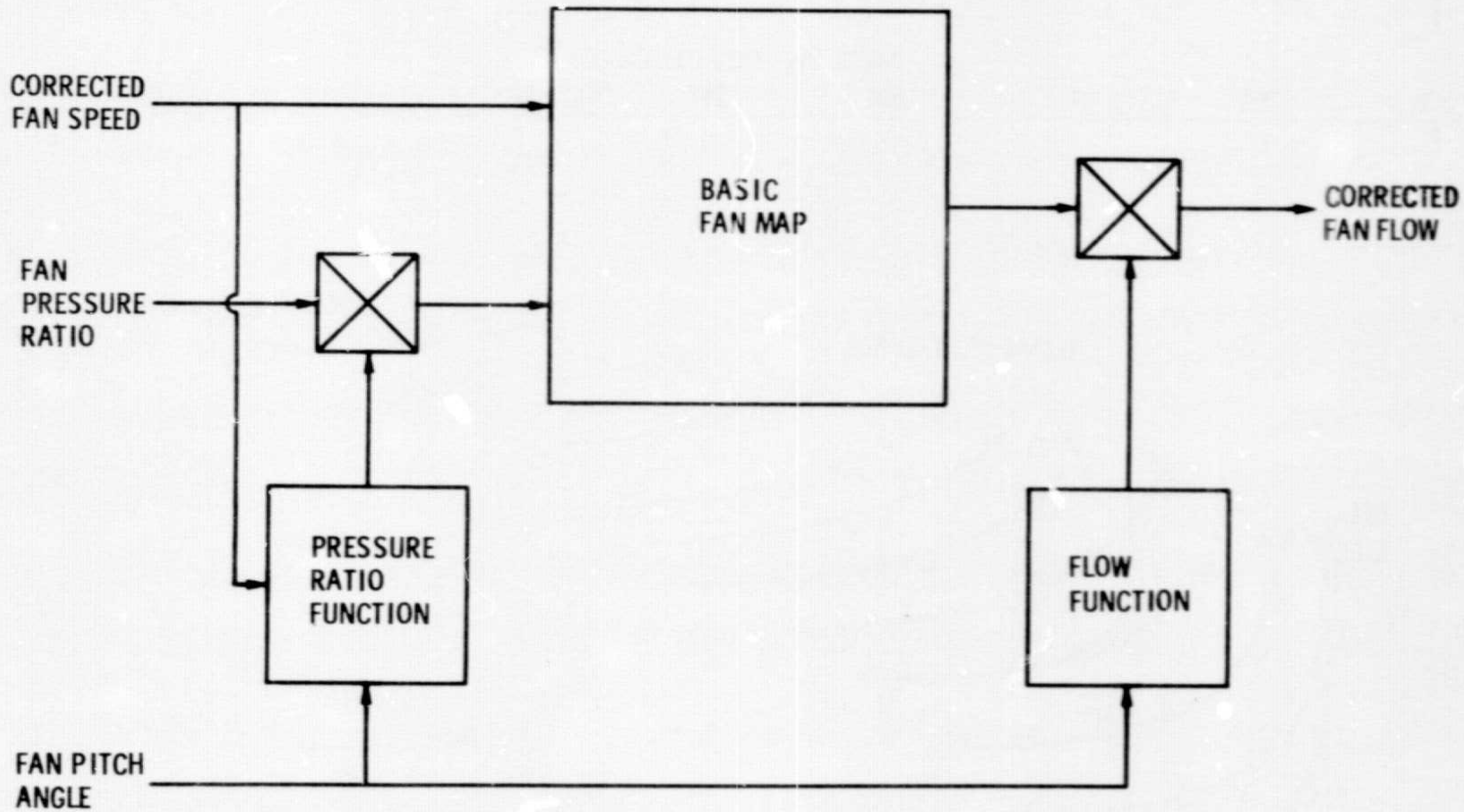

Figure 5. - Variable pitch fan representation and flow diagram.

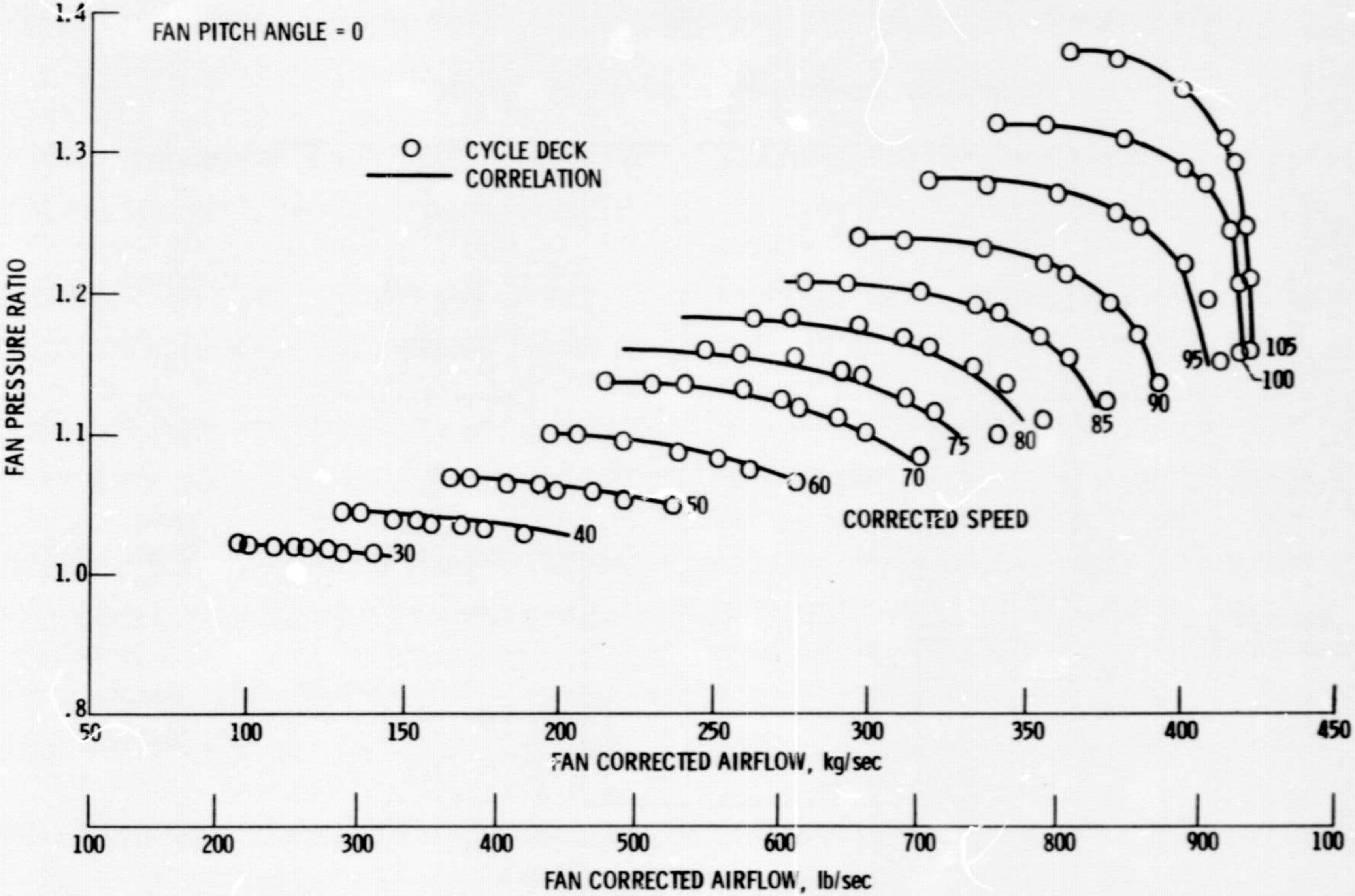

Figure 6. - Comparison of actual fan map to model correlation with fan pitch constant.

