Real-Time Pegasus Propulsion System Model V/STOL-Piloted Simulation Evaluation

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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. 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 V/STOL. The real-time propulsion model was formulated by applying a piecewise linear state variable methodology. The model has been programmed for interfacing with a Harrier aircraft simulation. Typical propulsion system simulation results are presented.

Introduction

DURING low-speed operations, V/STOL 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.

A conceptual evaluation of propulsion control systems for V/STOL aircraft was made under contract 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 V/STOL-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 V/STOL 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 V/STOL Propulsion Control Analysis Program reported in Ref. 1, an engine model was used to explore the merits of using a combined simulation of air-craft-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 V/STOL designs.

A Pegasus 11 propulsion system was chosen as the baseline V/STOL 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 give 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 Fig. 1. The engine weighs approximately 3540 lbm with an inlet diameter of 46 in. and a total uninstalled dry thrust of 19,500 lbf. Total design airflow

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is 435 lbm/s 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 counterrotating. Counterrotation 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 10,500 rpm at a pressure ratio of 5.6.

At a maximum design thrust of 19,500 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 0-98.5 deg. The four nozzles are mechanically linked to each other to insure that the vertical-to-horizontal angular position is identical for each thrust vector.

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

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 insures that the engine limitations are not exceeded.

Fuel flow to the engine is regulated by two metering devices—a metering valve and a throttle shutoff valve. The metering value 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%. 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%.

A number of engine-limiting functions are also included. These are 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 atempt 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 gal of water, which is sufficient for 90 s of operation.

The water injection system 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% when the throttle is in excess of 87% 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% 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 s 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 Fig. 2. Aerodynamic controls on the aircraft are standard control surfaces. However, 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 jects located at the wing tips 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

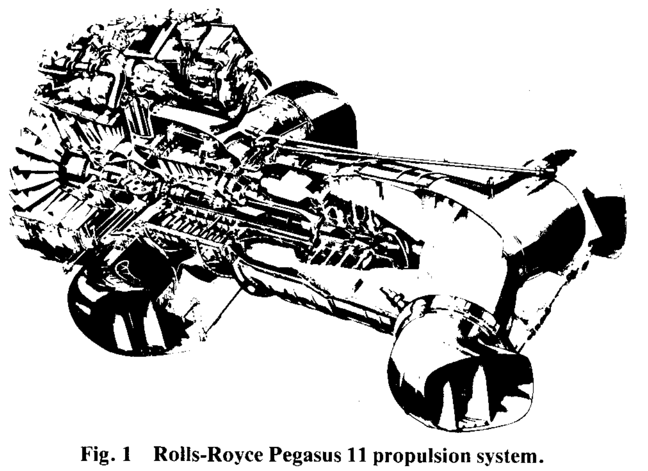

Fig. 1 Rolls-Royce Pegasus 11 propulsion system.

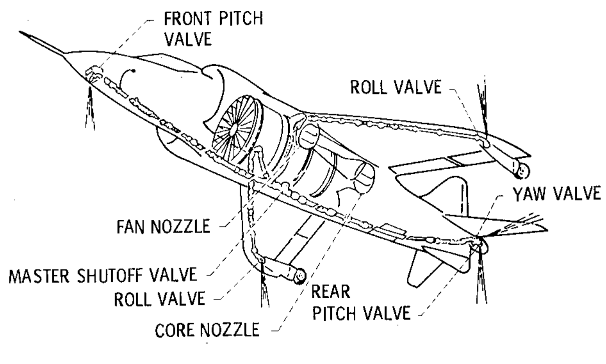

Fig. 2 Reaction control jet nozzle system.

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. The aerothermodynamic model was verified by correlating it both in steady-state and transient modes with experimental engine data supplied by the manufacturer.

A nonlinear propulsion system simulation such as this produces a model of high-frequency fidelity which does not, however, 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.

Real-Time Methodology

The real-time model is based on a piecewise linear state variable technique reported in Ref. 2. The state variable form is shown in Fig. 3, where X is the vector of state variables, $\dot{X}$ the time derivative of the state variables, U the control input vector, and Y 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 model 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 are uncontrollable by the inputs were eliminated. The final model considered only states that were within a 0.1-10 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,

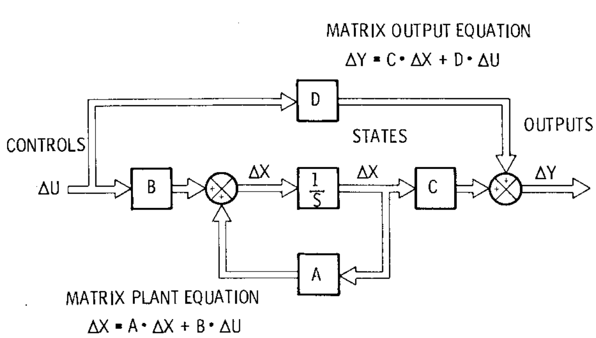

Fig. 3 Real-time model state variable representation.

