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A Real Time Pegasus Propulsion System Model for VSTOL Piloted Simulation Evaluation

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NASA

**A REAL TIME PEGASUS PROPULSION SYSTEM
MODEL FOR VSTOL PILOTED SIMULATION EVALUATION**

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Abstract

An emphasis on increased aircraft and propulsion control system integration and piloted flight simulator evaluation has created a need for high fidelity real time dynamic propulsion models. In recognition of this need, a real time propulsion system modeling technique suitable for use in man-in-the-loop simulator studies has been developed by NASA-Lewis and demonstrated using flight simulator facilities at NASA-Ames. This technique provides the system accuracy, stability and transient response required for integrated aircraft and propulsion control system studies.

A Pegasus-Harrier propulsion system was selected as a baseline for developing mathematical modeling and simulation techniques for VSTOL. Initially, static and dynamic propulsion system characteristics were modeled in detail to form a non-linear aerothermodynamic digital computer simulation of a Pegasus engine. From this high fidelity simulation, a real time propulsion model was formulated by applying a piece-wise linear state variable methodology. A hydromechanical and water injection control system was also simulated.

The real time dynamic model includes the detail and flexibility required for the evaluation of critical control parameters and propulsion component limits over a limited flight envelope. The model contains approximately 7.0K bytes of in-line computational code and 14.7k of block data. It has an 8.9 ms cycle time on a Xerox Sigma 9 computer.

The model has been programmed for interfacing with a Harrier aircraft simulation at NASA-Ames. Typical propulsion system simulation results are presented.

Introduction

During low speed operations, VSTOL aircraft depend not only on the propulsion system for lift, but also for the forces and moments needed for flight path and attitude control. Thus highly coordinated integrated flight and propulsion control systems are critical and necessary to the success of these advanced aircraft.

Simulation, with its inherent flexibility, will play a key role in the development of these integrated aircraft-propulsion control systems. These simulations will provide a comprehensive source of qualitative and quantitative information concerning the characteristics of aircraft and propulsion systems in a dynamic state. They will also serve as essential tools for the analysis and synthesis of control logic and as test vehicles for control software and hardware development.

Pratt and Whitney Aircraft, under contract with the NASA-Lewis Research Center, has made a conceptual evaluation of propulsion control systems for VSTOL aircraft in order to define critical control requirements and to identify critical technologies pertaining to the integration of aircraft and propulsion controls. One of the major technology areas of this program includes the development of mathematical modeling and simulation techniques applicable to the design of VSTOL integrated aircraft-propulsion controls. The long range objective of the program is to conduct a real time piloted simulation evaluation of an integrated aircraft-propulsion control on the NASA-Ames flight simulator facilities.

Since the advent of piloted simulators and the growing emphasis for systems integration, there has been an increasing need for higher fidelity real-time propulsion system models. Propulsion and integrated control system evaluation of VSTOL aircraft on flight simulators will require that

propulsion system simulations be realistic and include significant dynamics as well as important internal parameters. In recognition of this need, a dynamic digital real-time model of an advanced propulsion system has been developed which is suitable for use in man-in-the-loop simulator studies. This model provides the engine-control system accuracy, stability and transient response required for the intended studies. These studies might include the evaluation of critical control parameters, system response, system environmental effects and critical propulsion component aerodynamic, mechanical and thermodynamic limits. The model may also be used to analyze propulsion control failure modes and effects.

In the VSTOL Propulsion Control Analysis Program reported in (1), an engine model was used to explore the merits of using a combined simulation of aircraft-propulsion systems for analysis of propulsion control requirements. Simulations of this nature integrated into the design scheme provide an important cost effective tool in specifying, generating and conveying control requirements for the next generation VSTOL designs.

A Pegasus 11 propulsion system was chosen as the baseline VSTOL engine for developing mathematical modeling and simulation techniques. The real time engine model is a piecewise linear state variable representation derived from a detailed aerothermodynamic simulation of a typical Pegasus 11 engine. Dynamics included in the simulation are engine fan and compressor rotor dynamics, engine burner heat transfer dynamics, engine control dynamics, and sensor and actuator dynamics. This model provides steady state and transient characteristics for various engine pressures, temperatures, flows, stall margins and thrust. The model calculates transient performance by numerical integration of time-dependent differential state equations and contains the dynamics necessary to simulate aircraft forces resulting from engine thrust. The real time model also represents the engine fuel control system the water injection system and flight simulator interfaces.

The following sections present descriptions of the propulsion system, control system, real time methodology and model capabilities. Typical results from the propulsion system simulation are also presented.

Propulsion System Description

Engine Configuration

The engine modeled in this program is a nonmixed, twin-spool Pegasus 11 as shown in figure 1. The engine weighs approximately 3540 lbm with an inlet diameter of 46 in and a total uninstalled dry thrust of 19500 lbf. Total design airflow is 435 lbm/sec divided between the fan duct and engine core stream with a bypass ratio of 1.35.

The high and low pressure compressor spools are independent, coaxial and counter-rotating. Counter-rotation minimizes gyroscopic effects which is an important consideration in hovering operations. The three stage fan is driven by a two stage turbine at a design speed of 6500 rpm at a pressure ratio of 2.31. The high pressure compressor uses variable inlet guide vanes and is an eight stage compressor driven by a two stage turbine at a design speed of 10500 rpm at a pressure ratio of 5.6.

At a maximum design thrust of 19500 lbf, thrust is divided evenly between the fan and core nozzles. Pairs of nozzles rotate and deflect the nozzle flow from both the fan and turbine exits through a range of 0 to 98.5 degrees. The four nozzles are mechanically linked to each other to ensure that the vertical-to-horizontal angular position is identical for each thrust vector.

In order to provide aircraft attitude control, up to 22 percent of the high pressure compressor exit airflow is available for ducting to a remote reaction control puffer jet system.

Hydromechanical Control Configuration

The engine fuel control modeled is the Dowty hydromechanical control used on the Pegasus 11 engine. The fuel control is designed to meet engine performance throughout the flight envelope. At the same time, the fuel control unit ensures that the engine limitations are not exceeded.

The engine fuel control system is shown schematically in figure 2. Fuel flow to the engine is regulated by two metering devices; a metering valve and a throttle shutoff valve. The metering valve is effectively a variable orifice under the control of a low pressure compressor speed governor. The metering valve normally controls the fuel flow to the engine in the high fan speed range above 87 percent. The pressure drop across the orifice is controlled by a pressure drop regulator. The throttle shutoff valve meters fuel flow directly to the burner and is also used for shutting the fuel off completely. The pressure drop across it is maintained constant by a flow control pressure difference regulator. The throttle valve normally controls the fuel flow to the engine in the low fan speed range below 87 percent.

A number of engine limiting functions are also included. These include an acceleration control unit, a jet pipe temperature limiting control, an engine pressure ratio limiter, a combustion chamber pressure limiter and an airbleed reset unit for fuel compensation due to reaction control bleed. A manual fuel flow control is also provided in the event of fuel control unit failure.