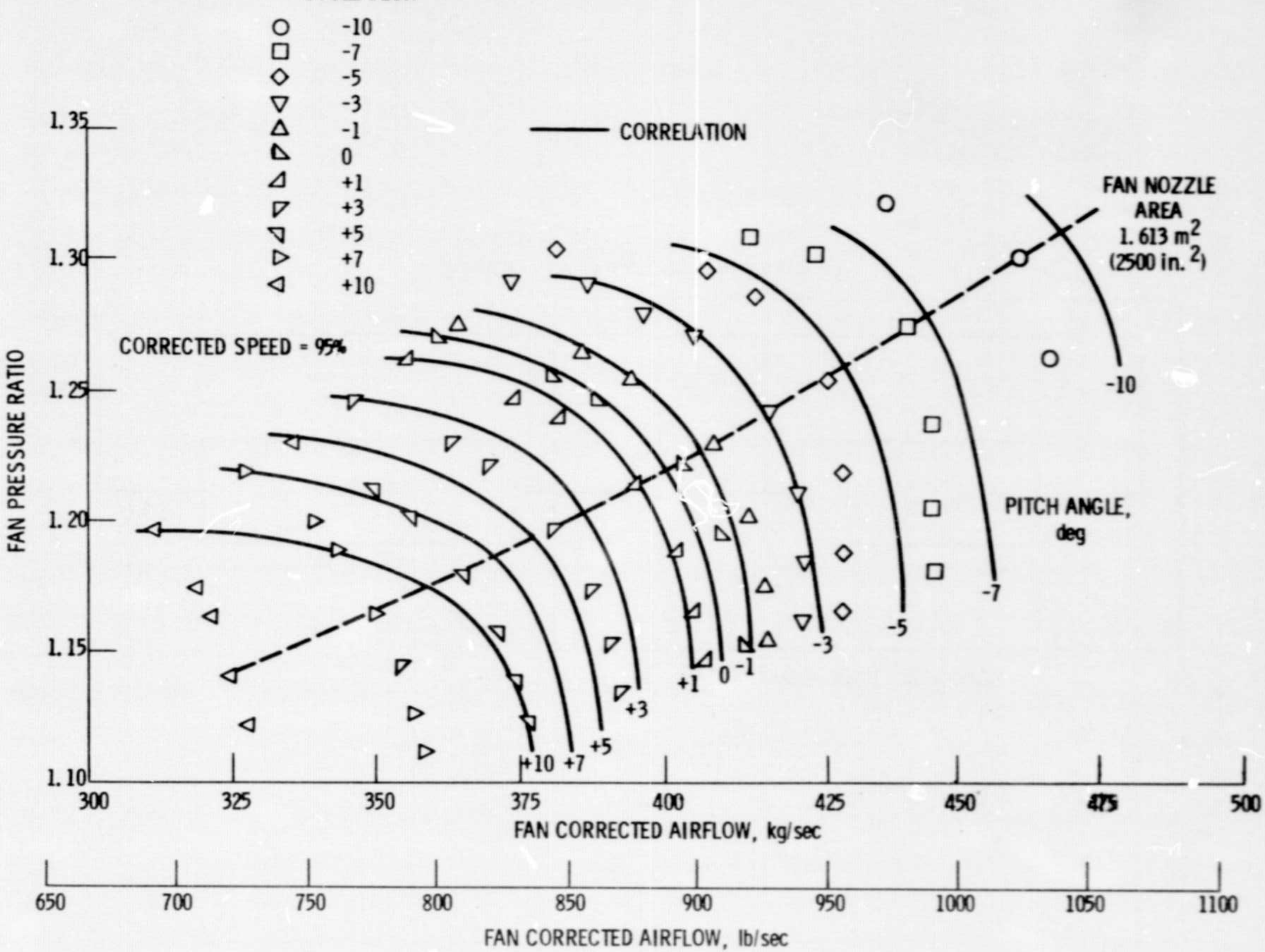

Figure 7. - Comparison of actual fan map to model correlation with fan corrected speed constant.

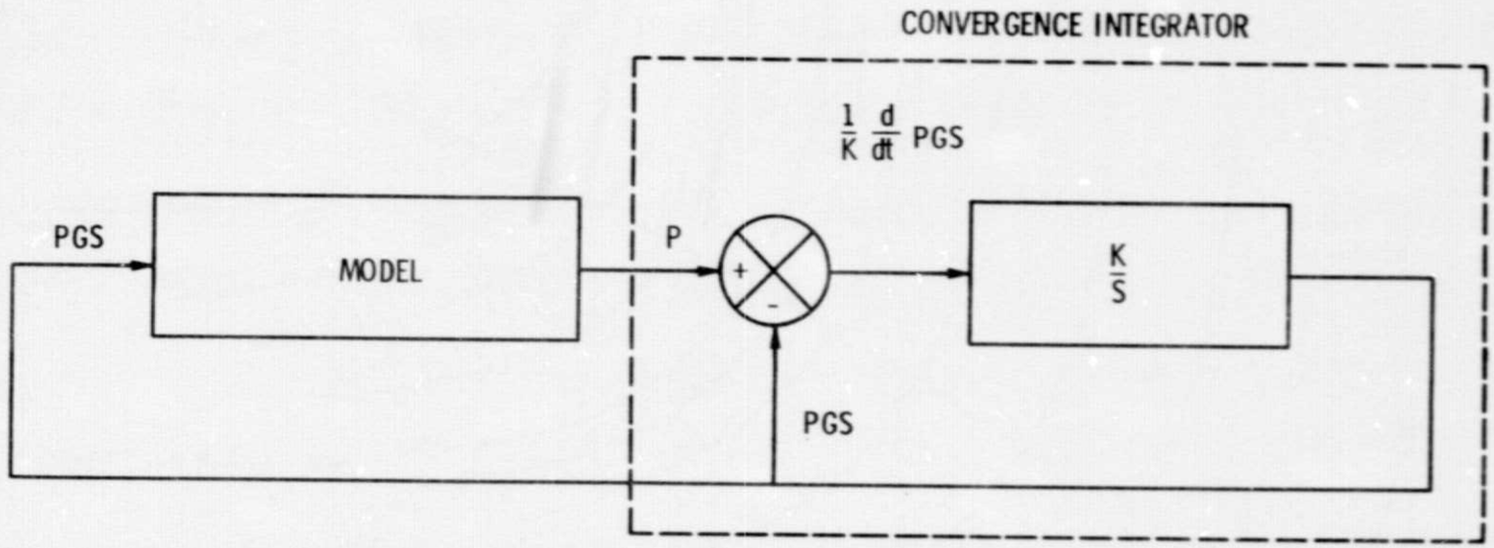

Figure 8. - Integration convergence method.