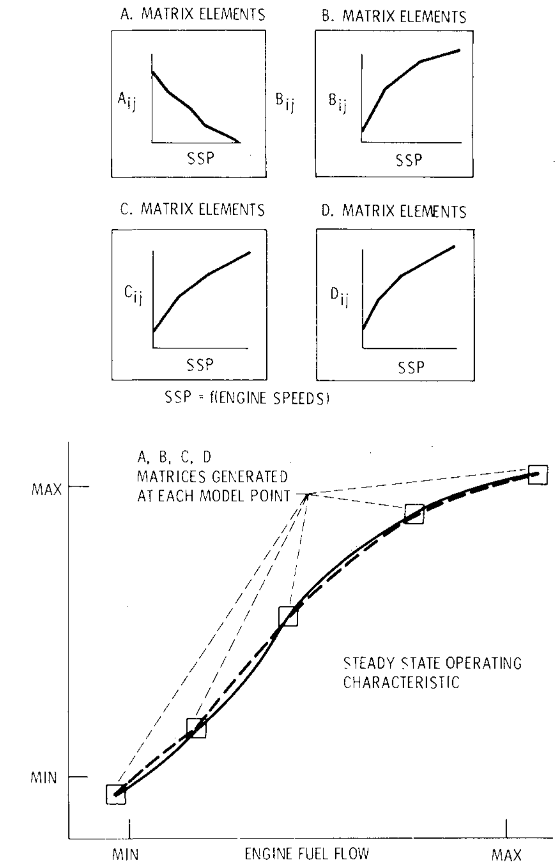

Fig. 4 State-scheduled parameter nonlinear real-time model.

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 GROSS THRUST
- FAN GROSS 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

Fig. 5 Real-time model state variable vectors.

each X is perturbed one at 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 Fig. 4.

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 (7-109%) up to 5000 ft altitude and 0.3 Mach number are represented. The state variable vectors used are shown in Fig. 5.

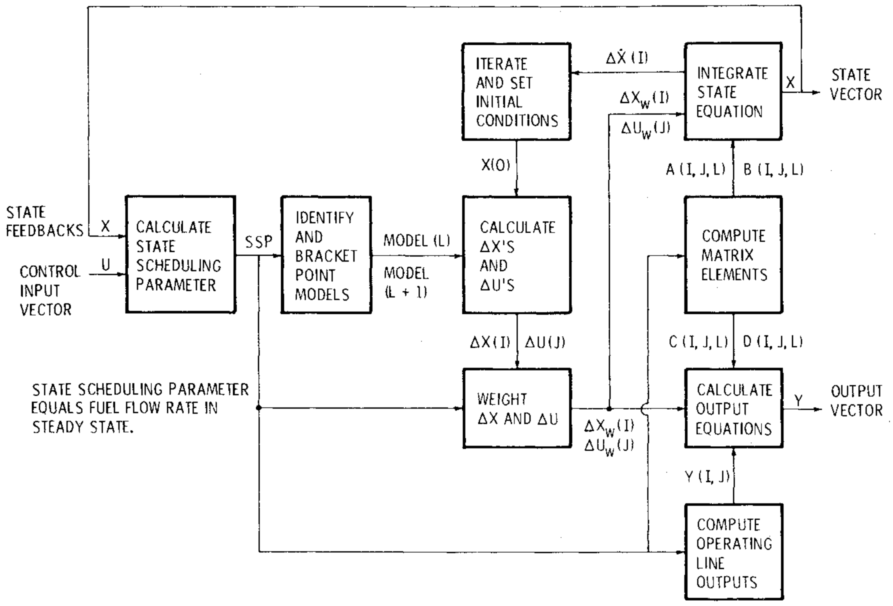

Fig. 6 State-scheduled state variable engine model.