Water Injection System

In a high load configuration, if an attempt was made to increase speed and thrust to meet vertical takeoff requirements, the turbine inlet temperature could be exceeded. To avoid this, a water injection system was provided to allow engine speed to increase for a given turbine inlet temperature. Water is introduced at the turbine inlet. Provision is made to carry 62.5 gallons of water which is sufficient for 90 seconds of operation.

The water injection system is shown schematically in figure 3. It is controlled by a selector switch in the cockpit, float level switches in the tank, a throttle control microswitch and a water pressure switch. Setting the selector switch "on" arms the system, raises the fan speed mechanical governor setting 4 percent when the throttle is in excess of 87 percent fan speed and energizes a fuel bypass solenoid. The bypass solenoid provides supplementary fuel flow to increase fan speed. If there is sufficient water in the tank, moving the throttle beyond a position which gives 92 percent fan speed operates a microswitch in the throttle control linkage which opens a solenoid valve to admit engine bleed air to the pump turbine. When water pressure reaches 240 psi the pressure switch operates to increase the jet pipe temperature limiter and engine life recorder datum settings and indicates a green light in the cockpit.

When 15 seconds of water is left, a float operated switch closes to indicate a low level warning in the cockpit. An empty level switch operates a relay to isolate the pump control circuit after the tank has been emptied. The system will continue to operate until all water is used, the throttle is retracted, or the selector switch is turned off. There is also a jettison feature in the system.

Reaction Control System

The aircraft is equipped with both aerodynamic controls and a reaction control system as shown in figure 4. Aerodynamic controls on the aircraft are standard control surfaces. But, these supply negligible control during vertical, hover and transition modes because of the low velocities in these modes. A reaction control system consisting of six fully modulating puffer jets located at the wingtips and at fore and aft fuselage locations is required to provide thrust control for roll, pitch and yaw motions during these modes. These puffer jets are mechanically linked to their respective aerodynamic control surfaces to accommodate control transfer during transition from vertical to horizontal flight. A master shutoff valve is linked to the nozzles so that bleed air from the engine is turned off when the nozzles are in the horizontal flight position.

Simulation Technique

Aerothermodynamic Detailed Simulation

A detailed nonlinear aerothermodynamic simulation of the baseline propulsion system forms the base for the real time propulsion model development. This nonlinear simulation is a high fidelity model that represents each component in the engine and control. Heat transfer dynamics, rotor dynamics and aerothermodynamics are modeled. This detailed digital simulation includes complete component performance maps and gas flow balance equations. The components are matched for aerodynamic stability from detailed stability audits that consider surge line and operating line destabilizing influences for steady state and transient operations.

A nonlinear propulsion system simulation such as this produces a model of high frequency fidelity which, however, does not run in real time. Extension to an all digital format for piloted simulators would require high sampling rates (small time steps) to maintain calculational stability. Real time would be virtually impossible. The general approach taken in the real time digital simulator model presented here was to represent dynamic response over a reduced frequency range but to maintain as much control system detail as possible. For the level of steady state and dynamic complexity required to meet this objective, steady state accuracy does not have to be compromised over detailed models.

The real time model must cover a wide range of frequencies as shown in figure 5. Expansion on the bandwidth is possible, but would involve trade-offs between real time capability and control or interface detail.

Real Time Methodology

The real time model is based on a piecewise linear state variable technique reported in (2).

The state variable form is shown in figure 6, where X is the vector of state variables, \dot{X} is the time derivative of the state variables, U is the control input vector and Y is the vector of observed or output parameters. A is the plant matrix and its elements are the partial derivatives of each state variable to the time derivative of each state variable. Elements of the output matrix C define the effect of each state variable on each output variable. The control matrix B and the direct couple matrix D define the effect of each control variable on each state variable time derivative and each output parameter.

A modal analysis was used to determine which states in the nonlinear aerothermo model are required to adequately represent the system within the desired bandwidth. The nonlinear aerothermo model was linearized to obtain the system A , B , C , and D matrices. An eigenvector-eigenvalue analysis of

the A matrix was performed. The eigenvectors were examined to associate eigenvalues with states. High frequency states outside the control bandwidth were eliminated. A mode controllability matrix was also defined. States which were uncontrollable by the inputs were eliminated. The final model considered only states which were within a 0.1 to 10 Hz bandwidth

Modeling large transient excursions efficiently and accurately in the state variable form depends on the number of models selected. With real time computation as a requirement, an optimum number of state models is required. Initially, a piecewise linear fit of the steady state operating line was performed to define the minimum resolution. These models were then augmented by additional models to accurately define transient response through the full power range.

The matrix partial derivatives are generated using an offset derivative technique. This technique is automated on the baseline nonlinear aerothermo simulation. In this process, each X is perturbed one at a time while holding all other X's and all U's constant. This allows calculations of the A and C matrix partial derivatives. Each U is then perturbed one at a time while holding all other U's and all X's constant. This allows calculation of B and D matrix partial derivatives. Several different levels of perturbations on the states and inputs are used.

To provide real time capability, the state variable models must be connected efficiently. The type of interpolation is flexible and could vary in each application. The interpolation is controlled by scheduling the matrix elements with an independent variable from the input vector U. Applying this methodology results in reducing several linear models to one nonlinear model as shown in figure 7.

Engine Model

Using the piecewise linear state variable methodology previously discussed, a real time propulsion model of the Pegasus 11 engine was formulated. The engine model consists of 14 state variable models with 6 inputs, 3 states and 21 outputs. Steady state and dynamic operations from ground idle to maximum power (7 to 109 percent) up to 5000 feet altitude and 0.3 Mach number are represented. The state variable vectors used are shown in figure 8.

Control Model

The control model was developed directly from detailed information on the hydromechanical fuel control and water injection system. All functions in the real control were modeled.

PROGRAM DESCRIPTION

The flight simulator state variable engine model is

a high fidelity propulsion model which provides steady state and transient characteristics for desired engine pressures, temperatures, airflows, surge margins, thrusts and rotor speeds. The computer program simulating the engine calculates both steady state and dynamic engine characteristics that are representative of a Pegasus 11-402 engine.

The state variable technique as shown in figure 7 involves generating a set of matrices or point models for various levels within the engine operating range from minimum (7 percent) to maximum (109 percent) power. These point models are then linked together by scheduling the matrix elements in each model as a function of both low and high compressor rotor speeds to form a piece-wise linear representation. For large power excursions from 7 to 109 percent, the coefficients of the differential equations vary continuously as both rotor speeds increase. After computing the small changes or deltas in states and controls as they deviate from the known steady state operating characteristics, the differential equations are integrated using a simple Euler integration to compute the transient engine response.

Figure 9 shows an overview block diagram of the important state scheduled parameter state variable model logic. The initial steady state point is calculated from the output and state operating lines. The initial time point of any transient run is assumed to be in a steady state condition.