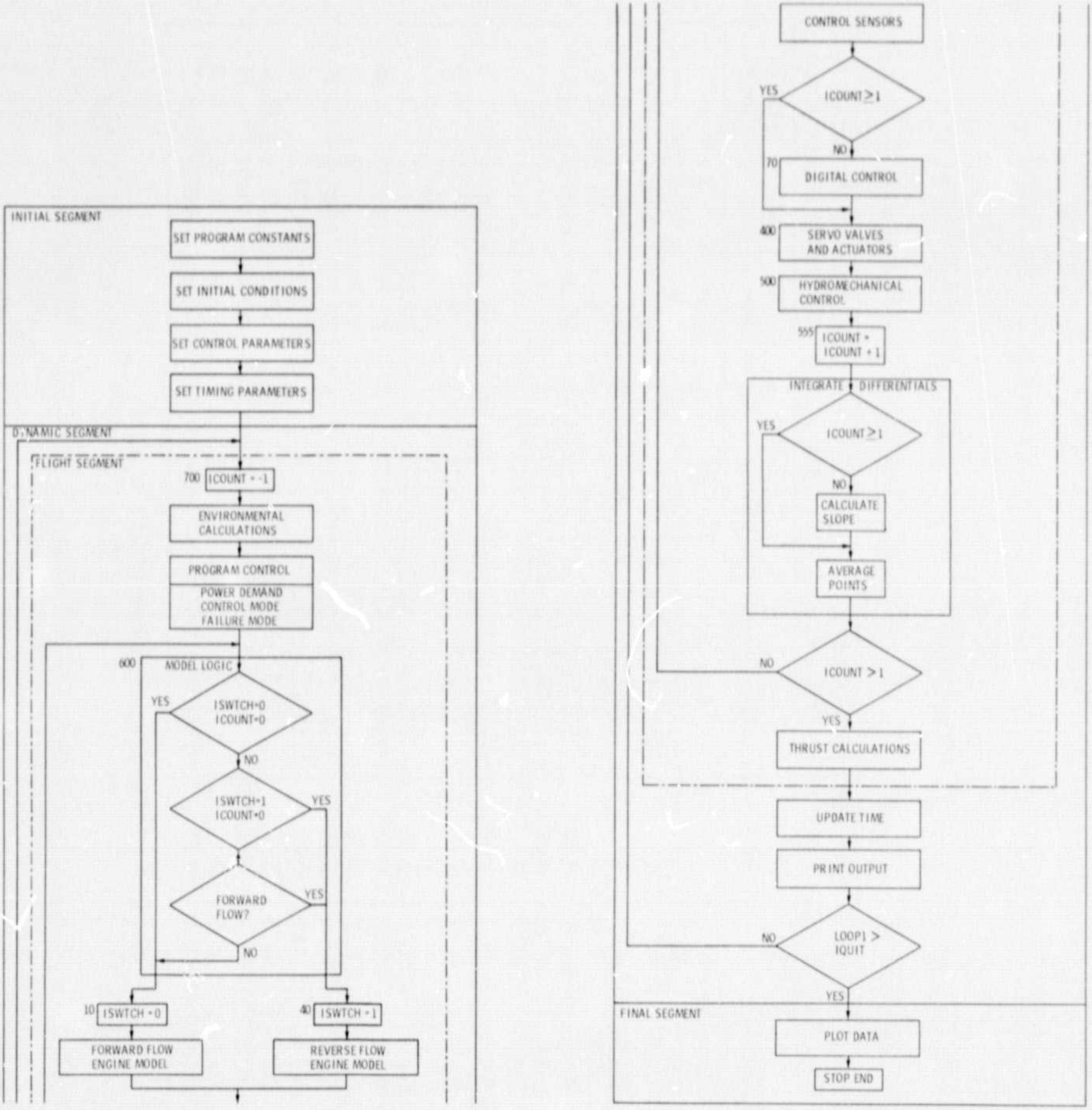

Figure 9. - Computer program flow diagram.

		100 PERCENT, TAKEOFF POWER SEA LEVEL STATIC STANDARD DAY			625 PERCENT, APPROACH POWER SEA LEVEL STATIC STANDARD DAY			100 PERCENT, REVERSE POWER SEA LEVEL STATIC STANDARD DAY		
		CYCLE DECK	MODEL	PERCENT ERROR	CYCLE DECK	MODEL	PERCENT ERROR	CYCLE DECK	MODEL	PERCENT ERROR
ALT	FT	0	0	----	0	0	----	0	0	----
MNO		0	0	----	0	0	----	0	0	----
FN	LB	17 319.2	17 367.4	0.28	10 703.2	10 646.4	-0.53	-6 427.0	-6 397.6	-0.46
NL	RPM	3 066.4	3 066.4	0	2 627.1	2 626.9	-0.01	2 476.87	2 472.5[illegible]	-0.18
BETAF	DEG	-2.14	-2.14	0	1.56	1.56	0	-85.0	-84.55	-0.47
W12	PPS	887.45	885.28	-0.24	730.64	726.93	-0.51	-587.33	-588.09	0.13
XM11		0.7897	0.7903	0.08	0.5424	0.5409	-0.28	----	----	----
A18	IN^2	2 608.7	2 608.7	0	2 8[illegible].71	2 817.71	0	----	----	----
NH	RPM	13 044.1	13 046.9	0.02	11 9[illegible]7.8	11 950.1	-0.23	13 060.2	12 960.8	-0.76
W25	PPS	67.70	67.65	-0.07	52.73	52.24	-0.93	50.27	48.80	-0.93
P25	PSIA	17.17	17.23	0.35	16.32	16.37	0.31	11.79	11.76	-0.25
T25	R	554.34	553.28	-1.64	541.31	540.16	-0.21	518.67	518.67	0
P3	PSIA	206.90	207.98	0.52	146.84	144.97	-1.27	155.07	152.59	-1.60
PS3	PSIA	205.00	206.06	0.52	146.08	144.24	-1.26	154.15	151.72	-1.58
T3	R	1 221.58	1 219.52	-0.17	1 087.60	1 085.62	-0.18	1 196.79	1 182.26	-1.21
WFM	PPH	5 505.8	5 504.6	-0.02	3 150.02	3 052.85	-3.08	4 331.1	4 084.6	-5.69
T4	PCT	100.0	99.56	-0.44	100.0	98.49	-1.51	100.0	96.66	-3.34
W8	PPS	69.22	69.18	-0.06	53.60	53.43	-0.32	51.47	50.94	-1.03
P8	PSIA	16.28	16.28	0	15.50	15.51	0.06	15.64	15.58	0.38
T8	R	1 606.02	1 594.38	-0.72	1 387.08	1 377.49	-0.69	1 744.12	1 665.19	-4.53

Figure 10. - Steady-state verification of QCSEE simulation.

