PROPULSION SYSTEM/FLIGHT CONTROL INTEGRATION FOR SUPERSONIC AIRCRAFT

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SUMMARY

The NASA Dryden Flight Research Center is engaged in several programs to study digital integrated control systems. Such systems allow minimization of undesirable interactions while maximizing performance at all flight conditions. One such program is the YF-12 cooperative control program. In this program, the existing analog air-data computer, autothrottle, autopilot, and inlet control systems are to be converted to digital systems by using a general purpose airborne computer and interface unit. First, the existing control laws are to be programed and tested in flight. Then, integrated control laws, derived using accurate mathematical models of the airplane and propulsion system in conjunction with modern control techniques, are to be tested in flight. Analysis indicates that an integrated autothrottle-autopilot gives good flight path control and that observers can be used to replace failed sensors.

INTRODUCTION

Supersonic airplanes, such as the XB-70, YF-12, F-111, and F-15 airplanes, exhibit strong interactions between the engine and the inlet or between the propulsion system and the airframe (refs. 1 and 2). Taking advantage of possible favorable interactions and eliminating or minimizing unfavorable interactions is a challenging control problem with the potential for significant improvements in fuel consumption, range, and performance.

In the past, engine, inlet, and flight control systems were usually developed separately, with a minimum of integration. It has often been possible to optimize the controls for a single design point, but off-design control performance usually suffered. The evolution of propulsion and flight controls is depicted in figure 1. Early aircraft had totally separate propulsion and flight control systems. Because these systems were manually controlled by the pilot, they were low response systems. With the advent of jet engines and supersonic aircraft, more complex control systems were required. In the flight control area, stability augmentation systems were used to compensate for unstable or high rate conditions and autopilots were used to reduce pilot workload. In the propulsion control area, active controls were devised to control engine nozzles and supersonic air inlet systems. However, even at this stage of complexity, the propulsion and flight control systems had a minimum of integration. Recently, the first step toward integration has been taken by mechanizing autothrottles. When used in conjunction with an autopilot, an autothrottle allows precise altitude and Mach number control. For efficient flight of future multimission aircraft, total integration of the propulsion and flight control systems will be necessary to minimize undesirable interactions and to optimize aircraft performance across the full flight envelope.

Because of the size and complexity of the controls integration problem, digital control is considered necessary. Digital control systems provide the logic necessary to handle the many variables and offer advantages in terms of speed, accuracy, and flexibility. The recent development of flight-qualified digital computers has made it attractive to investigate the use of digital integrated systems. In addition, analytical methods for analysis of large-scale, multivariable control problems are now in common use.

The NASA Dryden Flight Research Center (DFRC) has begun to investigate and evaluate advanced control concepts that show potential for improved aircraft performance. The investigations include the evaluation of new controls hardware in flight, the application of modern system analysis techniques to existing systems, and studies in the area of propulsion system/airframe interactions. Figure 1 shows three programs undertaken at DFRC to investigate digital control techniques and integrated control laws. The F-111 integrated propulsion control system (IPCS) program studied interactions between the inlet and the engine (ref. 3). The YF-12 cooperative airframe/propulsion control system program is directed toward the control of adverse interactions between the inlet and airframe, which can be severe for high speed cruise airplanes. For example, reference 4 indicates that the inlet bypass doors can generate as great a yawing moment as the rudders and in certain cases can cause the aircraft's Dutch roll mode to become unstable. The F-8 digital fly-by-wire program has already shown that digital control systems can be used in flight-critical applications (ref. 5). During a future program, such as the F-15 program, a totally integrated engine, inlet, and airframe control system will be designed.

This paper describes the YF-12 cooperative airframe/propulsion control system program: the program guidelines, the systems to be controlled, the selection of the digital system, and the advanced control laws presently being considered.

SYMBOLS

Physical quantities are given in the International System of Units (SI). Measurements were taken in U.S. Customary Units.

a_n	normal acceleration
$PpLM$	inlet total pressure used for calculation of duct pressure ratio
$PsD8$	inlet static pressure used for calculation of duct pressure ratio
p_s	static pressure measured at the nose boom

p_t	total pressure measured at the nose boom
Δp_α	nose boom differential pressure measured in the pitch plane
Δp_β	nose boom differential pressure measured in the yaw plane
α	angle of attack
β	angle of sideslip
Δ	change from initial conditions

PROGRAM GUIDELINES

The primary purpose of the YF-12 cooperative airframe/propulsion control system program is to evaluate the benefits in aircraft performance derived from the systems integration concept. The program has two phases (fig. 2). In the first phase (fig. 2(a)), the existing analog air-data computer, autopilot, inlet control, and autothrottle systems are converted to digital systems. Each of these analog systems has a suitable backup mode of operation, so redundancy is unnecessary for flight safety. This digital system will be flight tested to validate the hardware and software.

In the second phase (fig. 2(b)), the systems are integrated by using control laws developed from models of the propulsion system and the airplane's aerodynamics. Optimal control methods as well as classical methods will be used to derive the new control laws.

During the program, the existing system's hardware is to be used: that is, the actuators, transducers, and fuel controls are to remain unchanged. The primary emphasis of the propulsion system control study is on the inlet. Engine control changes will be limited to throttle inputs and possibly trim functions for some engine parameters. Engine control was studied in detail during the F-111 IPCS program (ref. 3).