Transient operation occurs as follows. The last time step values for the rotor speed states are used to calculate the state scheduling parameter (SSP). This parameter contains information about the dynamic states at any time during the transient. DX's and DU's from the model points above and below the SSP are computed. A relative distance weighting scheme is used to combine a delta from the model point above with the delta from the model point below. The SSP is also used to schedule the A, B, C, D partial derivatives. These matrix elements are stored in a linear equation form which allows for rapid interpolation between the discrete model points. State derivative computations are performed by the matrix multiplication of the A and B elements with the DX's and DU's computed earlier. The derivative vector is then integrated by Euler integration.

The steady state model output is calculated from the operating line curves. The operating line output levels change as the SSP varies. Transient deviations from the operating line must be calculated. This is done through the output equation which makes use of the same DX and DU vectors input to the state derivative equation. The DY vector represents deviation from the operating line. Summing the steady state operating line values and DY elements gives the output vector.

Transients are shown in figures 10 and 11 that

exhibit the accuracy with which the state variable model matches the aerothermo Pegasus 11 representation for a 7 to 100 percent power excursion at sea level with water injection and at an altitude of 5000 feet.

Application To Piloted Simulator

To satisfy the requirements of real time piloted simulation, innovative mathematical modeling is required (3,4). One must attain the desired level of fidelity yet have the computations accomplished in a limited amount of time. Also, since the propulsion system is only a part of a larger simulation, only a fraction of the total computation time is available for the propulsion system calculations. Real time, then, in the context of overall simulation requirements, implies that the propulsion simulation must be faster than real time.

The program structure consists of the piece-wise linear engine representation, the engine control model and a set of propulsion system force and balance equations. The control system model provides the interface with the aircraft-flight control simulation. Figure 12 schematically identifies the interfaces with the propulsion system. The aircraft and engine elements are combined by means of interfacing logic that provides fan and core nozzle thrust calculations, reaction control system thrust calculations, external environmental disturbance effects and pilot stick movements in terms of roll, pitch, yaw and height requests.

Aircraft System

The aircraft model used was a typical Harrier AV-8A. The model includes nonlinear aerodynamics, engine and reaction control response, stability augmentation, actuator dynamics and a simplified landing gear model. The model consists of a group of basic subroutines applicable to any aircraft and a set of specific aircraft model subroutines which have been configured to represent the AV-8A Harrier.

The basic subroutines handle trim initialization, coordinate transformations, the integration of differential equations and the interpolation of tabulated nonlinear functions. These were adapted from simulation programs used at the NASA Ames Research Center to perform real time simulations.

Control inputs, forces and moments and disturbance inputs are determined by user supplied routines which must be varied to represent specific aircraft types and environmental conditions. The aircraft model includes an aerodynamics subroutine which determines three force and three moment coefficients by interpolating tabulated values of aerodynamic functions. A separate subroutine is used to represent the Pegasus 11 engine operating at low altitude and Mach number. Engine speed,

nozzle angle and reaction control thrust dynamics are included. This engine model is referred to as the simple engine model. In the simulation study presented here, this simple engine model is replaced by the state variable model. A simplified model of the landing gear including vertical force, braking force and pitching moment is also used.

The ship model used was that of a Spruance class destroyer. Environmental conditions could be varied from calm to sea state 6. A ship air-wake turbulence model was included. Ship dynamics are modeled as six degree of freedom sinusoidal motion. The ship was assumed to have a fixed mean position about which it oscillates. Wind over the deck is composed of a steady induced wind equal to the ship speed plus a separate north and east component of independently specified natural wind. No turbulence model designed specifically for VSTOL aircraft exists. A model developed for conventional carriers is used. This model calculates free air turbulence as well as ship wake turbulence which may be varied in amplitude. The wake intensity is calculated as a function of range, altitude and lateral position relative to the flight deck.

Flight Control

A state rate feedback implicit model-following type controller (6) is used in the basic flight control. This flight control concept was applied to all axes of the aircraft model. Power management controls and pilot displays were designed to match the various modes of control provided by this type of flight controller.

Within the overall flight controller are two variants. The Type 1 control system employs control augmentation in all degrees of freedom. Included here, in the transition flight mode, is a vertical axis pilot control based on vertical velocity command. In this type the propulsion system is within the closed flight control loop.

The Type 2 system employs control augmentation in the attitude degrees of freedom only. Translation, or flight path control, is through thrust and thrust vector angle inputs from the pilot to the propulsion system. Velocity command is not provided in this system.

Each control variant used a head-up display (HUD) that included flight director information. A complete description of the flight control concept is given in (6).

Simulator

A small fixed base simulator (C06) was the principal tool used in evaluating the state variable propulsion system simulation. The simulator was driven by a Xerox Sigma 9 digital computer in conjunction with a PDP-11 for HUD generation.

Test Plan

The primary objective in the simulation effort was to evaluate the propulsion system model performance for use in future piloted simulations involving the Harrier aircraft and advanced integrated flight-propulsion control concepts. To achieve this objective within the limited time available for the simulation exercise, a stringent test condition was chosen with a minimum of test parameters. The basic piloting task was to fly an IFR curved approach transition at 120 knots to an initial station keeping point 12000 feet down range and land on the destroyer at a fixed sea state 6 with wind over deck from the east at 25 knots. The only variables in the test were turbulence and control variant type.

In addition to this standard flight task, a test for maximum control power at hover was run to determine reaction control system forces and moments for comparison with published aircraft data. A small perturbation test was also made to compare the new state variable model thrust response to the simple engine model.

Simulation Results

Model Performance. The state variable propulsion system model performed within the aircraft model environment over the full operating range without run-time Fortran errors or missed intervals during the test program. The model exhibited a high level of calculational stability. For a simulation frame time of 50 ms the propulsion system model executed in 8.9 ms for a real-to-execution time ratio of 5.6. This compares with a 3.8 ms execution time for the simple engine.

Engine Performance. A comparison of the state variable engine model forward and rear nozzle thrusts to that of the simple engine is shown in figure 13 for a power lever step increase from 60 to 70 degrees. For the simple engine both the forward and rear nozzle thrusts exhibit a lag response with a time constant of about 0.25 seconds. For the state variable model, on the other hand, the thrust exhibits a first order lag response with a time constant of 0.5 seconds in the front nozzle and a moderately damped second order response with a time constant of about 0.25 seconds in the rear nozzle. These characteristics are important in designing integrated flight controls that include the engine in a closed loop.

Control Performance. Figure 14 shows a series of engine parameters as a function of time for typical landing task flights using the Type 2 flight controller. Within this flight controller, propulsion system vectored thrust is controlled directly by the pilot through the power lever and nozzle angle. Altitude information is communicated to the pilot through a flight director via the HUD. Altitude is maintained through the flight controller.

Overall engine model operation is stable. Core and fan thrusts follow power lever inputs closely with second order effects of bleed superimposed by fuel control compensation.

In the transition phase the most significant effects are the smooth nozzle angle action and bleed flow. Bleed flow in this phase is demanded from reaction control system which in turn is commanded from the flight controller. At hover, bleed activity increases significantly due to reaction control demand by the pilot. At this point the nozzle angle is fixed at a slight forward position to account for wind and ship velocity.