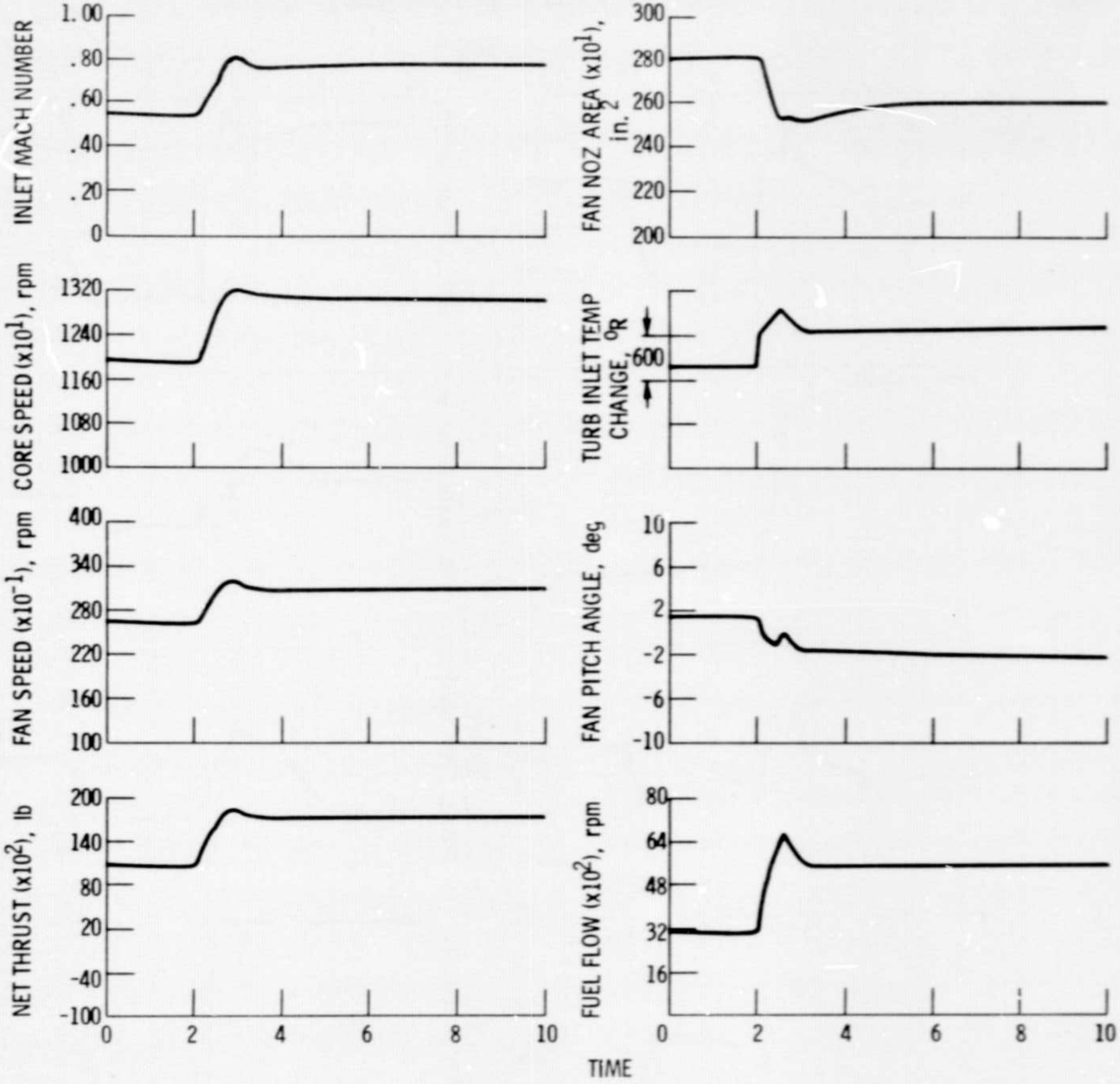

Figure 11. - Typical approach and waveoff transient.

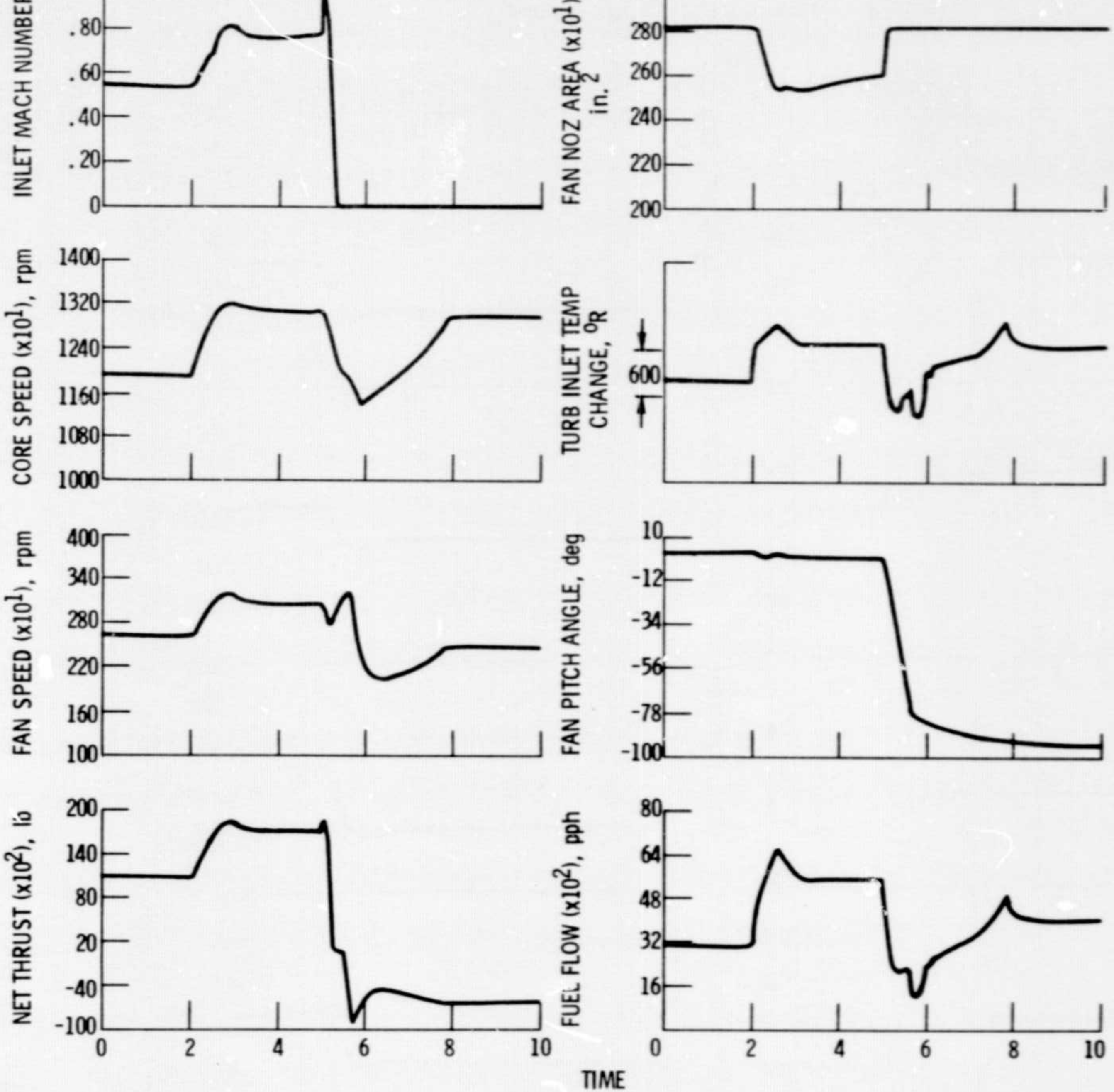

Figure 12. - Typical aborted takeoff to reverse transient.