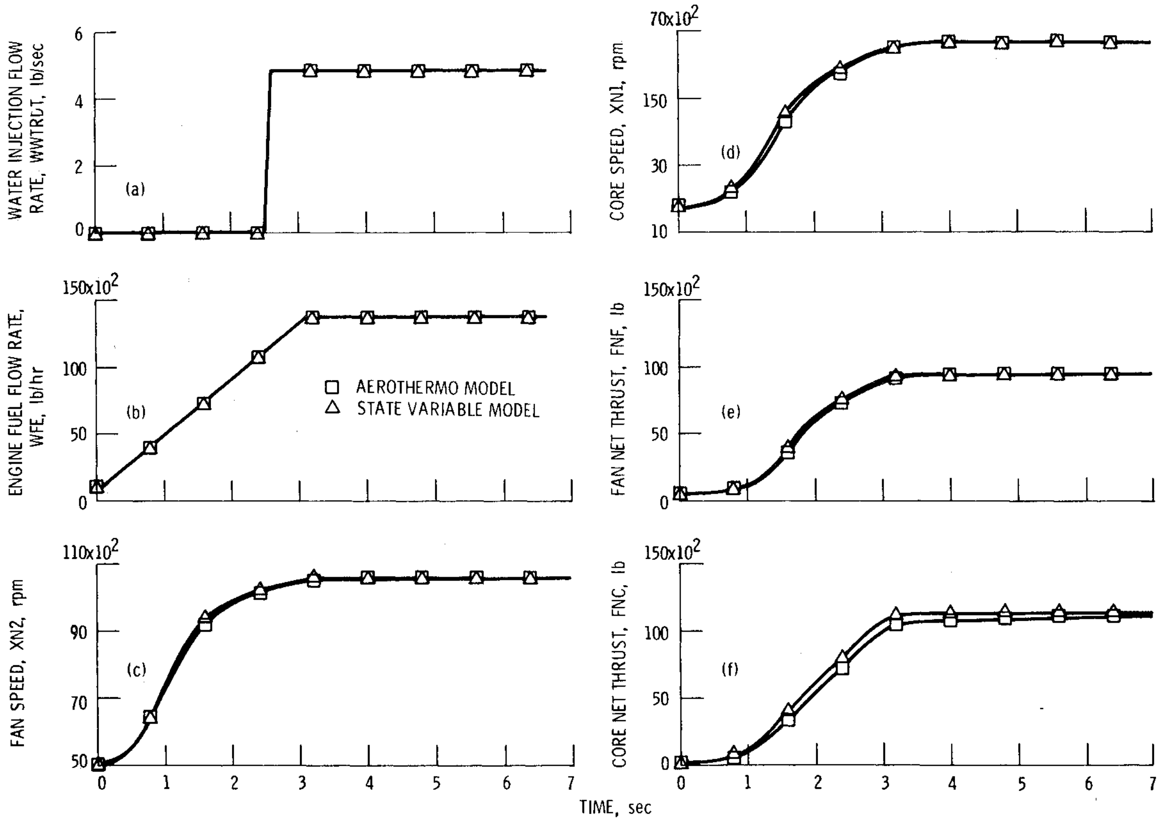

Fig. 7 Full-range fuel transient with water injection at 92% fan speed, sea level static.

