NASA TM-83343

NASA Technical Memorandum 83343

NASA-TM-83343 19830017440

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Prepared for the
Sixth International Symposium on Air Breathing Engines
cosponsored by the International Society on Air Breathing Engines and the
Association Aeronautique et Astronautique de France
Paris, France, June 6–11, 1983

NASA

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E-1558

Abstract

The NASA Lewis propulsion controls research program is aimed at providing advanced technology for airbreathing engine control systems. The research is motivated by the continuing increase in complexity of engines and their controls. The scope of the NASA research program, described herein, includes control theory and methodology, real-time propulsion system simulation, electro-optical control system components, integrated flight/propulsion controls and stall recovery research. Multivariable control theory is applied to the design of multiple input and output engine controls. Highly-accurate, real-time engine simulations are utilized for control development and checkout. Electro-optical control components are developed for use in electronic control systems having fiber optic data links. Integrated controls are developed for VSTOL and Rotorcraft propulsion systems. Post-stall models of engine systems are developed to aid in understanding and control of post-stall engine behavior.

Introduction

The NASA propulsion controls research program is aimed at providing advanced technology for airbreathing engine control systems. The program is conducted and managed by the NASA Lewis Research Center. The research is motivated by the increased complexity of airbreathing engines which has occurred in recent years and which is expected to continue through the balance of the century. Engines having seven manipulated variables (control inputs) are already in service, and engines having ten variables are being tested. The increased number of variables has made it more difficult to provide hydromechanical engine controls having high reliability, low cost and weight. As a result, supervisory electronic engine controls are already in service and full-authority digital electronic controls are in development.

The increased number of control inputs and controlled outputs also motivates the development and application of multivariable control theory. The classical single-input, single-output control design techniques are inadequate for multi-input, multi-output systems that have significant cross-coupling between loops. In spite of their complexity, the control designs produced by multivariable control theory are readily programmed on electronic computers.

The scope of the NASA research program includes control theory and methodology, real-time propulsion system simulation, electro-optical control system components, integrated flight/propulsion controls, and stall recovery research. Advanced, computer-aided, multivariable control design techniques are required to permit the systematic design of high-performance controllers for future engines having highly interactive, multi-input, multi-output control loops. Accurate simulations of these engine systems are required to develop and evaluate the control designs. Furthermore, real-time operation of the simulations are required to check out and evaluate the control implementation prior to full-scale engine testing. Electro-optical control system components (sensors and actuators) are attractive for use in electronic control systems having fiber optic data links. Integrated flight/propulsion controls can improve performance of the total aircraft/propulsion system whenever there are significant interactions between the aircraft and propulsion variables. Integrated controls are particularly important for aircraft systems in which the propulsion system provides lifting forces and moments in addition to forward thrust, as in V/STOL aircraft systems. Finally, stall recovery research will provide a basic understanding of factors which influence the recoverability of engine systems following an engine stall and will, hopefully, allow for the development of automatic controls for avoidance of and recovery from stall.

All of the above research areas will be described in the following sections.

Control Theory and Methodology

Multivariable Control

The increased numbers of inputs and outputs associated with modern high performance aircraft engines has motivated the application of multivariable control theory to the design of controls for these engines. One such effort involved the development and evaluation of a multivariable control (MVC) for the Pratt & Whitney Aircraft (P&WA) F100 engine. The control laws were designed by Systems Control Technology Inc. (SCT)[1] using Linear Quadratic Regulator (LQR) theory under a contract jointly sponsored by NASA Lewis Research Center and the Air Force Aeropropulsion Laboratory. The F100 engine was selected for the program because it has six control inputs - Fan Inlet Guide Vanes, Compressor Variable Vanes, Main Combustor Fuel Flow, Compressor Bleed, Augmentor Fuel Flow, and Exhaust Nozzle Area.

The overall program objective was to demonstrate the benefits of using the LQR synthesis technique in the design of a practical multivariable control system that could operate a turbofan engine over its flight envelope. The advantages of the LQR approach include (1) enhanced performance obtained through use of cross-coupled controls, (2) maximum use of engine variable geometry for set point regulation, and (3) a systematic design procedure that can be applied efficiently to future engine systems. The scope of the control design effort included both set point regulation and transition control, over the entire flight envelope.

The overall effort consisted of three phases. In the first phase, control logic was designed by SCT based on a family of linear operating point models of the F100 engine. The control logic was then evaluated by P&WA using a digital, non-real-time simulation of the engine. The control logic included integral terms to eliminate steady-state offsets. In addition, feed-forward terms were included to permit rapid set point transition. The operating point control gains were interpolated to give control capability across the flight envelope.