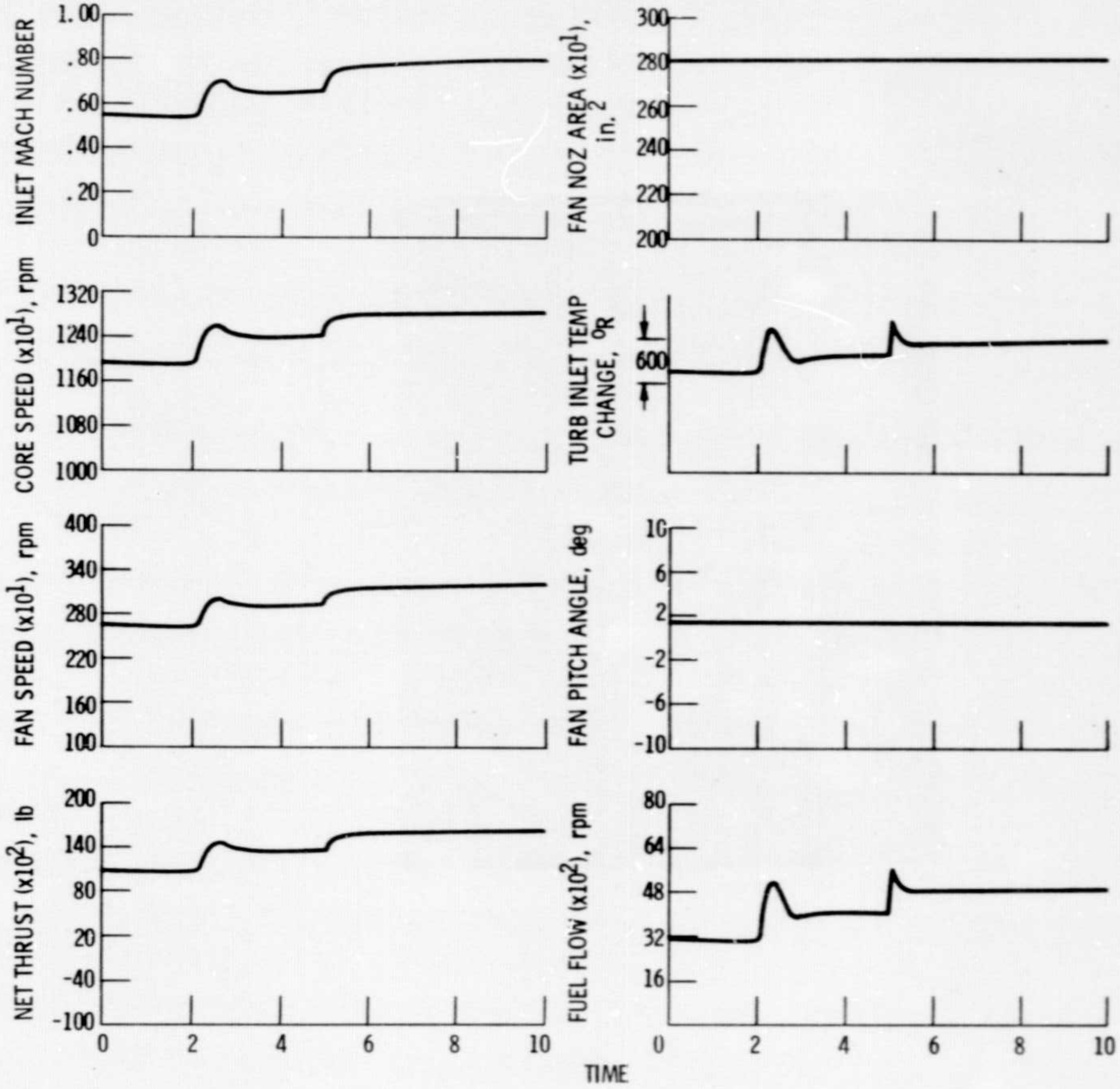

Figure 13. - Simulated control computer failure transient.

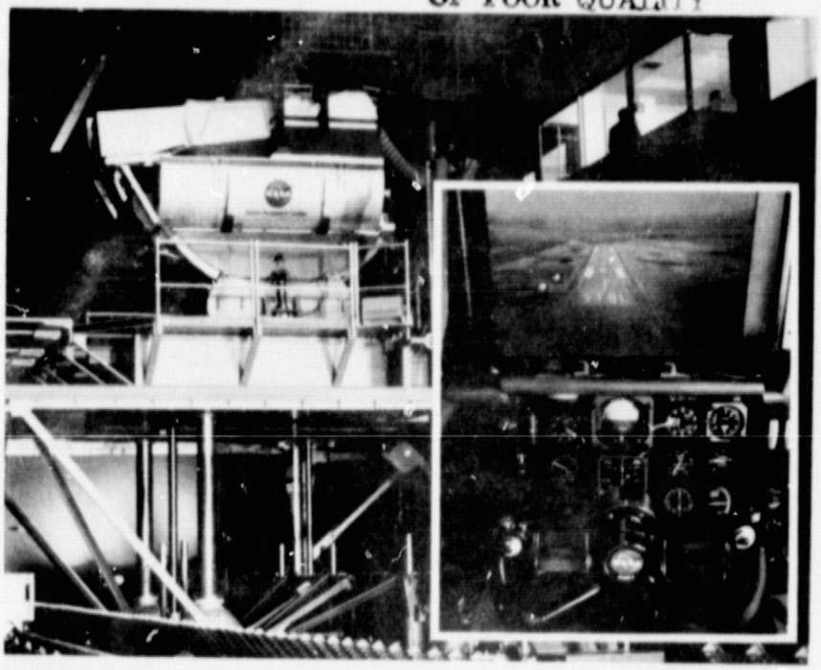

Figure 14. - FSAA facility.

