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A Piecewise Linear State Variable Technique for Real Time Propulsion System Simulation

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James R. Mihaloew
Lewis Research Center
Cleveland, Ohio

and

Stephen P. Roth
Pratt and Whitney Aircraft Group
West Palm Beach, Florida

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FOR REAL TIME PROPULSION SYSTEM SIMULATION

James R. Mihaloew
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

Stephen P. Roth
Pratt and Whitney Aircraft Group
Government Products Division
West Palm Beach, Florida

ABSTRACT

The emphasis on increased aircraft and propulsion control system integration and piloted simulation has created a need for higher fidelity real time dynamic propulsion models. A real time propulsion system modeling technique which satisfies this need and which provides the capabilities needed to evaluate propulsion system performance and aircraft system interaction on manned flight simulators has been developed at NASA-Lewis and demonstrated using flight simulator facilities at NASA-Ames.

A piecewise linear state variable technique is used. This technique provides the system accuracy, stability and transient response required for integrated aircraft and propulsion control system studies. 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 bytes of block data. It has an 8.9 ms cycle time on a Xerox Sigma 9 computer.

A Pegasus-Harrier propulsion system was used as a baseline for developing the mathematical modeling and simulation technique. A hydromechanical and water injection control system was also simulated. The model has been programmed for interfacing with a Harrier aircraft simulation at NASA-Ames.

Descriptions of the real time methodology and model capabilities are presented.

INTRODUCTION

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

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 aircraft on flight simulators require that propulsion system simulations be realistic and include significant dynamics as well as important engine parameters. Such simulations provide the capability to evaluate propulsion systems and their interaction with aircraft controls. One such modeling technique to accomplish this capability is described in (1) and (2). A dynamic digital real-time model of an advanced propulsion system based on a piecewise linear methodology to meet the same requirements is described in this paper. This model provides the engine-control system accuracy, stability and transient response required for studies which 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.

A Pegasus 11 propulsion system provided the baseline engine for developing the mathematical modeling and simulation technique. The engine model is a piecewise linear state variable representation which was 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 and engine control dynamics. 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 levels. This higher fidelity propulsion control model provides steady state and transient characteristics for various engine pressures, temperatures, flows, stall margins and thrust.

Application of the model to a simulated flight program and evaluation results are presented in (3).

REAL TIME METHODOLOGY

The real time methodology is based on a piecewise linear state variable technique (4). Within this process, the engine model uses state variables and matrix formulations to represent the engine process at specific operating points. The effort presented here was directed toward applying this methodology to model gross engine transients accurately and efficiently. The methodology includes the following steps:

(1) apply a modal analysis and sensitivity study of the detailed base model to select model states and input controls

(2) optimize state variable model selection to accurately define steady state and transient characteristics over a specified range

(3) generate accurate model partial derivative matrices using offset derivative techniques

(4) connect and schedule the state variable model partial derivatives to represent gross transients

(5) employ a simple but accurate integration scheme for fast computation

(6) optimize programming for real time operation

State Variable Representation

The state variable representation is shown in figure 1. It is characterized by the following two equations:

$$\dot{X} = A X + B U \tag{1}$$

$$Y = C X + D U \tag{2}$$

Equation 1 is a linear constant coefficient matrix differential equation that represents computation of engine dynamics. Equation 2 is a linear algebraic equation that represents computation of the observed engine parameters. 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. Its elements are the partial derivatives of the time derivatives of each state variable to 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.

Modal Analysis

A modal analysis is used to determine which states in the nonlinear aerothermodynamic model would adequately represent the system within the required control bandwidth. The nonlinear aerothermodynamic model is then linearized to obtain the system A, B, C and D matrices. An eigenvector-eigenvalue analysis of the A matrix is performed. The eigenvectors are examined to associate eigenvalues with states. High frequency states outside the control bandwidth as shown on figure 2 are eliminated. A mode controllability matrix which defines the effect of control inputs on states was also generated. States which are uncontrollable by the inputs are eliminated. The result is a set of state variable vectors for the real time model.

Model Resolution

Modeling gross transient excursions efficiently and accurately in the state variable form depends on the number of models selected. Initially, a piecewise linear fit of the steady state operating line is performed to define a minimum resolution. These models are then augmented with additional models to accurately define transient response through the full power range and any extremely nonlinear areas.

Matrix Partial Derivative Generation

State variable techniques can be employed to obtain a linear approximation of a nonlinear system by considering operation in the vicinity of a particular operating point. Matrices A, B, C and D are characterized by:

$$a_{ij} = \frac{\partial \dot{x}_i}{\partial x_j} \tag{3}$$

$$b_{ij} = \frac{\partial \dot{x}_i}{\partial u_j} \tag{4}$$

$$c_{ij} = \frac{\partial y_i}{\partial x_j} \tag{5}$$

$$d_{ij} = \frac{\partial y_i}{\partial u_j} \tag{6}$$

To generate finite difference approximations of the partial derivatives, the steady state level of each state variable and system input is independently stepped in both a positive and negative direction while holding the other state variables and system inputs fixed. Corresponding values of the state variable derivatives and system outputs are recorded for each step change. Each matrix partial derivative is calculated by taking an average of both step values:

$$a_{ij} = \frac{\partial \dot{x}_i}{\partial x_j} \approx \frac{\dot{x}_{i,x_j+\delta x_j} - \dot{x}_{i,x_j-\delta x_j}}{2\delta x_j} \tag{7}$$

This process was automated on the detailed nonlinear base model. First, each X is perturbed one at a time while holding all other states and control inputs constant. This allows calculation of the A and C matrix partial derivatives. Each U is then perturbed one at a time while holding all other controls and states constant. This allows calculation of the B and D matrix partial derivatives.