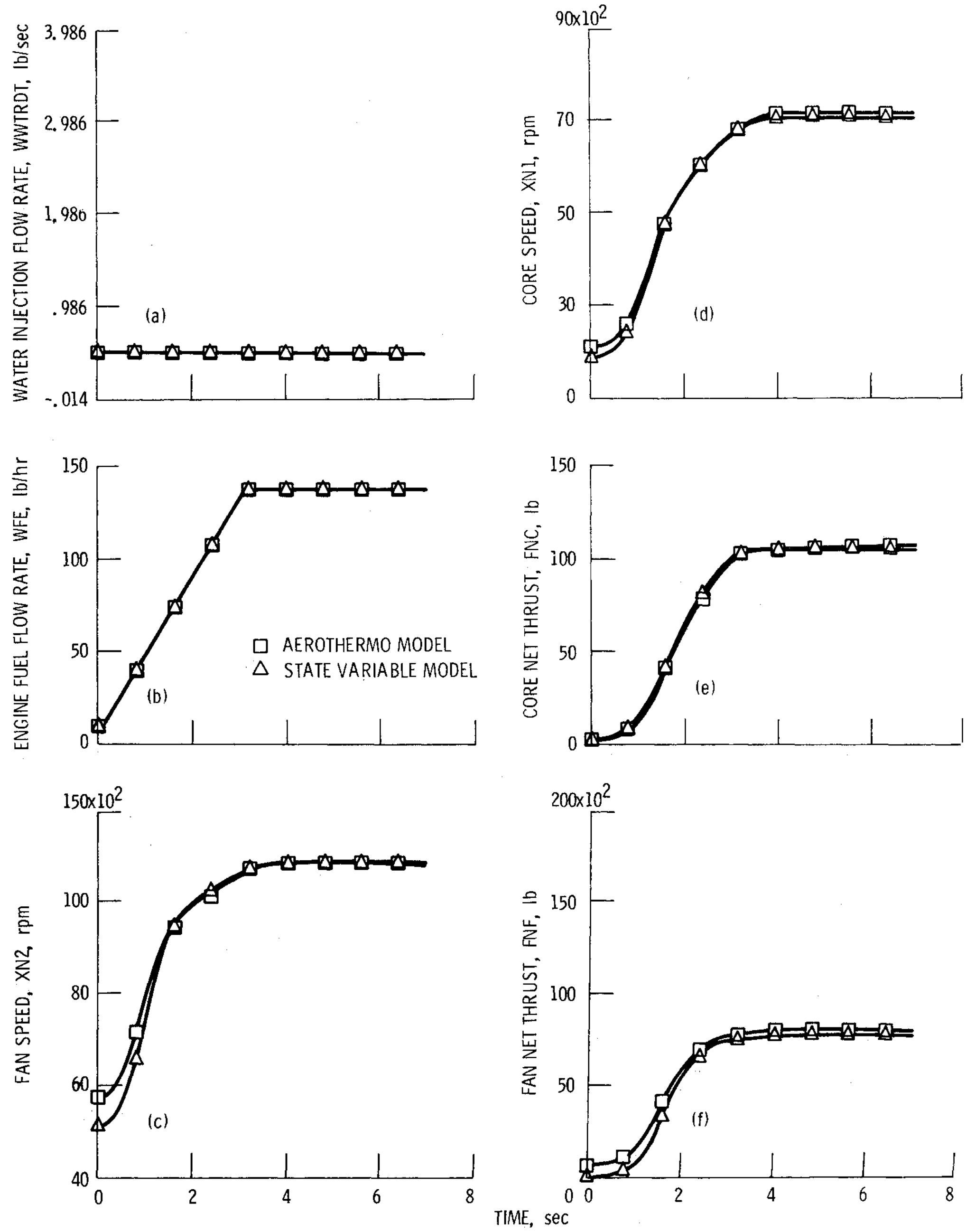

Fig. 8 Full-range fuel transient at 5000 ft altitude.

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 Fig. 4, involves generating a set of matrices or point models for various levels within the engine operating range from minimum (7%) to maximum (109%) 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 piecewise linear representation. For large power excursions from 7-109%, 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 6 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

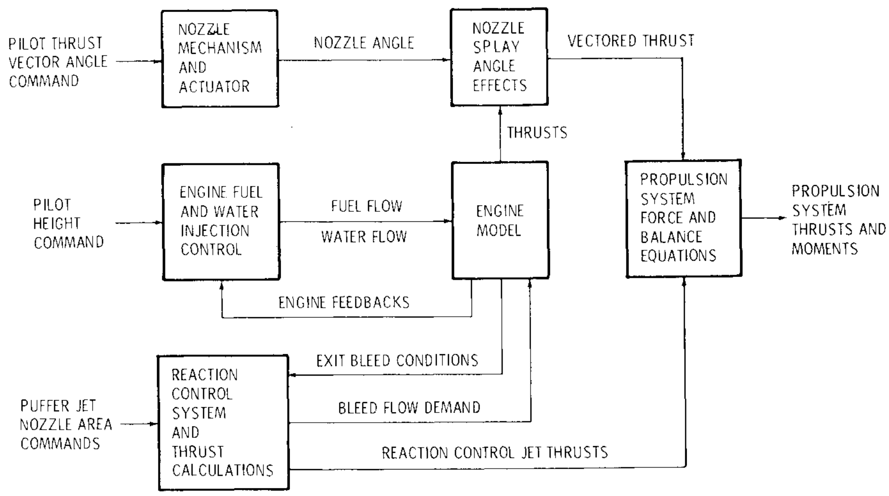

Fig. 9 Propulsion system model for aircraft integration.