In phase 2, the multivariable control logic was programmed on a digital minicomputer. The minicomputer was to control an actual F100 engine in phase 3. This control implementation was checked out and evaluated[2] using a real-time simulation of the F100 engine[3] programmed on the Lewis Hybrid Computer System (Fig. 1). The programming of the control on the minicomputer and the development and programming of the real-time engine simulation were performed by Lewis engineers. The control was programmed in assembly language using fixed-point arithmetic in order to minimize the cycle time. The real-time engine simulation was a nonlinear, component-level representation of the engine and included lumped-volume and rotor dynamics. Maximum use was made of analog equipment to achieve real-time capability. The resulting simulation accurately represented the engine's steady-state and transient performance across the entire flight envelope. This allowed a thorough checkout and evaluation of the control to be conducted[3] prior to the engine system evaluation (see Fig. 2).

Following completion of the control evaluation on the real-time engine simulation, the minicomputer implementation of the multivariable control was used to control an F100 engine in an altitude test facility in phase 3.[4] Interface hardware was developed to allow the minicomputer to drive the engine's bill-of-material, hydromechanical actuators and to provide electrical feedback signals to the computer. The resulting test setup allowed control authority to be switched at test time to either the bill of material control or the research digital control. A complete steady-state and transient evaluation of the multivariable control was performed over the entire flight envelope. The LQR based control performed well at all flight conditions. The engine experimental evaluation proceeded smoothly because of the thorough evaluation which had been conducted previously in using the real-time engine simulation.

Failure Detection and Accommodation

In a follow-on effort, sensor failure detection, isolation, and accommodation (FDIA) algorithms have been developed for the F100 engine under a NASA Lewis contract to P&WA and SCT.[5] In this effort, algorithms are being developed to detect if one or more engine sensors have failed (i.e., are providing inaccurate information). The algorithms also will isolate the failed sensors and construct analytical replacements for the failed sensors using other information sources.

The first task, performed by P&WA, was to define and quantify failure characteristics for typical sensors according to the failure categories: out of range, drift, and noise. Next, a failure mode effects and criticality analysis (FMECA) was conducted using simulations of the F100 engine and the multivariable control developed earlier. The purpose of the FMECA was to identify critical failures (i.e., those which would result in engine surge, excessive thrust variation, or rotor overspeed).

An FDIA scoring system was developed, which quantitatively and qualitatively evaluated candidate concepts in terms of (1) DIA criteria - the ability to meet minimum aircraft operational requirements in the event of sensor failures, (2) DIA detection performance - how well failures are detected and accommodated, and (3) DIA Figure of Merit, consisting of qualitative benefits of bettering the DIA criteria.

Available techniques for DIA were reviewed for applicability. Five concepts were formulated by SCT, based on the use of modern control techniques such as Kalman filters. A simplified engine simulation was used to screen the concepts, and two of the concepts were then selected for more detailed evaluation. This further screening process resulted in the selection of one DIA concept, which was then programmed and evaluated by P&WA using a detailed nonlinear simulation.

In the selected DIA concept, failure detection is based upon range and residual checks. Isolation is accomplished by hypothesis testing of filter residuals. Failures are accommodated by reconfiguring a Kalman filter to produce estimates of all sensor outputs based upon the set of available, or unfailed, sensor outputs.

In addition to the selected DIA concept, another DIA algorithm, based on parameter synthesis, was also investigated. The evaluation results for the advanced and parameter synthesis algorithms were compared. It was concluded that the advanced technique is viable for gas turbine engine applications and provides a more systematic design approach than does the parameter synthesis method. Given a reasonably accurate plant model and sensor failure characteristics, the design of the various Kalman filters and detection and isolation tests is relatively straightforward.

The FDIA algorithms along with the MVC/LQR control logic, will be programmed on a Lewis-developed microcomputer control facility. This facility includes two Intel-8086 16-bit microprocessors which operate in parallel to provide the control logic. An interface unit allows exchange of information with simulations or engines, and a monitoring unit records and displays engine and control variables during a test. The FDIA algorithms will be checked out using the real-time F100 engine simulation, then experimentally evaluated on an F100 engine.

Frequency Domain Methods

In addition to the time-domain LQR method, several frequency-domain MVC design techniques have been utilized and reported. One such technique which has received particular attention is the Multivariable Nyquist Array (MNA) method. In an in-house effort, Lewis engineers are designing an MNA control for the F100 engine and will compare the performance of LQR and MNA control designs.