At touchdown the power lever is brought to idle and the aircraft "drops" to the ship deck. Bleed flow continues to vary due to the action of the reaction control system commanded by the flight controller which is responding to the ship's roll, pitch and yaw motions. Normally the flight control would be disengaged at touchdown.

Figure 15 shows a series of engine parameter transients for the standard flight task using, however, the Type 1 flight controller. With this controller, as described previously, the engine is within an altitude flight controller loop. The power lever angle is demanded as a function of altitude to provide a prescribed flight path commanded from the flight director. The control gains and implicit engine model time constant are the same as those used with the simple engine model.

As shown, the engine breaks into a limit cycle oscillation. Expanded time scale traces of the oscillation indicate that the engine fuel control is responding to power lever angle demand from the flight controller. This kind of interactive response is typical of integrated flight-propulsion controls where the engine control response is within the flight control bandwidth and the flight controller is analyzed without the advantage of realistic engine response characteristics.

Figure 16 shows the same typical flight task except that the implicit model in the altitude flight controller has been modelled to approximate the state variable engine model response. The implicit model time constant was chosen to approximate the engine fan thrust response and the flight controller gain was reduced by a factor of 4. As shown, the transient indicates no evidence of oscillation. However, it was evident from the flight data that the altitude controller, although acceptable, was not as responsive. Other similar flights indicated that designing the implicit controller to represent the state variable engine model response also gave satisfactory results.

Concluding Remarks

A state scheduled state variable propulsion system model of a Pegasus 11 engine has been developed for

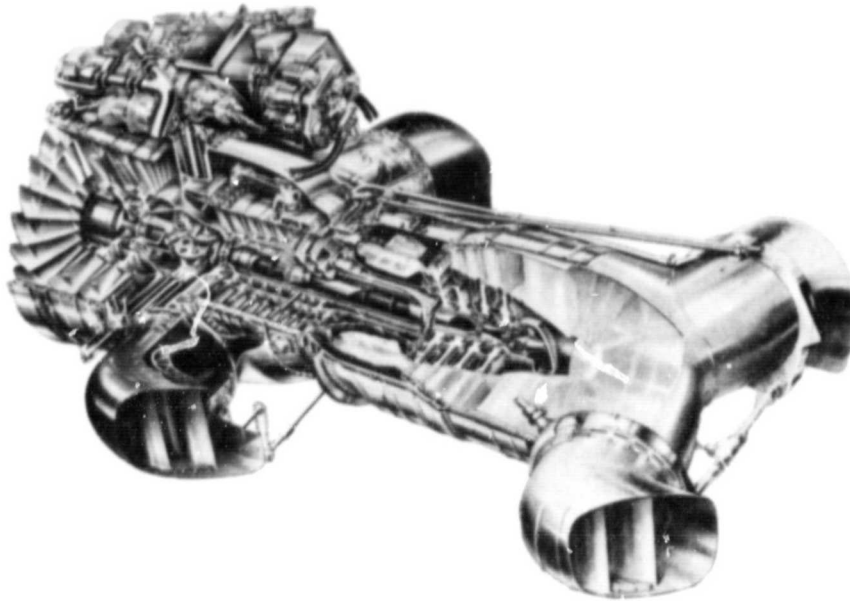
real time flight simulator application. The model was exercised in a limited flight program using a Harrier aircraft simulation with an implicit model-following flight controller.

The propulsion system model performed very well within the flight environment exhibiting excellent calculational stability and satisfactory cycle time characteristics. No run-time errors or missed intervals occurred. The engine and control transient characteristics were typical of a turbofan engine.

The propulsion system exhibited an oscillatory characteristic within the closed loop implicit model-following flight controller. Further analysis of this flight control within the context of the state variable model is required to provide satisfactory flight performance.

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Figure 1. - Rolls-Royce Pegasus 11 propulsion system.

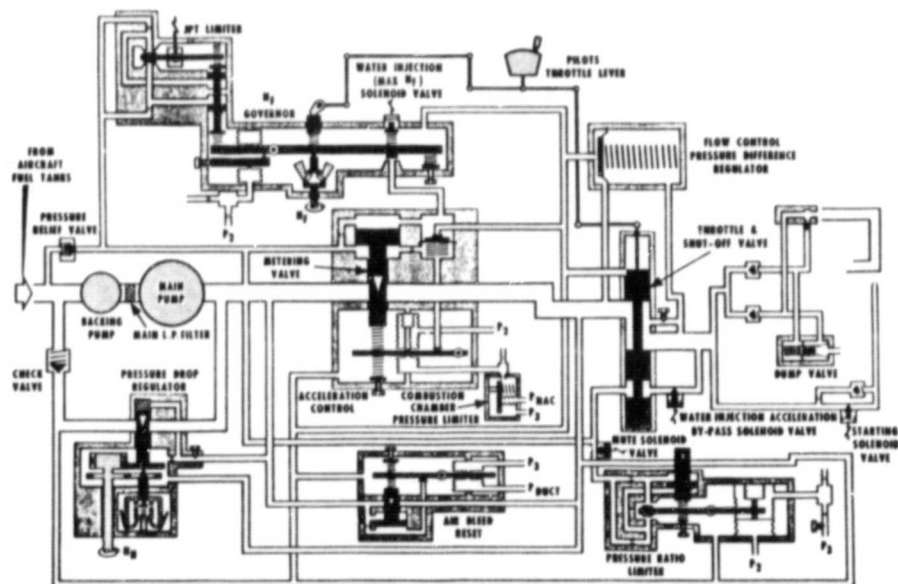
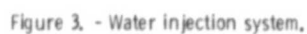


Figure 2. - Fuel flow control system.



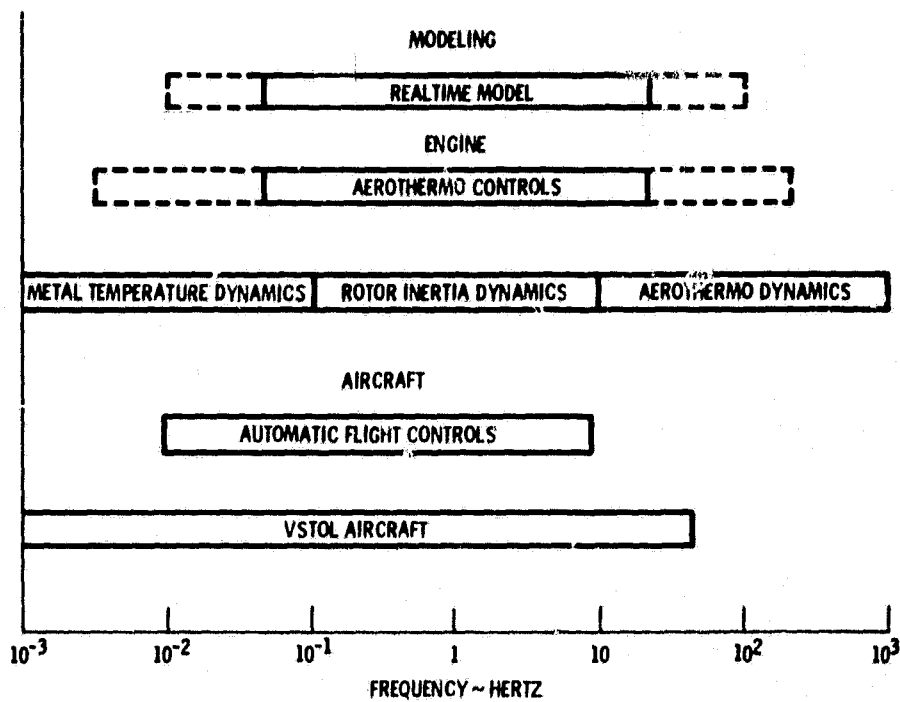


Figure 5. - Modeling frequency range of interest.