Several different levels of perturbations on the states and inputs are used. Perturbation step size was minimized to prevent driving model parameters out of range but made large enough to excite each state variable and output parameter. The best overall agreement between the linear base model and the nonlinear models occurs when the states are perturbed about 0.5 percent and the inputs about 3.0 percent. The partial derivatives generated by the offset derivative technique are reasonably accurate for steady state at each condition for which they were generated. For large transients, however, this is not necessarily true and a forced steady state match may be required to ensure steady state accuracy from one state variable model to the next along the engine operating line. To avoid this, all perturbations are measured from a steady state operating line model which insures steady state accuracy over the whole range.

State Scheduling Parameter

The state variable models must be connected efficiently to provide continuous operation over the entire range of the model. The interpolation is controlled by scheduling the matrix elements with an independent variable called the state scheduling parameter (SSP):

$$\mathrm{SSP} = f(X) \tag{8}$$

This parameter is derived from the state variable vector and indicates the relative energy level of the engine system. Application of this procedure results in reducing several linear models to one nonlinear model as shown in figure 3.

State Vector Integration

A simple self starting and reasonably accurate integration scheme is required to minimize excessive function evaluation and computation time. Euler integration was found to meet these requirements and was subsequently adopted for this model development.

PROGRAM DESCRIPTION

Figure 4 contains an overview block diagram of the important state scheduled parameter state variable model logic.

The code contains first pass checks and initialization steps. The initial steady state point is calculated from the state and output operating lines. The initial time point of any transient run is assumed to be in a steady state condition, which requires that:

$$A\Delta X + B\Delta U = 0 \tag{9}$$

Since the state derivatives will not be zero on the first pass if the initial point is not on the operating line, multiple passes are made through the state dynamic calculation loop until the states settle. The solution will be a set of steady state values where the ΔX vector is given by:

$$\Delta X = A^{-1} B\Delta U \tag{10}$$

Transient operation occurs as follows. The last time step values for the states are used to calculate the SSP. Bracketing model points are then identified relative to the SSP level. The SSP is also used to schedule the A, B, C and D matrix elements. These matrix elements are stored in a linear equation form (point-slope) which allows for rapid computation between the discrete model points. ΔX's and ΔU's from the model points above and below the SSP are computed. A relative distance weighting scheme is used to combine deltas from the model point above with deltas to the model point below. This basepoint smoothing is set by the model point distance from the current SSP value.

State derivative computations are performed by the matrix multiplication of the A and B elements with the ΔX's and ΔU's computed earlier. The derivative vector is then Euler integrated and summed into the storage vector holding the cumulative state level. The cumulative ΔX is passed out of the matrix integrator and vector summed with the basepoint values. This final result is then the actual state level to be used for both output and calculating the new SSP.

The basic values for the output parameters are set through the operating line curves as functions of the SSP. Base output levels change as the SSP dynamically varies indicating engine energy level changes. In addition to the basic transient response, deviations from the output operating line must be calculated. This is done through the output equation which uses the same ΔX and ΔU vectors used in the state derivative equation. The ΔY vector computed then represents the change in output values from the current set of operating line output values. Summing this value and ΔY elements gives the required total output response vector.

APPLICATION

The methodology presented here was applied to the Rolls-Royce Pegasus 11 propulsion system (3). This system is used in the Harrier VSTOL aircraft. The primary purpose was to generate a real time digital model for use at the NASA-Ames flight simulator facility to evaluate integrated control concepts for VSTOL aircraft.

The source for the real time model development is a comprehensive aerothermodynamic simulation of the Pegasus 11. Data from Rolls-Royce was used to represent minimum engine steady state performance on all parameters. A band of 3 percent for specific fuel consumption and 1 percent for thrust and jet pipe temperature was established as an acceptable matching tolerance. Four different match points were chosen covering the full power range. As shown in figure 5, the results obtained at these points on the aerothermodynamic simulation were within 1 percent of the minimum Pegasus 11 steady state performance.

Transient simulation accuracy was obtained by adjusting rotor inertias to specific Pegasus 11 values. The results are shown in figure 6. The apparent differences in the initial steady state are attributed to differences in the steady state and transient Pegasus 11 data. The transient accuracy was computed by comparing the maximum rates of change. This was within 5 percent for all engine parameters.

The state variable input and output vectors used in the real time model are shown in figure 7. The state vector was derived from the modal analysis. The input or control vector and output vectors were determined primarily by fuel control and flight envelope requirements. Fourteen linear models are used to define the Pegasus 11 operating characteristics from ground idle at 7 percent power to full maximum at 109 percent power.