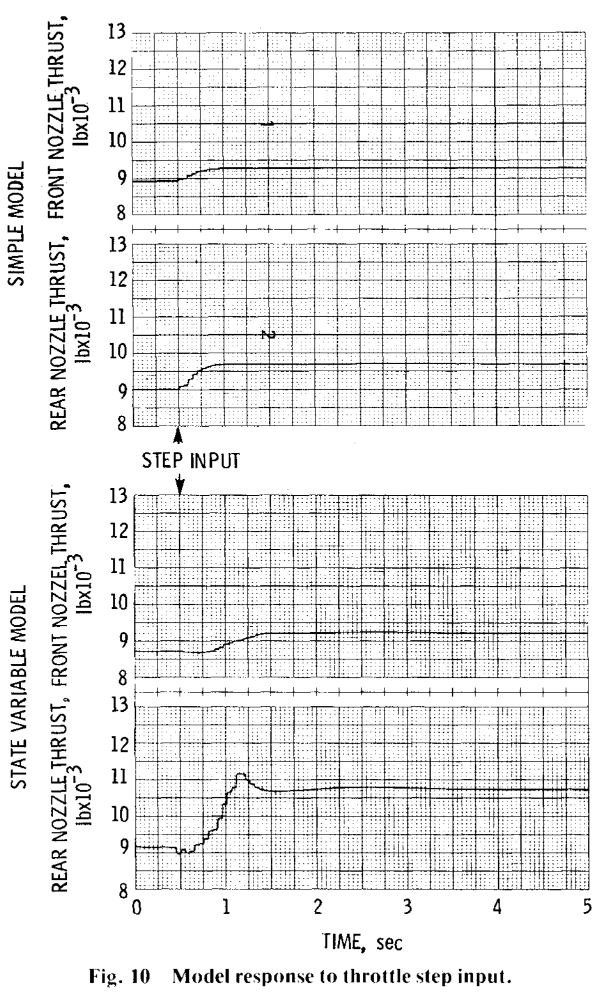

Fig. 10 Model response to throttle step input.

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, and 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 intergration.

The steady-state model output is calculated from the operating line curves. The operating line outputs 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 Figs. 7 and 8 that exhibit the accuracy with which the state variable model matches the aerothermo Pegasus 11 representation for a 7-100% power excursion at sea level with water injection and at an altitude of 5000 ft.

The experimental engine data used to verify the aerothermo model were not available for direct correlation with the real-time model. Real-time model fidelity is inferred from the aerothermo model correlation.

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 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 piecewise 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 9 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 to perform other 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 simplified model of the landing gear, including vertical force, braking force, and pitching moment is also used. A separate subroutine is used to represent the Pegasus 11 engine operating at low altitude and Mach number. In the original aircraft model, the engine dynamic response to throttle changes is modeled as a rate-limited, first-order lag response in engine speed. The time constant varies with engine speed. 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 described previously.

The ship model used was that of a Spruance class destroyer.[5] 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 V/STOL 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 Ref. 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 stationkeeping point 12,000 ft downrange 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 Fig. 10 for a power lever step increase from 60 to 70 deg. The apparent, but not real, oscillatory characteristic of the traces is due to the sampling rate of digital-to-analog conversion at the recorders. For the simple engine, both the forward and rear nozzle thrusts exhibit a lag response with a time constant of about 0.25 s. For the state variable model, on the other hand, the thrust exhibits a first-order lag response with a time constant of 0.5 s in the front nozzle and a moderately damped second-order response with a time constant of about 0.25 s in the rear nozzle. These characteristics are important in designing integrated flight controls that include the engine in a closed loop.

Control Performance

Figure 11 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. Attitude is maintained through the flight controller.

Overall engine model operation is stable. Core and fan thrusts follow power level 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 12 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 level 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