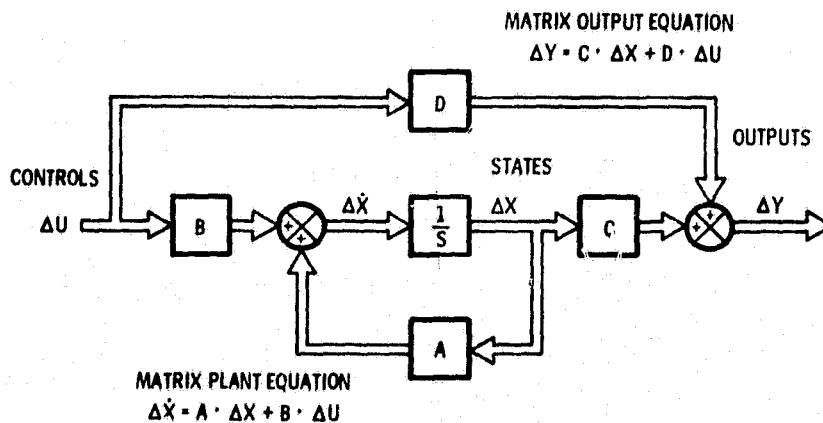


Figure 6. - Real time model state variable representation.

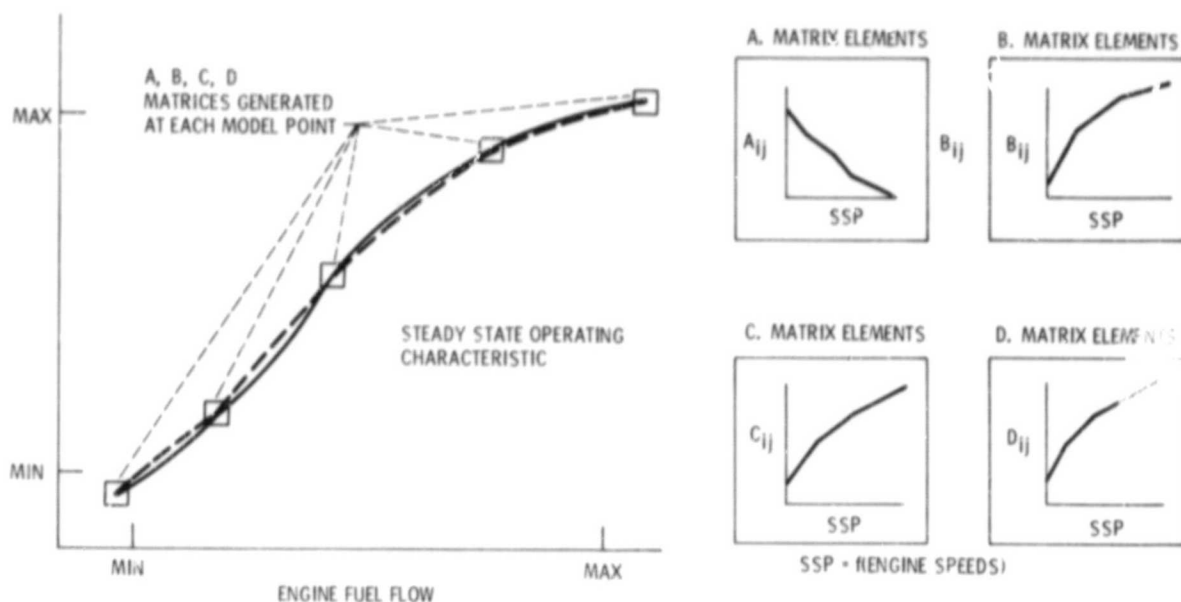


Figure 7. - State scheduled parameter nonlinear real time model.



Figure 8. - Real time model state variable vectors.

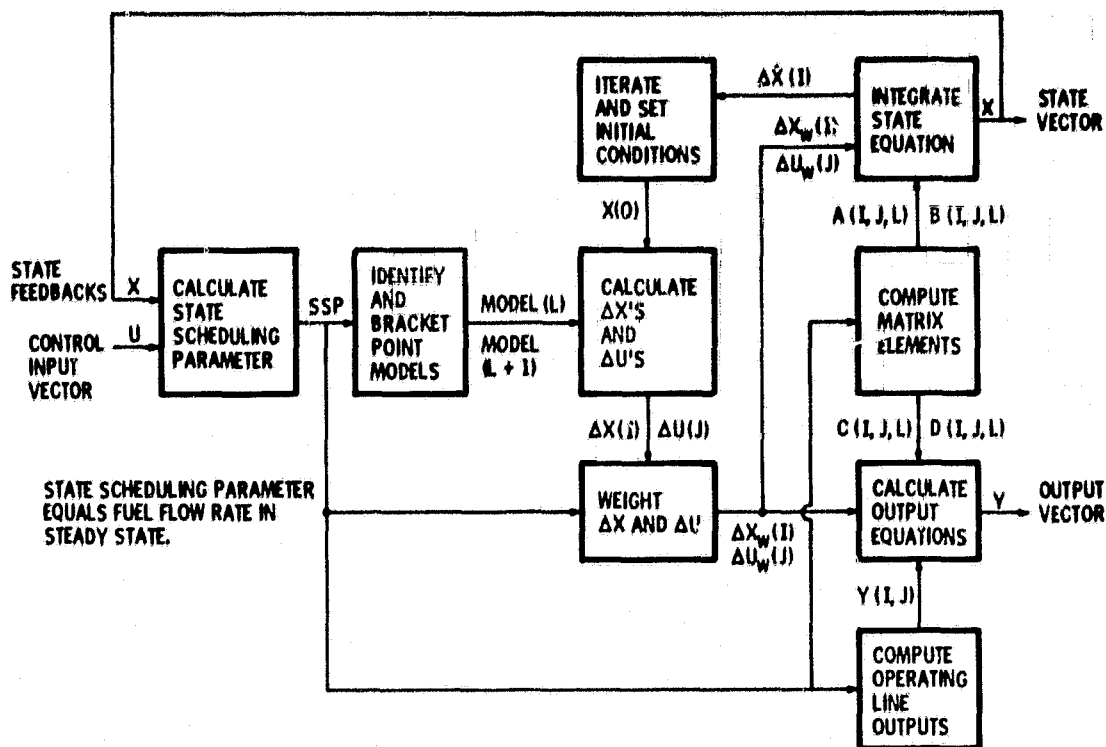


Figure 9. - State scheduled state variable engine model.