These point models are linked together by scheduling the matrix elements at each model as a function of the SSP. In this model the SSP was defined as the average of the steady state fuel flows that would occur at each particular current state value:

$$SSP = \sum_{i=1}^{n} \frac{W_{f_i}}{n} \qquad (11)$$

Thus, steady state fuel flow becomes an intermediary state scheduling parameter derived from the state vector.

The resulting 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 the Pegasus 11 engine.

RESULTS

The operational real time digital model contains approximately 7.0K bytes of in-line computational code and 14.7K bytes of block data. Programming techniques developed in (1) and (2) were used to optimize the code for real time operation. The block data contains all of the ABCD matrix data for the 14 models and supporting functions. With minor changes in the code, the number of models used could easily be changed.

For a simulation time step size of 50ms the propulsion system model executed in 2.3ms on a Univac 1110 for a real-to-execution time ratio of 21.7. On the Xerox Sigma 9 computer used at NASA-Ames, the execution time was 8.9ms for a ratio of 5.6. These computation times included a detailed hydromechanical control and an aircraft force and balance section. The engine portion consumed about 75 percent of the total execution time. The matrix operations involved in the state variable equations consumed 40 percent of that time.

A number of sets of transient test cases were run to demonstrate the real time digital Pegasus 11 model accuracy and capabilities. Only the engine section was used here. The test cases show response to full range 3 second fuel flow ramp transients. The minimum to maximum fuel flow ramp provides a moderately rapid transient disturbance that allows the full set of engine partial derivatives to be exercised. A test case at each corner of the flight envelope as shown in figure 8 is considered. An additional test case at sea level static with response to the same fuel flow input but including a water injection step at 92 percent fan speed was also run. Data from each case was compared with the aerothermodynamic simulation from which it was derived. All parameters are in percent of full range.

Transients are shown in figures 9 and 10 for only the full range acceleration at 5000 feet altitude and the same case with water injection at sea level static.

The full range acceleration altitude run, figure 9, demonstrates the effects of altitude on the model. Transient behavior and high power steady state levels are very closely matched especially for the output thrusts. Since thrust is the primary output to the aircraft simulation, it is essential to have thrust representative of the real system. Also, although not shown here, differences up to 6 percent were exhibited in some internal engine parameters, in particular, jet pipe temperature and fan and compressor surge margin. These differences could be significant if they were used as a sensed parameter in a control system.

The test case with water injection, figure 10, showed much the same accuracy. There was no particular difficulty in modeling the steady state or dynamic effects with water injection.

Results of the other test cases, although not shown here, were similar. The effect of combined altitude and speed showed that altitude had the most effect. Full range transient matching was excellent here with most differences occuring again at low power levels. Speed effects alone had a relatively insignificant effect on the state variable model. High and low steady state level and transient profiles matched extremely well.

The engine model presented here was combined with a detailed representation of a hydromechanical fuel control and integrated into a simulation for the Harrier aircraft. The results of that evaluation are given in (4).

CONCLUDING REMARKS

A state scheduled state variable methodology has been used to generate a real time digital propulsion system simulation for piloted simulators. The methodology proved effective in generating a model of excellent accuracy over a limited operational range as compared to the aerothermodynamic model from which it was derived. The methodology provides a very flexible means to accomplish a real time model in a reasonably short time.

The model executed 5.6 times faster than real time using an integration time step of 50ms. Computation time analysis indicated that approximately 30 percent of the cycle time was consumed in matrix operations. It appears that this could be a high payoff area for future development. Although the total amount of code generated in this model is high, 21.7K bytes, this is generally not a limiting factor in real time simulations.

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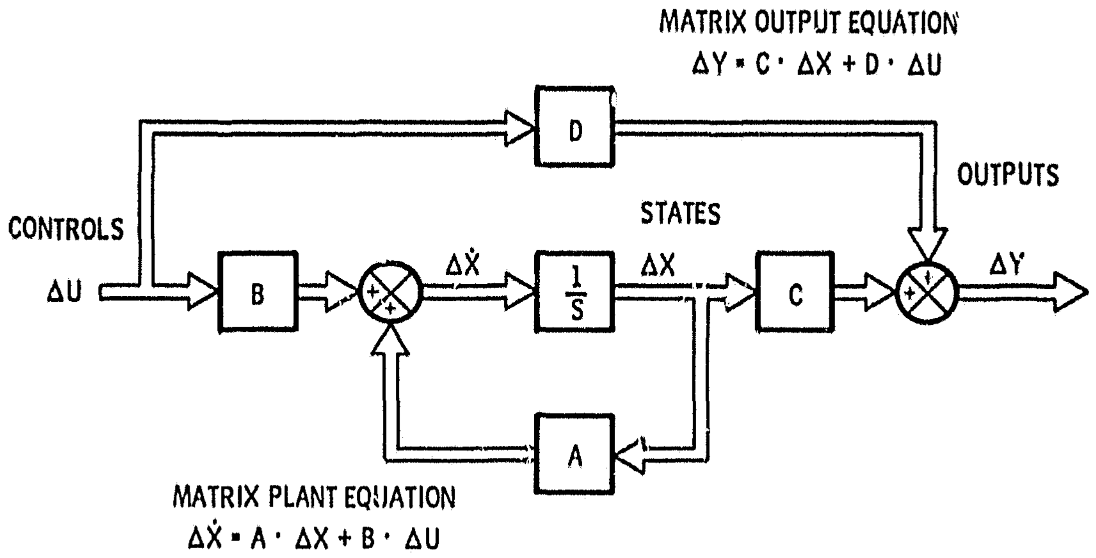

Figure 1. - Real time model state variable representation.