Real-Time Simulation

The hybrid computer (Fig. 1) has been and continues to be the workhorse for real-time, nonlinear, full-envelope, aerothermodynamic simulations of engine systems at Lewis. The simulations employ mathematical models such as the one illustrated in Fig. 3. Here, each engine component is represented by a set of maps that describes the steady-state performance characteristics of that component. The individual component models are interconnnected by control (mixing) volumes which account for the storage of mass and energy within the engine. Rotor speeds are calculated by integrating excess shaft torques. The effects of variable geometry are introduced into the model as corrections (biases) to the fixed-geometry performance maps. Additional levels of detail may be included in the model to improve the steady-state and/or transient accuracy of the model. These may include time-varying fluid properties, heat transfer between gas and metal, multilump component models, variations in turbine cooling air, and turbomachinery clearance variations. Real-time hybrid engine simulations have been developed for several engines and used as tools in the development of advanced digital electronic control systems.

Lewis has recently initiated an effort to apply digital microprocessors, operating in parallel, to the real-time engine simulation task. This multifaceted program includes advanced software as well as hardware technology. One objective of the Lewis program is to design, build, and test a prototype digital simulator(6) that will be capable of simulating a detailed aerothermodynamic model of a turbofan engine in real-time. The basic structure of the simulator being proposed is shown in Fig. 4. The heart of the system is a transfer controller that synchronizes N 16-bit processing elements (P.E.'s) on a high-speed data transfer bus. All but two of the P.E.'s perform simulation computations. One of the remaining P.E.'s is dedicated to input/output functions. The last P.E. is a special-purpose processor that links low-speed, operator commands to the high-speed simulator. This P.E. is termed the "real-time extension" of the front-end processor. The microprocessor-based front-end processor provides the operator's interface to the simulator and handles peripheral communications, program loading, etc.

The real-time operation of the simulator depends on the simulation calculations being distributed among the P.E.'s by the user in such a way that the sum of the largest compute time and the transfer time does not exceed the specified step size (frame time).

In addition to developing simulator hardware, the research effort also includes software development. Research and development is underway on programming languages, compilers/translators, on operating system and other user-friendly software tools. Also, techniques for partitioning the simulation among the microprocessors, and numerical integration techniques appropriate for parallel processing are being developed.(7)

Electro-Optical Control Components

The use of fiber optics for transmission of data has great potential for application to future propulsion control systems. Fiber optics offer possible lower weight and greater resistance to lightning strikes and EMI than conventional conducting cables. In conjunction with fiber optic data transmission, the use of other optical control components such as passive optical sensors and optically switched actuators offers the potential for increased reliability and reduced complexity.

Sensors

Two types of optical temperature sensors are being developed under contract to Lewis. One sensor type uses rare-earth elements whose optical transmission characteristics are a unique function of temperature. This sensor is being developed for NASA by the United Technologies Research Center (UTRC).(8) In this scheme glass is doped with a rare-earth, europium, and drawn into a fiber. Rare-earth materials like europium have absorption peaks at wavelengths in the visible region that are unique functions of temperature. By measuring the transmitted light at selected wavelengths, the temperature of the fiber can be determined. An experimental section of europium doped glass was fabricated for a proof of concept demonstration (Fig. 5). In the test setup two wavelengths of light are transmitted via the optical cable to the sensors. One wavelength passes through the rare-earth doped fiber. Its transmission characteristic is a function of temperature. The other wavelength is not affected by the rare-earth material and thus represents a reference wavelength to factor out the cable and connector losses. Laboratory tests of this sensor have included operation up to 400° C. Accuracy and resolution of this laboratory model were better than 1 percent.

A second temperature sensor which is under development (Fig. 6) is based on the Fabry-Perot interferometer, in which multiple reflections of incident white light in a gap between transparent plates results in amplification of some frequencies and attenuation of others. The gap thickness is temperature sensitive due to material expansion properties. Therefore, the spectral intensity pattern can be used to determine gap thickness and temperature.

Actuators

Optically switched actuators are also of interest for application in electronic control systems with fiber-optic data links. An optical photoswitch has been developed by UTRC under contract to NASA Lewis for this application. This system consists of a diode to protect the electronics from the inductive load, a JFET power switch and phototransistor. All these components are made of gallium arsenide because this system will require operation at high temperature (260° C) for extended periods of time. A photograph of the high temperature photoswitch is shown in Fig. 7. This photoswitch has the capability to switch up to 100 mA of current with off state voltage of 20 V.