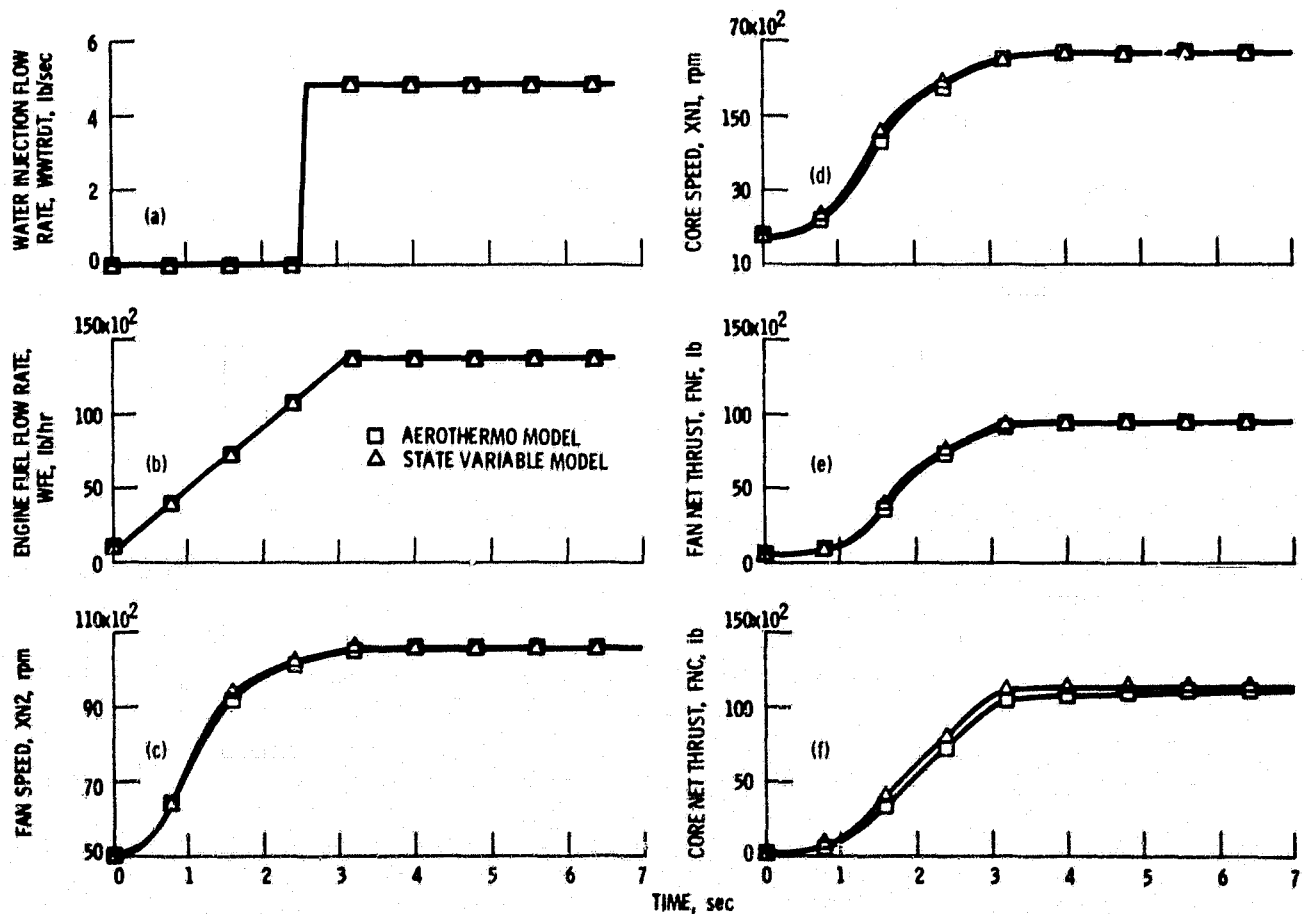


Figure 10. - Full range fuel transient with water injection at 92 percent fan speed, sea level static.