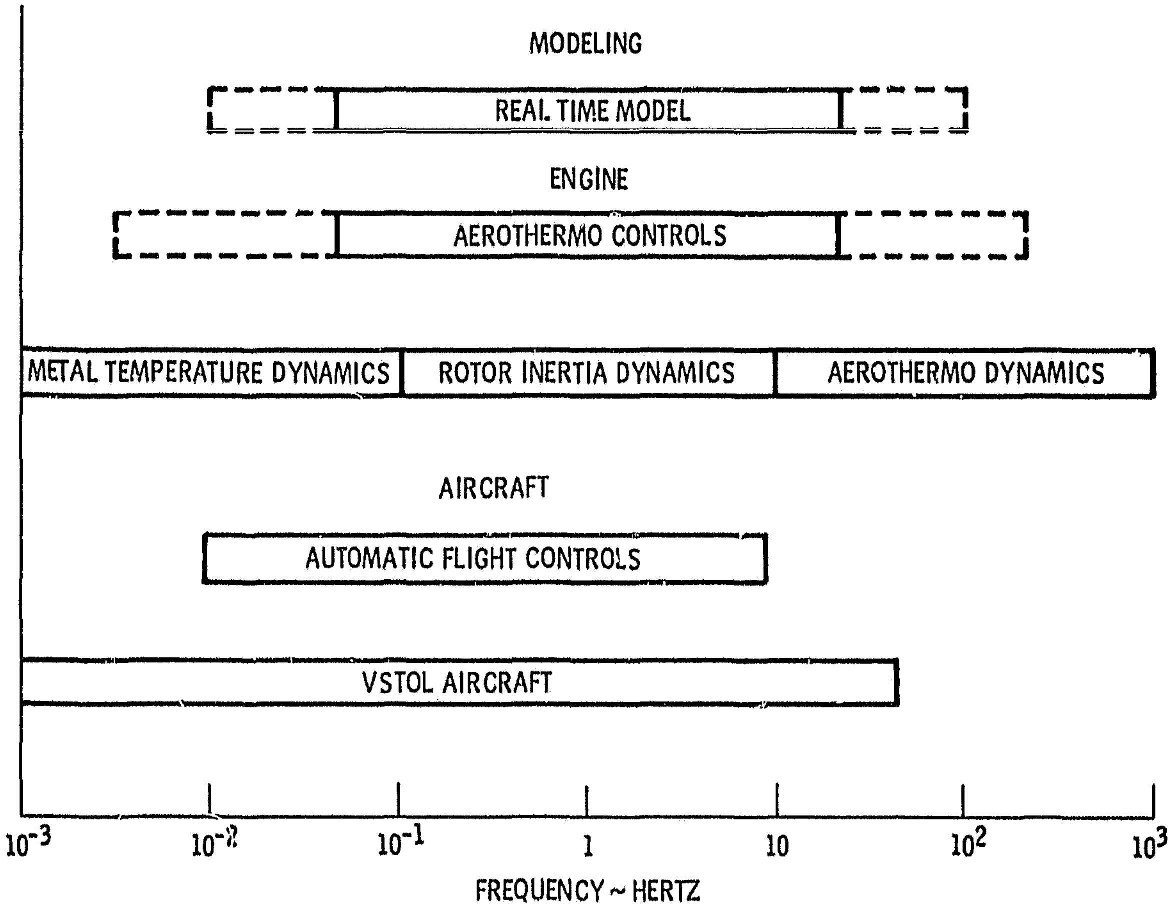

Figure 2. - Modeling frequency range of interest.