Integrated Controls

Integrated flight/propulsion controls will allow increased performance, maneuverability and reliability for advanced, high performance aircraft. In the case of V/STOL and Rotorcraft aircraft, integrated controls will significantly reduce pilot workloads since, in these aircraft, the propulsion system provides lifting forces and moments in addition to thrust. Integrated controls for V/STOL aircraft are being studied in a joint program involving NASA Ames and Lewis, featuring piloted simulation at Ames. Lewis provides real-time engine system simulations(9,10). Ames provides real-time aircraft simulations. Integrated controls are being developed as a joint effort (Fig. 8).

Integrated controls are also being developed at NASA Lewis for Rotorcraft systems. In this application, integrated controls can provide greatly improved gust load alleviation thereby reducing pilot work load significantly. In addition, rotor speed droop following autorotation can be minimized.

Stall Recovery Research

A research program aimed at an understanding of factors which affect the recoverability of an engine following compressor stall is being conducted. A dynamic simulation of a typical two-spool turbofan engine has been developed,(11) that includes post-stall characteristics for the compressor. In the simulation, an engine surge is induced with a simulated fuel pulse or other disturbance, and the simulation calculates the resulting transient response. Depending on the choice of key parameters such as compressor bleed, the simulated surge cycle terminates either in automatic recovery to normal operation, or in a low-thrust rotating-stall condition (see Fig. 9). The simulation will be used to study control modes for avoidance of and/or recovery from rotating stall, as well as to identify key engine design parameters which can improve engine stall recoverability.

Concluding Remarks

The next generation of aircraft engines will likely utilize full-authority digital electronic controls. Control design will be performed using computer-aided multivariable control design techniques. Transmission of information between the digital control and engine sensors and actuators may utilize fiber optic cables, and optical sensing and actuation techniques. Sophisticated real-time engine simulation will continue to be used for control development and possibly also in flight for condition monitoring, fault accommodation, and adaptive control.

The NASA Lewis propulsion controls research program is aimed at development of the key advanced technologies in all of the above areas, so as to facilitate the introduction of these technologies in future engine control systems.

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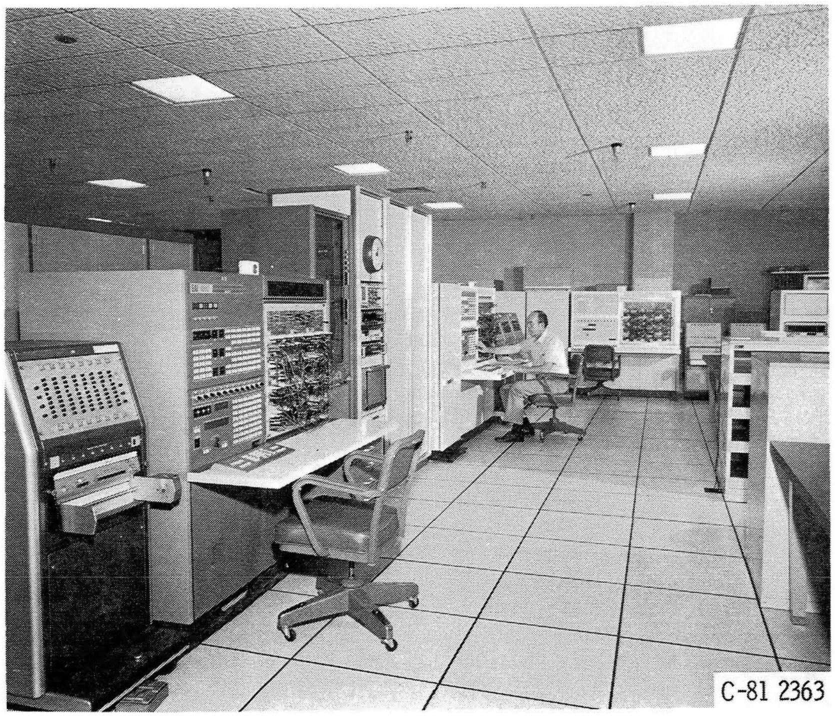

Figure 1. - Lewis hybrid computer facility.