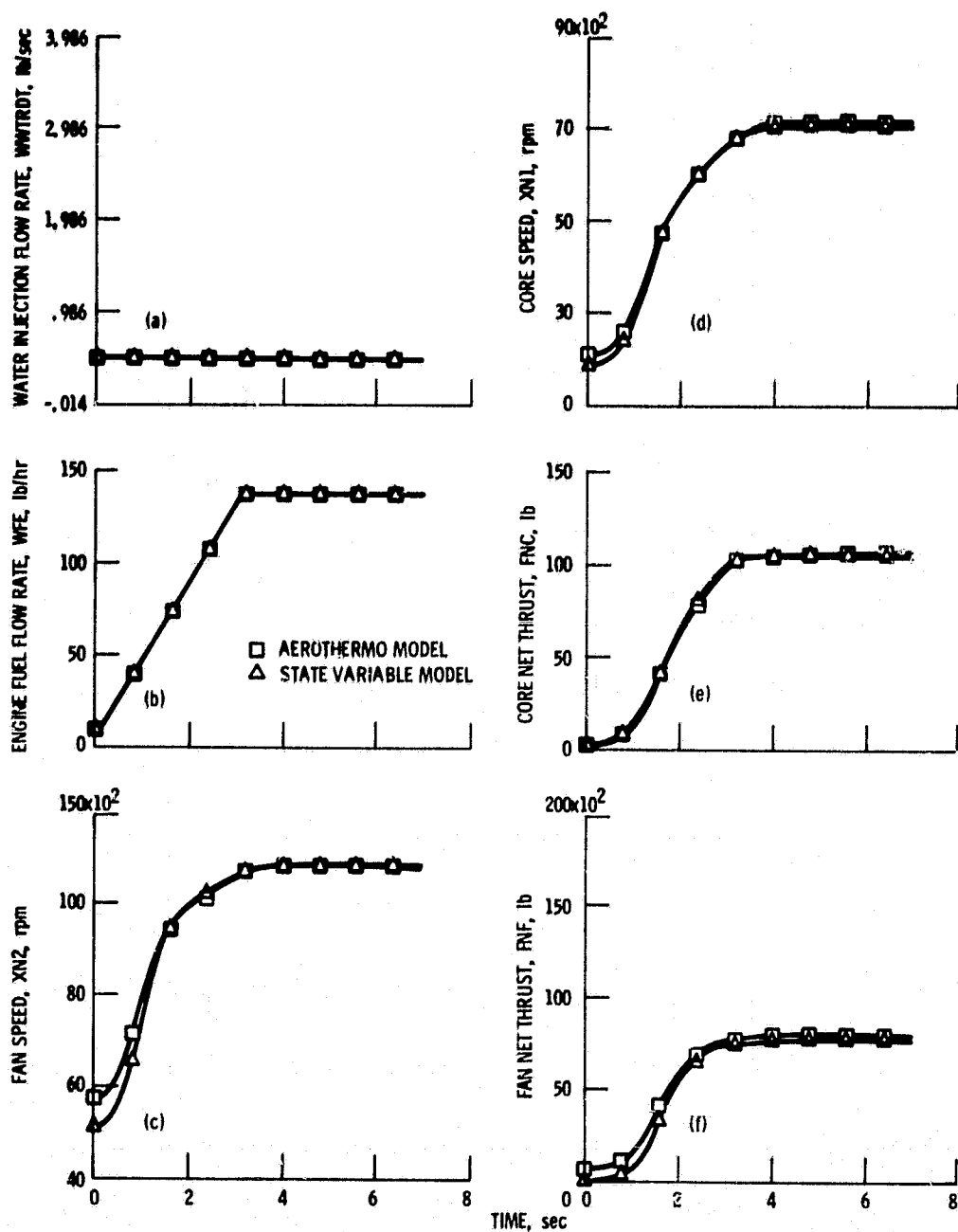


Figure 11. - Full range fuel transient at 5000 feet altitude.

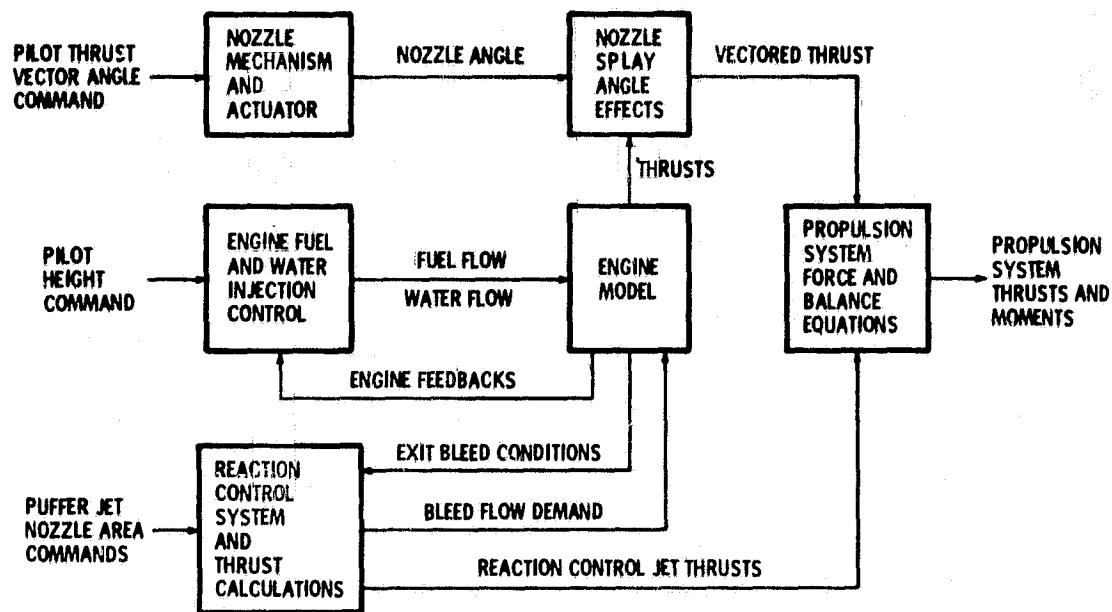


Figure 12. - Propulsion system model for aircraft integration.

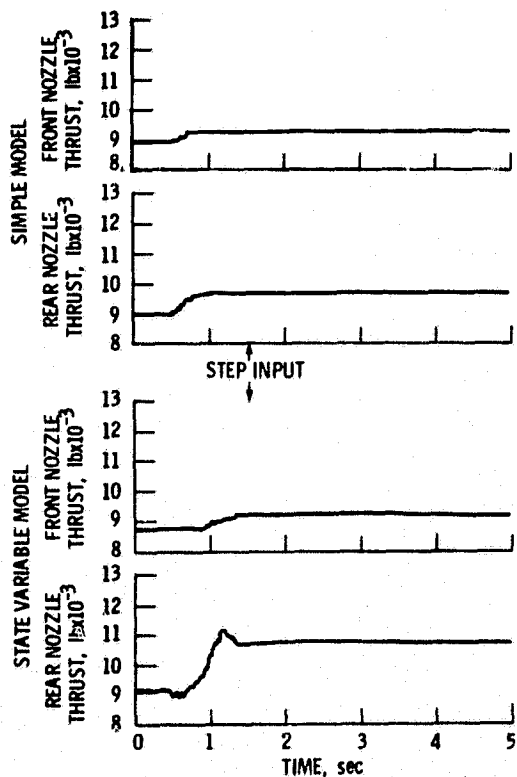


Figure 13. - Model response to throttle step input.

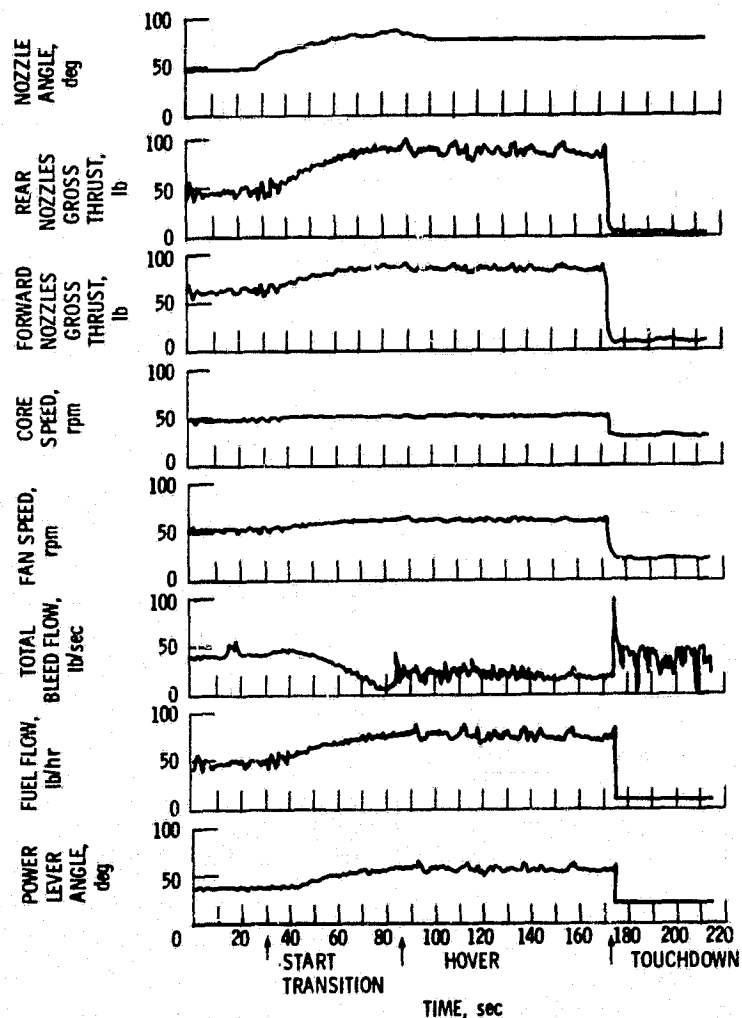


Figure 14. - Approach and landing engine transients using type 2 flight controller.