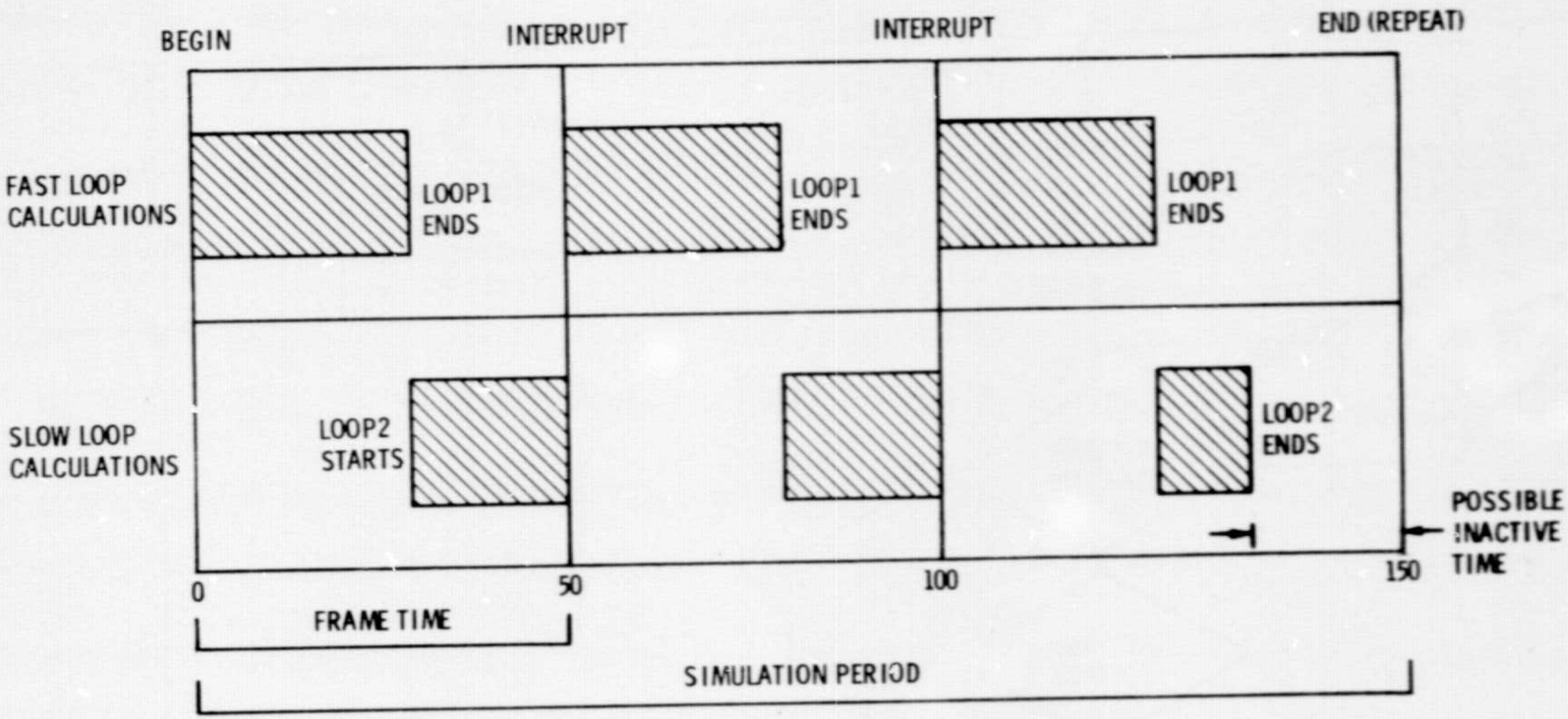

Figure 15. - Multirate loop scheme for QCSEE~EBF simulation.

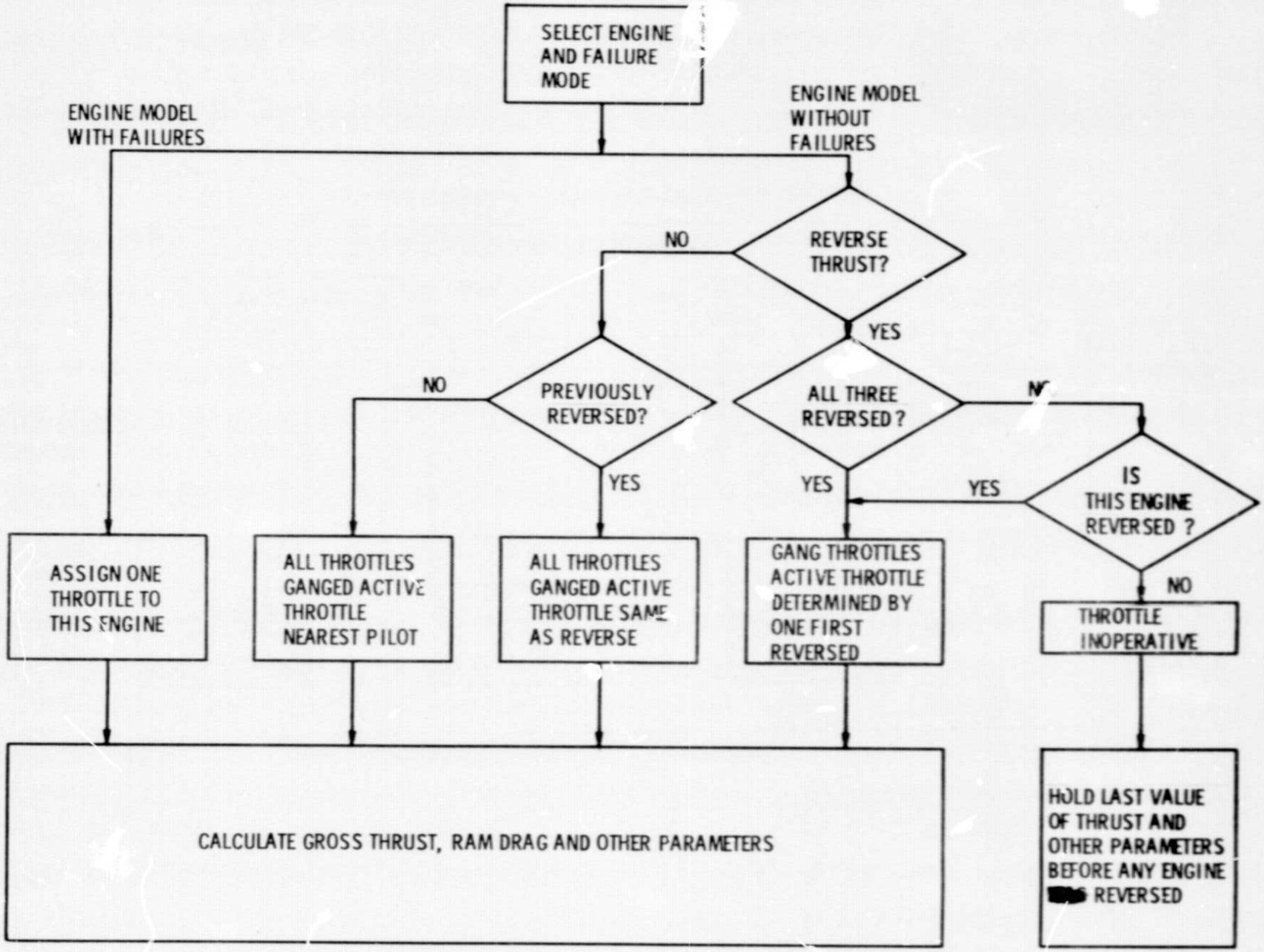

Figure 16. - Multiengine switching logic scheme.

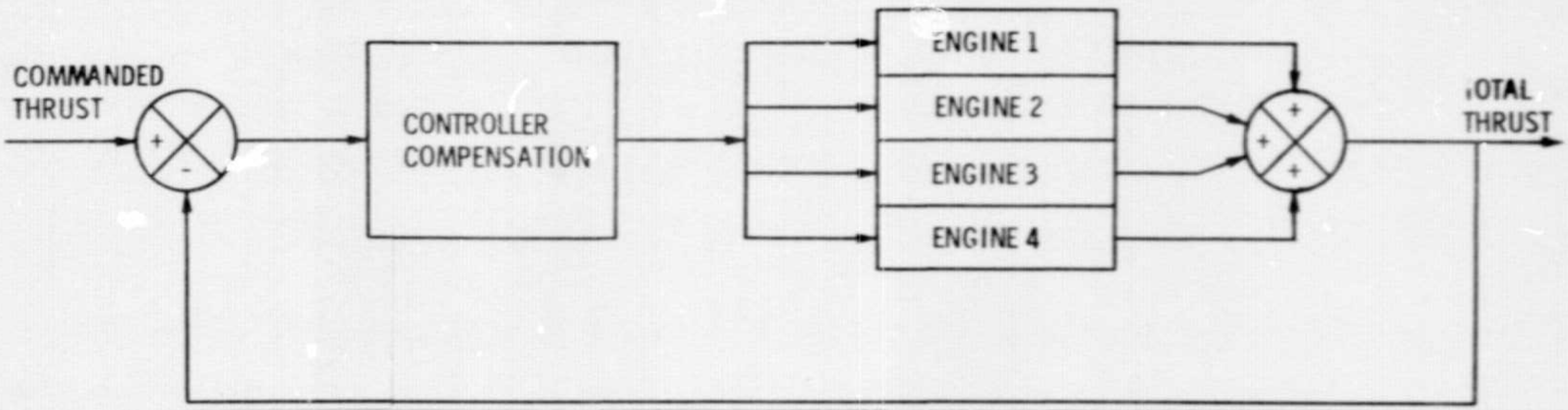

Figure 17. - Conceptual thrust command control system.