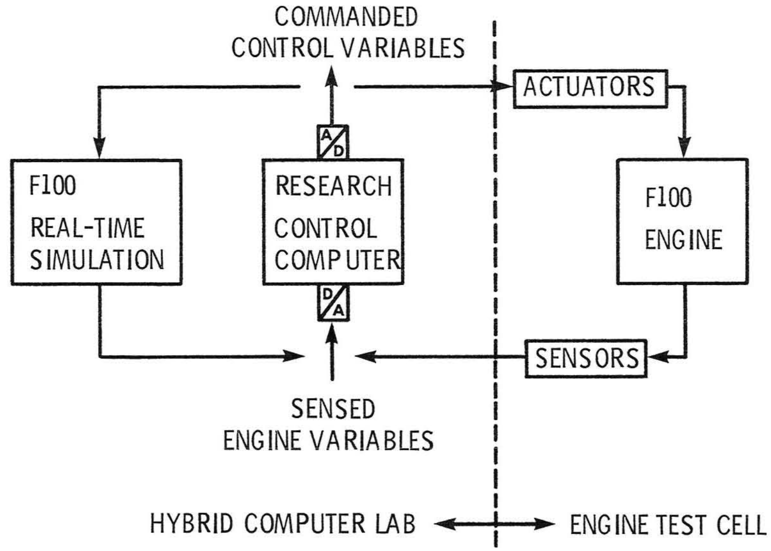

Figure 2. - F100 multivariable control evaluation.

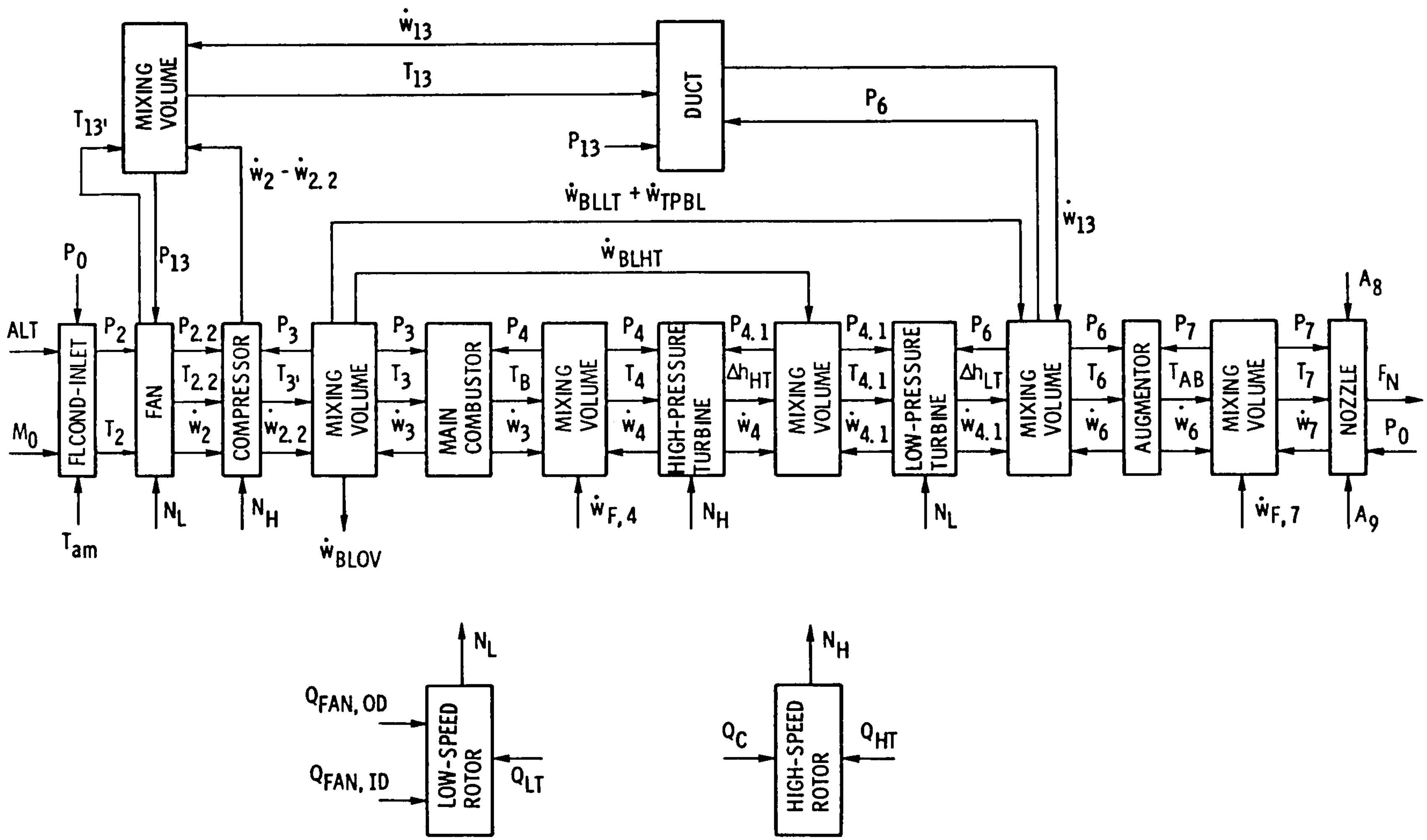

Figure 3. - Computational flow diagram of augmented turbofan engine simulation.