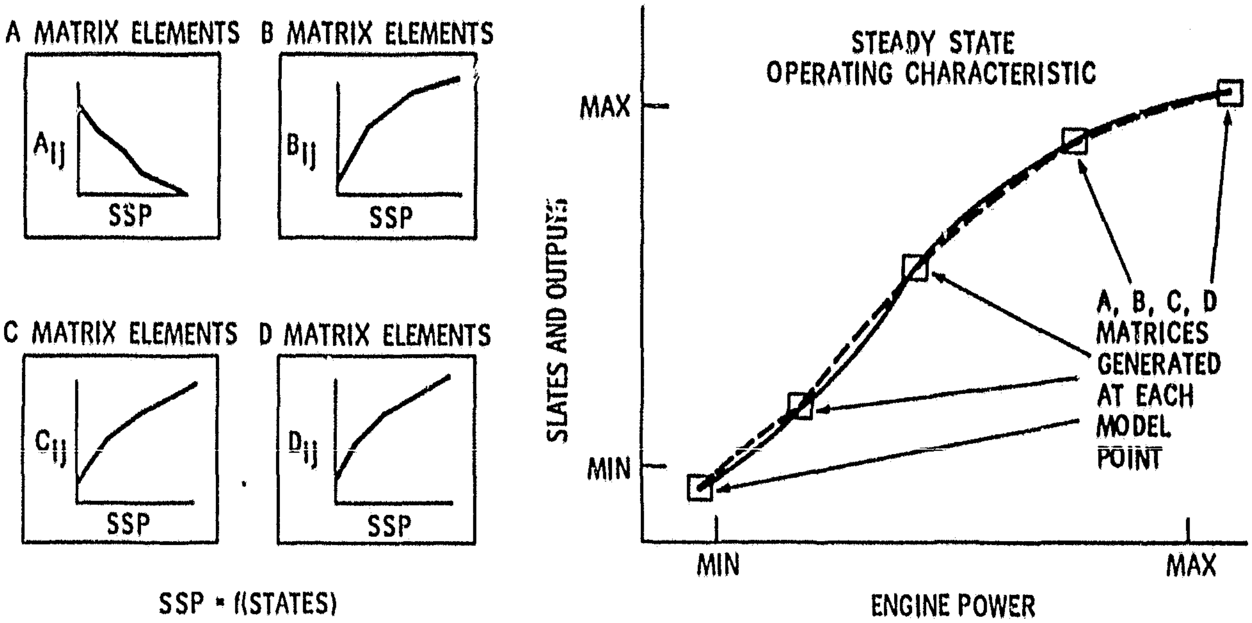

Figure 3. - State scheduled parameter nonlinear real time model.

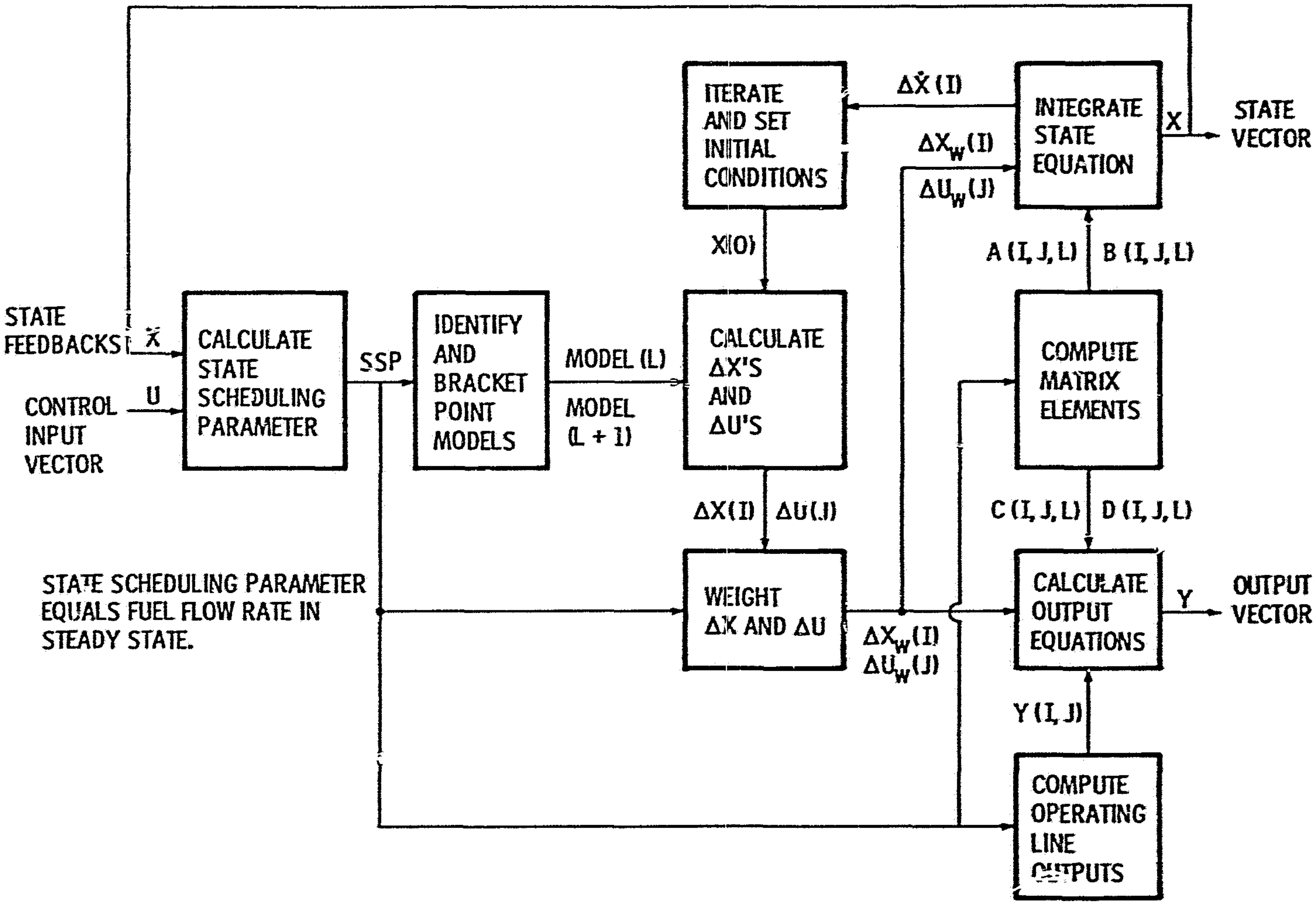

Figure 4. - State scheduled state variable engine model.