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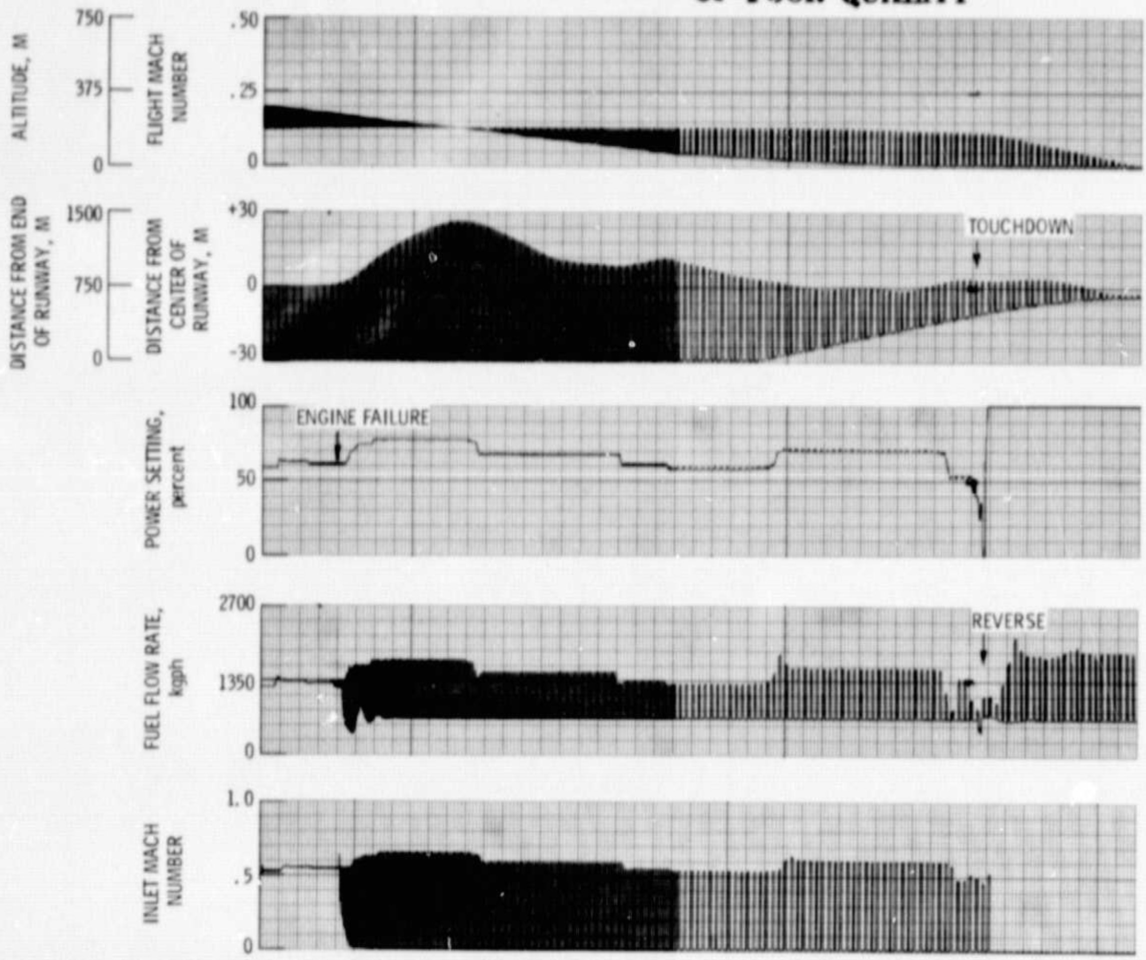

Figure 18. - Time history of an approach with engine failure landing and reverse - without thrust command.

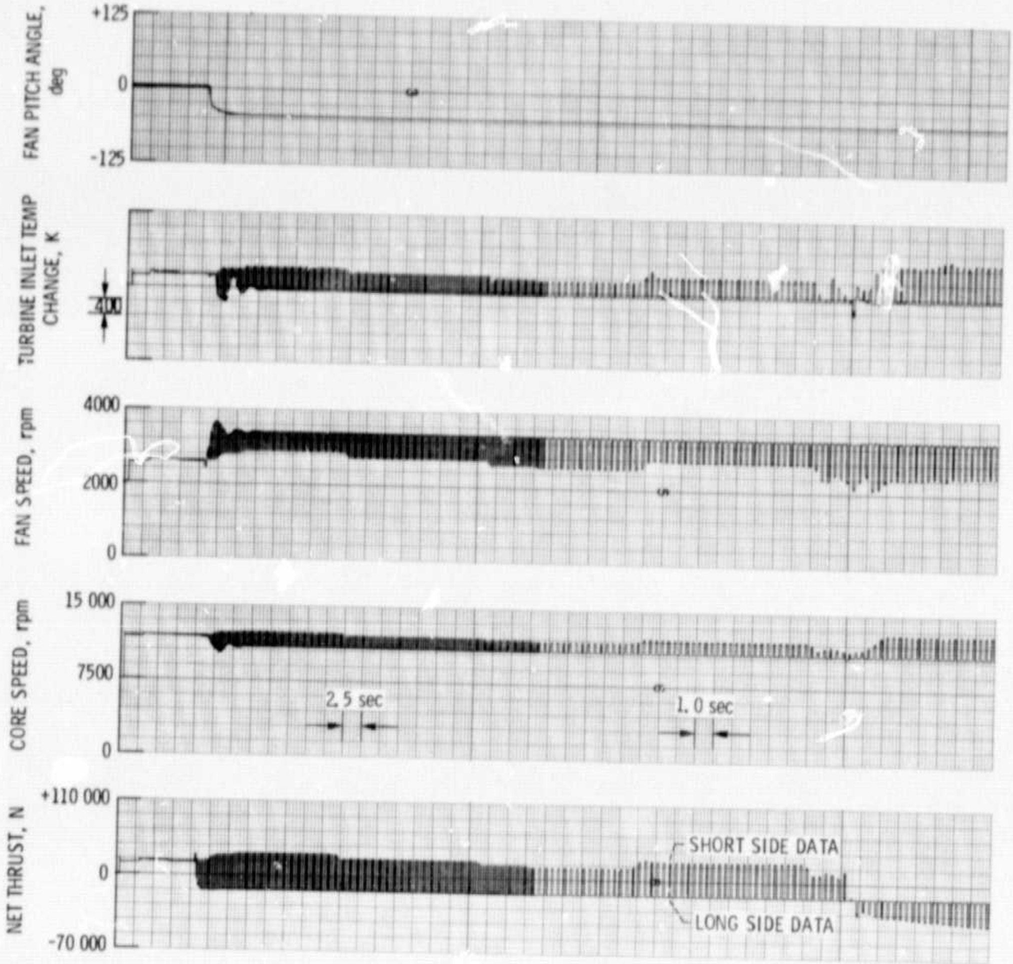

Figure 18. - Concluded.