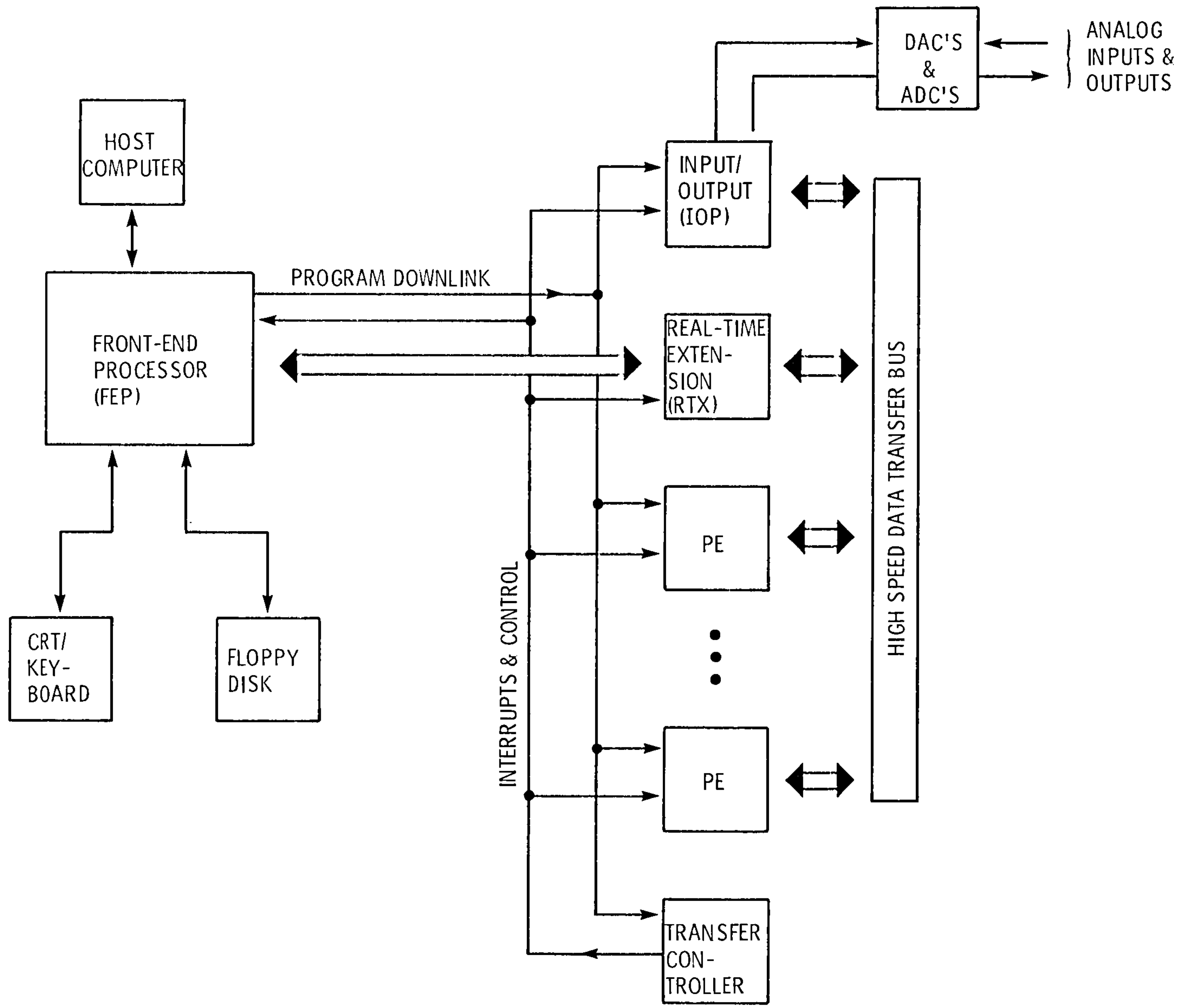

Figure 4. - LeRC real-time digital simulator structure.