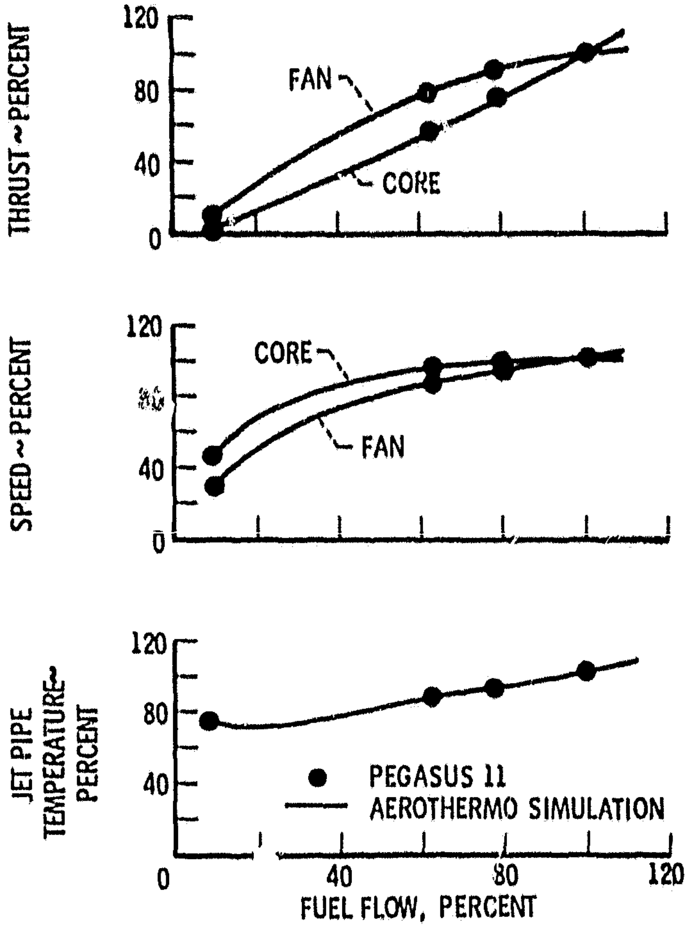

Figure 5. - Pegasus 11 simulation steady state match.

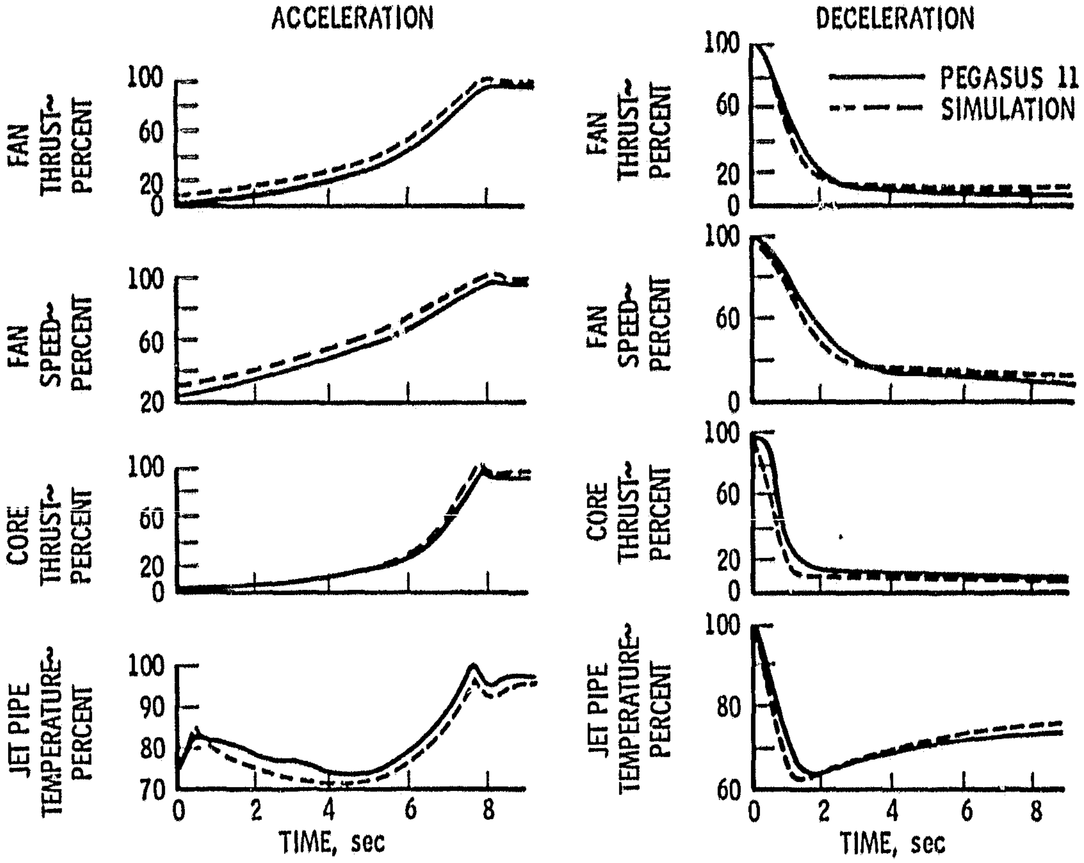

Figure 6. - Pegusus 11 simulation transient match.