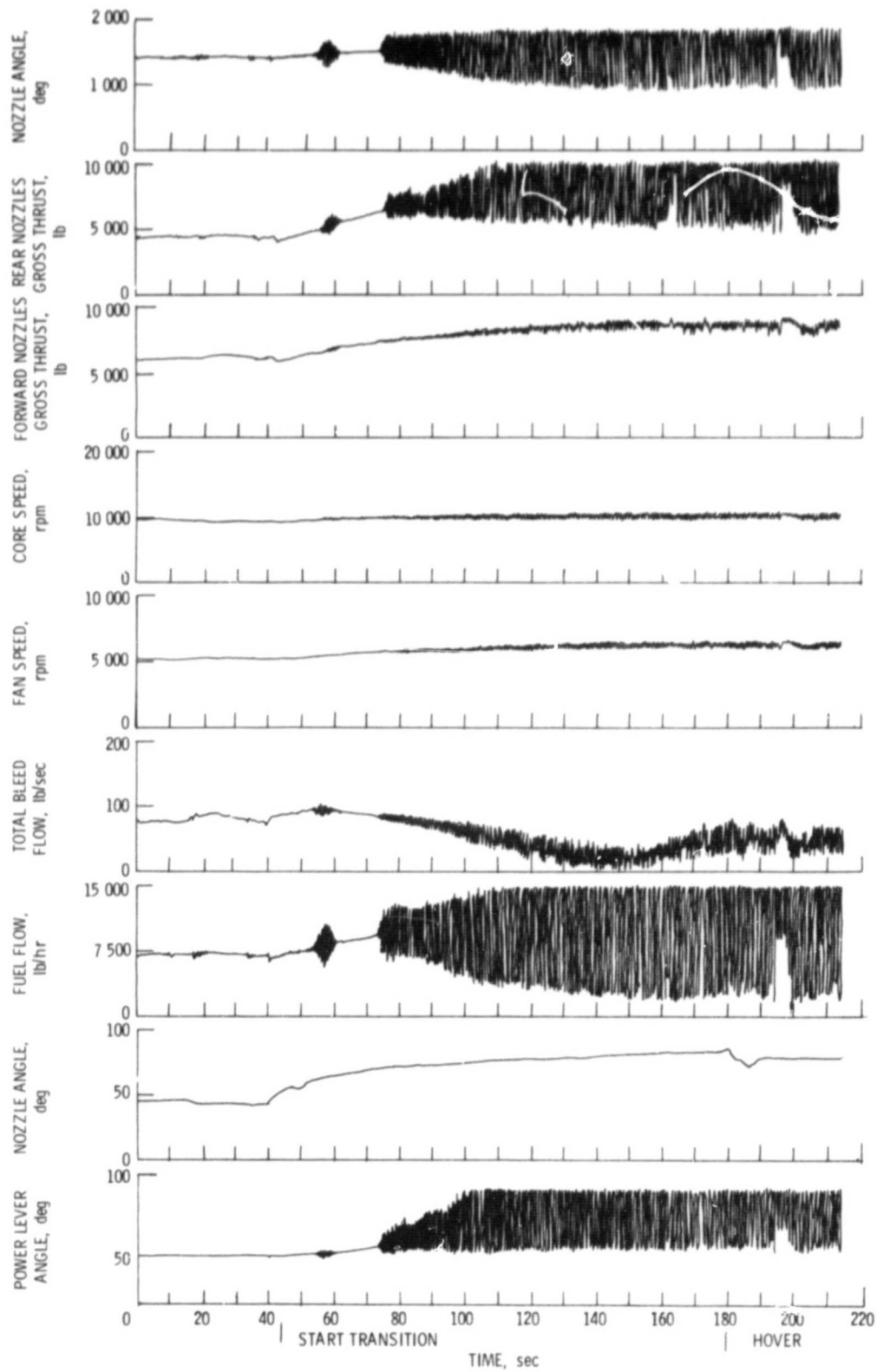


Figure 15. - Approach and hover engine transients using type J flight controller with simple engine control constants.

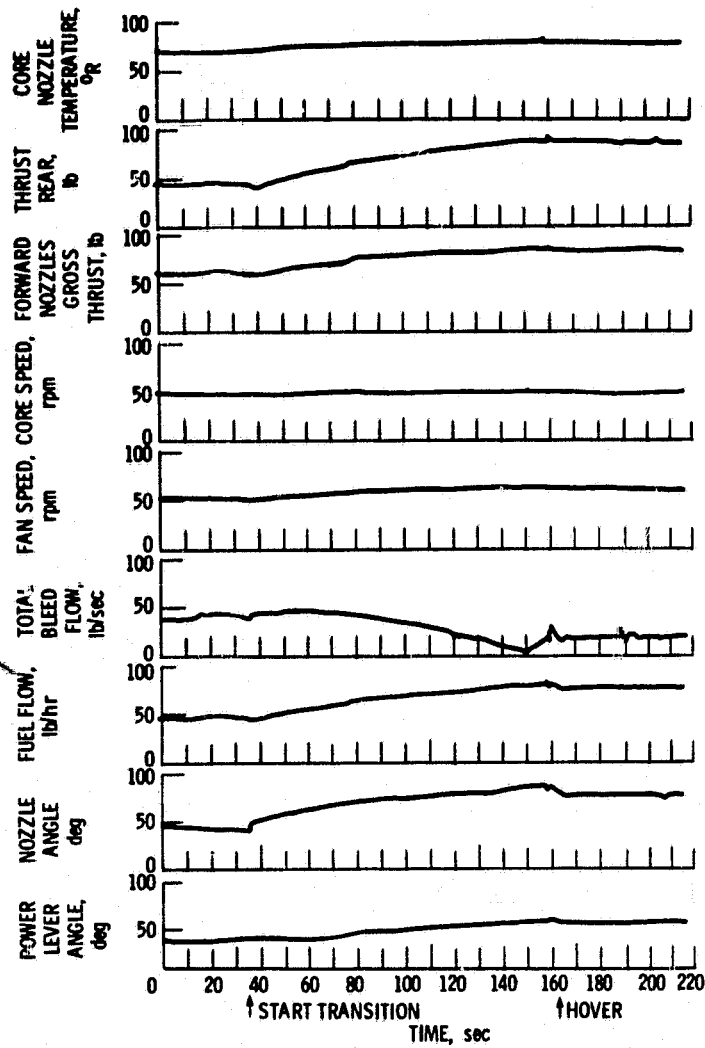


Figure 16. - Approach and hover engine transients using type I flight controller with state variable control constants.