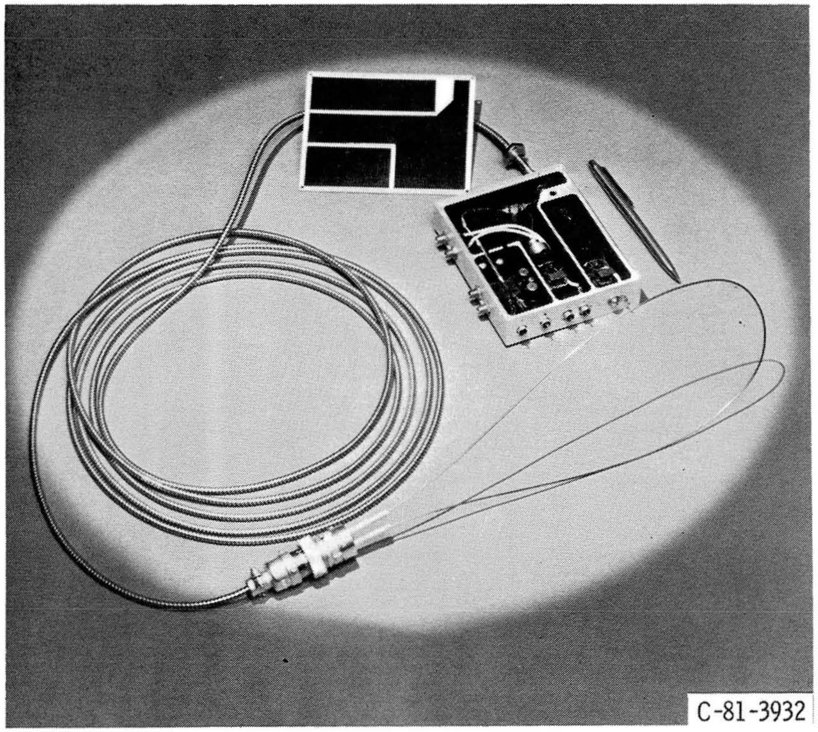

Figure 5. - Doped-fiber optical temperature sensor.

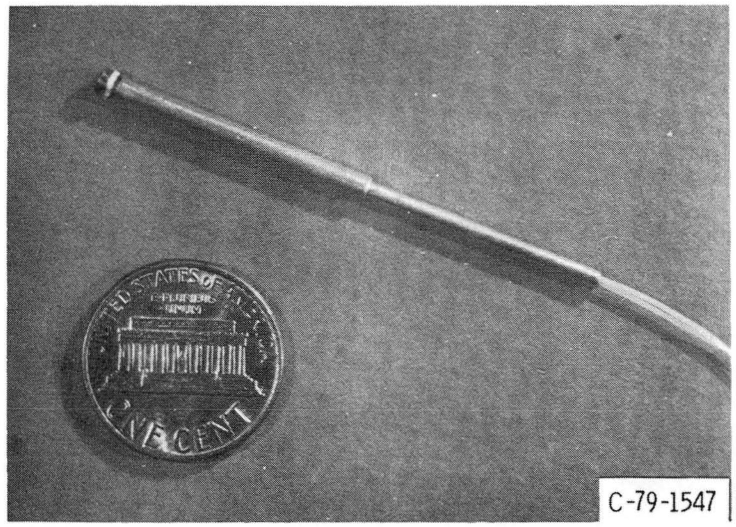

Figure 6. - Fabry-Perot temperature sensor.