CONTROL VECTOR

ΔU =
- FUEL FLOW
- WATER INJECTION FLOW
- REACTION CONTROL BLEED FLOW
- ENGINE FACE PRESSURE
- ENGINE FACE DELTA TEMPERATURE
- AMBIENT PRESSURE

STATE VECTOR

ΔX =
- LOW ROTOR SPEED
- HIGH ROTOR SPEED
- BURNER METAL TEMPERATURE

OUTPUT VECTOR

ΔY =
- CORE NET THRUST
- FAN NET THRUST
- FAN PHYSICAL
- AIRFLOW
- HIGH COMPRESSOR PHYSICAL AIRFLOW
- FAN AVERAGE PRESSURE RATIO
- HIGH COMPRESSOR PRESSURE RATIO
- FAN NOZZLE DUCT TEMPERATURE
- FAN NOZZLE DUCT PRESSURE
- HIGH COMPRESSOR INLET TEMPERATURE
- HIGH COMPRESSOR INLET PRESSURE
- BURNER INLET TEMPERATURE
- BURNER INLET PRESSURE
- HIGH TURBINE INLET TEMPERATURE
- HIGH TURBINE INLET PRESSURE
- LOW TURBINE INLET TEMPERATURE
- LOW TURBINE INLET PRESSURE
- CORE NOZZLE DUCT TEMPERATURE
- CORE NOZZLE DUCT PRESSURE
- THRUST SPECIFIC FUEL CONSUMPTION
- FAN SURGE MARGIN*
- CORE SURGE MARGIN*

*AUXILLARY MODEL OUTPUT COMPUTATIONS

Figure 7. - Real time model state variable vectors.

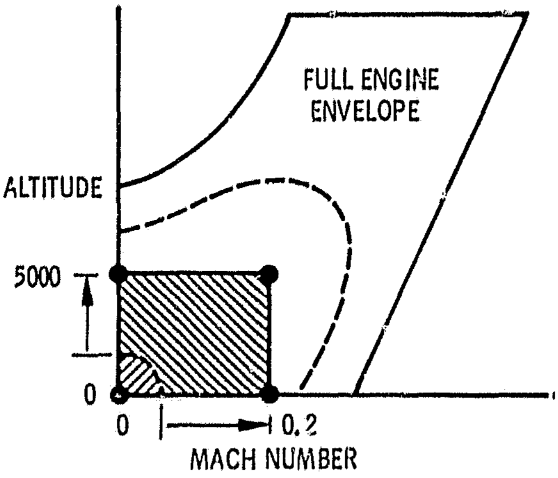

Figure 8. - Real time model flight envelope.