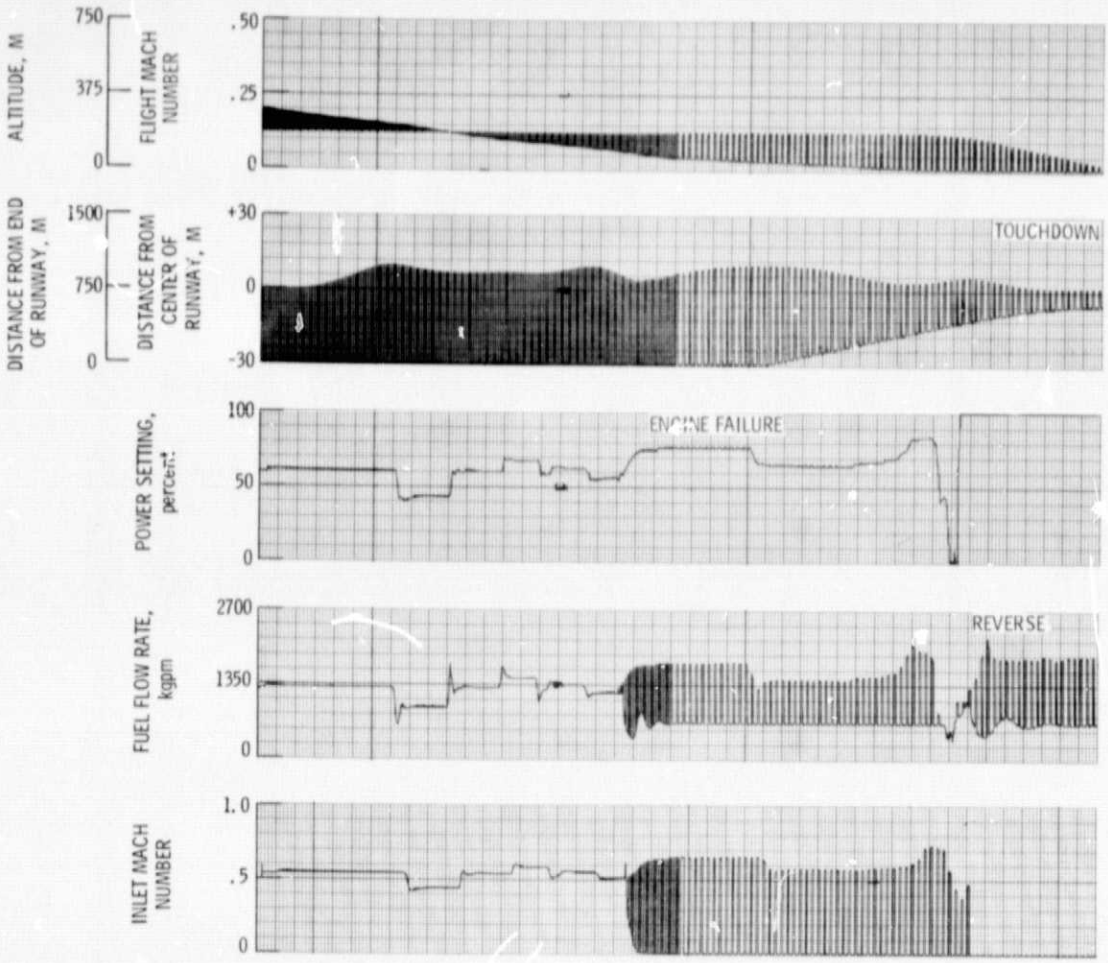

Figure 19. - Time history of an approach with engine failure landing and reverse - with thrust command.

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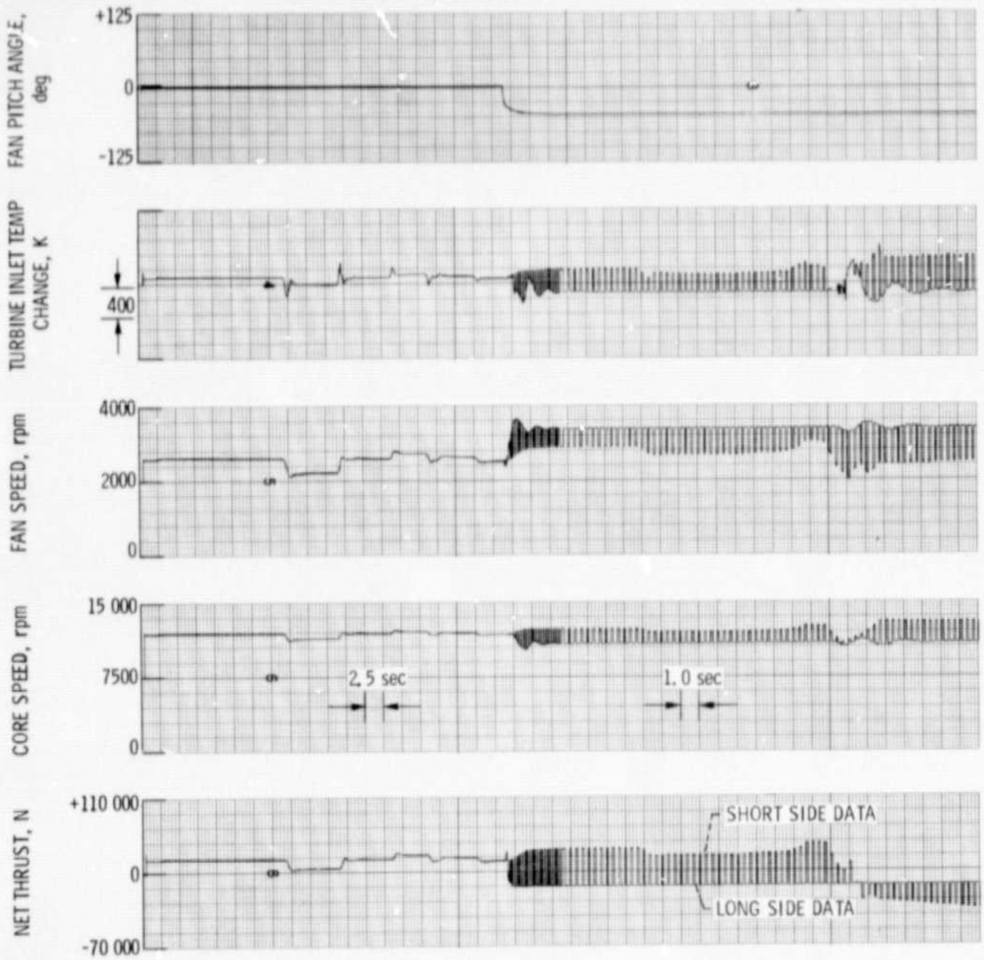

Figure 19. - Concluded.

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16. Abstract

In the past propulsion system simulations used in flight simulators have been extremely simple. This results in a loss of simulation realism, eliminates significant engine and aircraft interaction dynamics and prevents generation of important internal engine parameters. Reasonably detailed simulations will be necessary to permit system evaluations in a simulated flight environment. A real time digital simulation of a STOL propulsion system was developed which generates significant dynamics and internal variables needed to evaluate system performance and aircraft interactions using manned flight simulators. The simulation ran at a real-to-execution time ratio of 8.8. The model was used in a piloted NASA flight simulator program to evaluate the simulation technique and the propulsion system digital control. The simulation is described and results shown. Limited results of the flight simulation program are also presented.

17. Key Words (Suggested by Author(s))
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