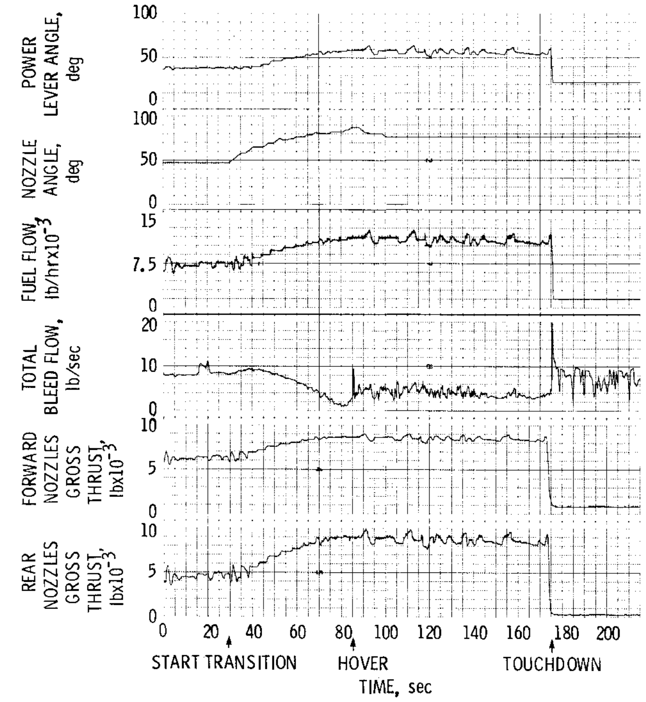

Fig. 11 Approach and landing engine transients using type 2 flight controller.

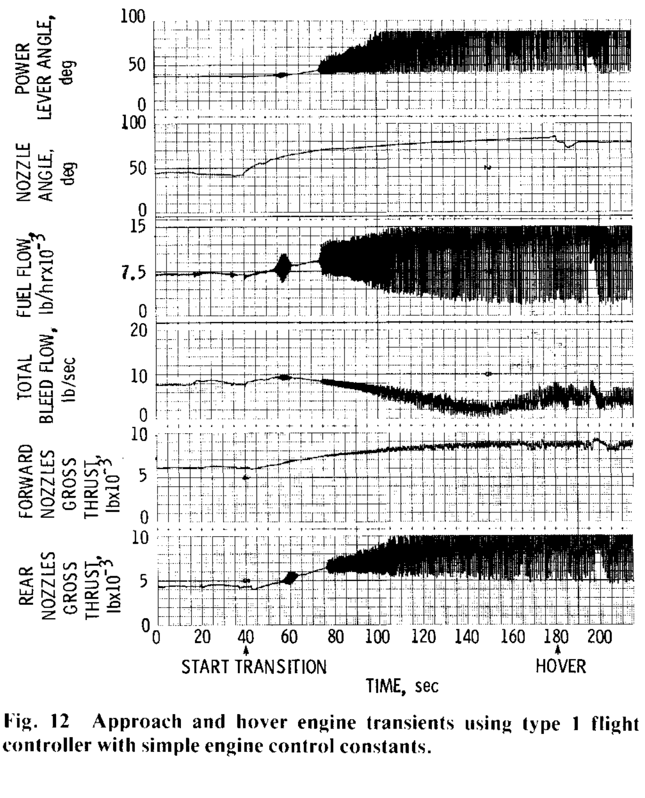

Fig. 12 Approach and hover engine transients using type 1 flight controller with simple engine control constants.

engine fuel control is responding to power level 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 13 shows the same typical flight task, except that the implicit model in the altitude flight controller has been modeled 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

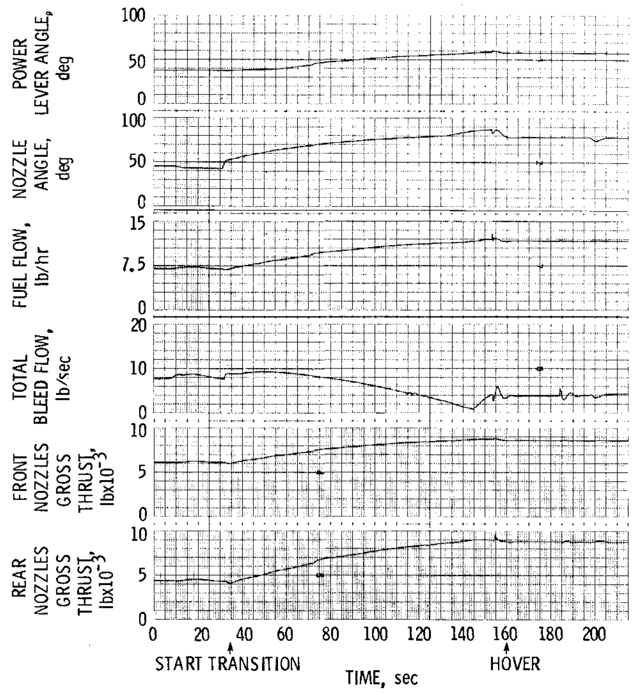

Fig. 13 Approach and hover engine transients using type 1 flight controller with state variable control constants.

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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