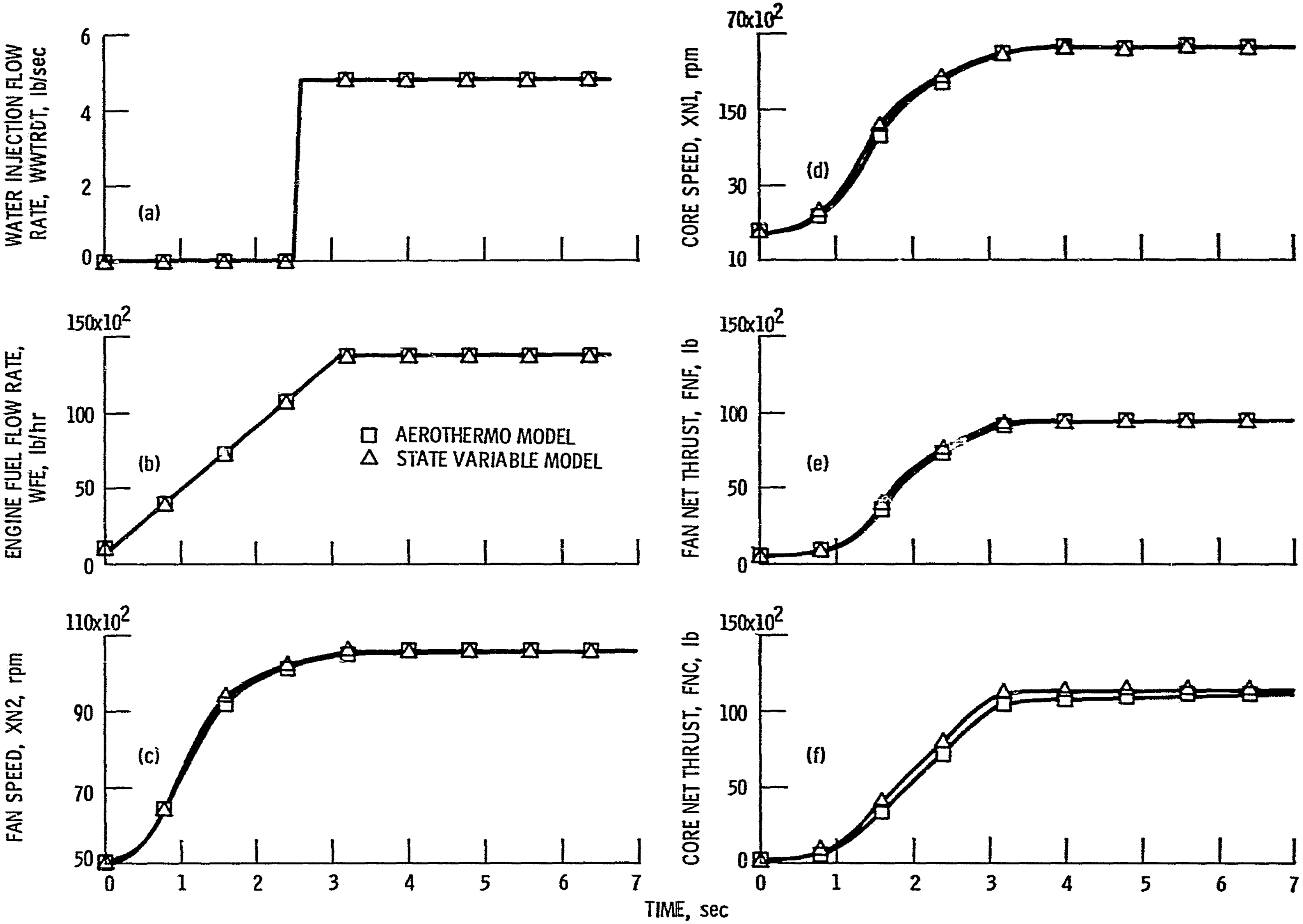

Figure 9. - Full range fuel transient with water injection at 92 percent fan speed, sea level static.

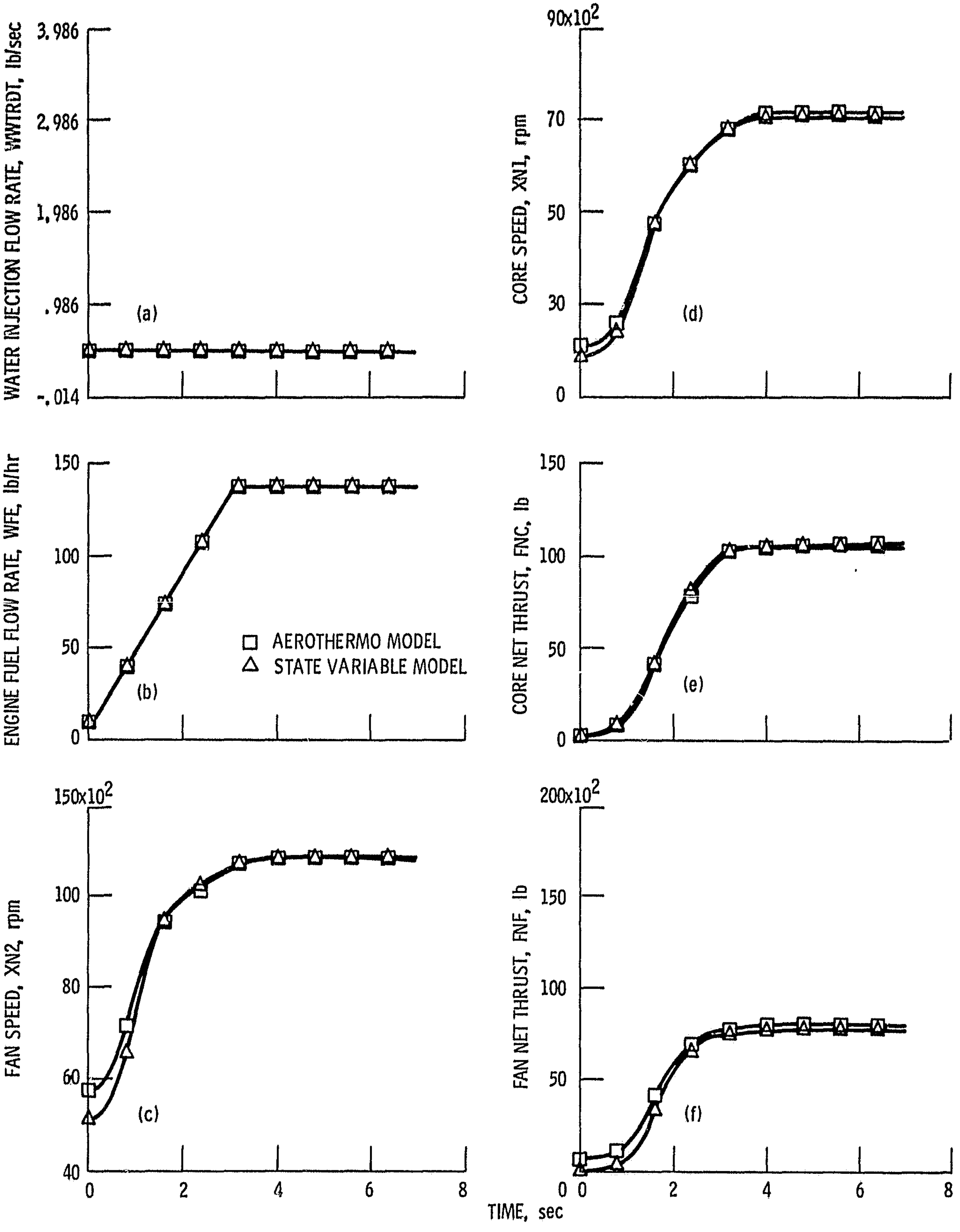

Figure 10. - Full range fuel transient at 5000 feet altitude.