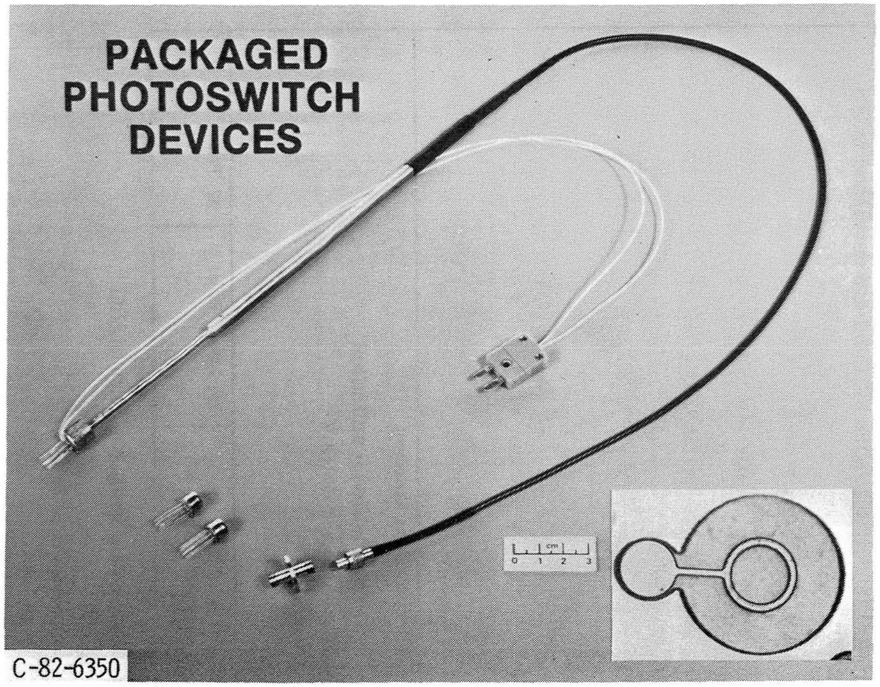

Figure 7. - Optical photoswitch.

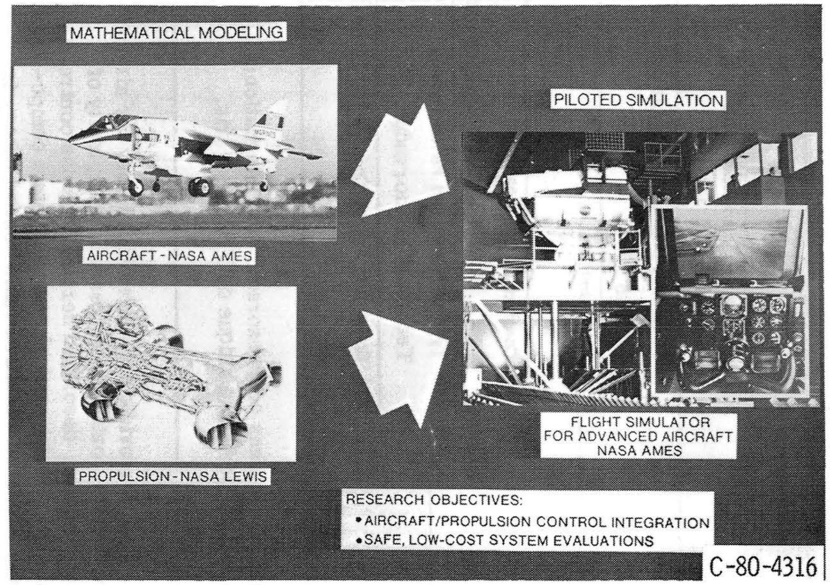

Figure 8. - V/STOL controls research.

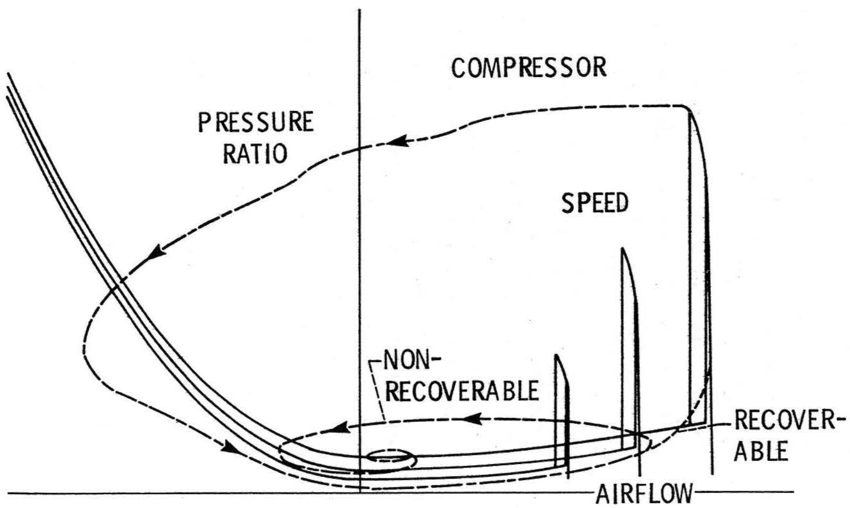

Figure 9. - Turbofan engine post-stall simulation.

1. Report No. NASA TM-83343	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle NASA PROPULSION CONTROLS RESEARCH		5. Report Date
		6. Performing Organization Code 505-40-5B
7. Author(s) Fred Teren		8. Performing Organization Report No. E-1558
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the Sixth International Symposium on Air Breathing Engines cosponsored by the International Society on Air Breathing Engines and the Association Aeronautique et Astronautique de France, Paris, France, June 6-11, 1983.

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Dynamics Controls Propulsion	Unclassified - unlimited STAR Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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