AIRPLANE DESCRIPTION

The two-place, twin-engined YF-12 airplane (fig. 3) is capable of extended flight at Mach numbers greater than 3.0 and at altitudes above 24,380 meters. The airplane has a delta wing planform and a long, slender fuselage with prominent chines. A nacelle is mounted approximately halfway out on each wing. An all-movable vertical fin is mounted on top of each nacelle to provide directional control and stability. Longitudinal and roll control is provided by elevons located inboard and outboard of each nacelle. The propulsion system of the airplane consists of an axisymmetric mixed-compression inlet and a J58 afterburning turbojet engine. The airplane has an air-data system which determines such parameters as Mach number, altitude, angle of attack, and angle of sideslip. An autopilot, inlet computers, and autothrottles provide automatic control for the airplane and inlets. A block diagram of the existing analog control system is shown in figure 4.

AIR-DATA SYSTEM

The air-data system (ref. 6) is composed of a nose boom and an air-data computer. The nose boom of the YF-12 airplane (fig. 5) features a compensated pitot-static probe and an offset hemispherical head flow-direction sensor. The compensated pitot-static probe senses impact pressure, p_t, at the probe tip and static pressure, p_s, at two sets of orifices. These orifices provide the pressure measurements for the airplane's air-data computer, inlet computers, and pilot instruments. Measurements of angle of attack and angle of sideslip are obtained from the hemispherical head flow-direction sensor. Flow angularity in the pitch and yaw planes is determined from the four surface pressures on the hemispherical head. A computer uses the differential pressures Δp_α and Δp_β to compute angle of attack and angle of sideslip.

The air-data computer (fig. 5) converts pitot-static pressures into proportional rotary shaft positions, which are equivalent to static pressure and dynamic pressure. Total temperature, used in the calculation of true airspeed, is converted to a shaft position. By means of analog computation, which uses cams, gears, and gear differentials, these shaft rotations are transposed into data outputs and the terms necessary for further internal computation. The outputs include true airspeed, pressure altitude, Mach number, knots equivalent airspeed (KEAS), Mach number and altitude rates of change, and logarithmic representations of static pressure and compressible dynamic pressure. Also calculated are differences between Mach number and a Mach number schedule, differences between KEAS and a KEAS schedule, and a KEAS bleed schedule as a function of Mach number.

AUTOPILOT SYSTEM

The autopilot subsystem provides a way to achieve hold modes in the roll and pitch axes during flight. The autopilot performs best at the design flight conditions. The use of the autopilot is optional and often depends upon the mission requirements. The autopilot uses outputs from the air-data computer, the automatic navigation system, and the flight reference system to maintain its modes of operation. The autopilot outputs are summed with stability augmentation system (SAS) outputs and applied to the flight control surface actuators.

Roll Axis

The roll autopilot (fig. 6) provides three modes of control: attitude hold, heading hold, and automatic navigation. In the attitude hold mode, a roll rate gyro input and an attitude hold reference signal from the flight reference system are used. In the automatic navigation mode, automatic navigation system outputs are used. In the heading hold mode, outputs from the flight reference system are used. Roll axis autopilot outputs are combined with roll SAS outputs, and the resulting signals are supplied to the elevon actuators.

Pitch Axis

The autopilot pitch axis provides five modes of control: attitude hold, Mach hold, KEAS hold, altitude hold, and Mach trim. An automatic trim circuit functions during all of these modes. A block diagram showing inputs to the pitch autopilot is shown in figure 7. The attitude hold mode uses the pitch attitude reference, logarithmic static pressure, and pitch rate gyro inputs. A pitch wheel on the pilot's panel allows minor corrections to the reference attitude. The Mach hold mode uses signals of Mach number error and Mach number rate of change from the air-data computer. The KEAS hold mode is similar to the Mach hold mode except that KEAS rate of change and KEAS error inputs are used. The KEAS hold mode is capable of maintaining a specified KEAS bleed line. The altitude hold mode uses signals of altitude and altitude rate of change from the air-data computer to keep pressure altitude constant. Modifications to the altitude hold mode are discussed in reference 7. The pitch axis autopilot outputs are combined with the pitch SAS outputs and fed to the elevon actuators.

The Mach number trim system provides artificial speed stability during aircraft accelerations or decelerations in the Mach number range from 0.2 to 1.5 whenever the pitch autopilot is disengaged. The system uses Mach number inputs from the air-data computer, which, after processing, are fed to the pitch trim actuator.

AUTOTHROTTLE SYSTEM

The autothrottle system has two control modes: Mach number hold and KEAS hold. The purpose of the system is to allow these modes of operation without changing the longitudinal flight path of the airplane. Mach number error, KEAS error, and pitch attitude inputs go to the system from the air-data computer and the flight reference system (fig. 8). The autothrottle computer processes the inputs and produces a command signal which goes to the autothrottle servos. Both engines are controlled symmetrically. Autothrottle authority is limited to the afterburning range.

INLET SYSTEM

The inlet (fig. 9) is of the translating spike type, with approximately 40 percent of the compression occurring externally and 60 percent internally. Boundary layer air is removed through a slotted surface on the spike and a ram scoop or shock trap on the cowl. Forward bypass doors of the rotary type are used to match engine airflow to inlet airflow and to control the position of the terminal shock wave. Aft bypass doors just in front of the compressor face provide additional bypass capacity for intermediate Mach numbers. Aft bypass airflow and shock trap bleed air are ducted rearward to the ejector of the J58 engine. Spike bleed and forward bypass flow are dumped overboard through louvered exits. A more detailed description of the inlet is given in reference 8.

INLET CONTROL SYSTEM

In the automatic inlet control system, normal acceleration from a transducer near the aircraft center of gravity as well as Δp_α, Δp_β, p_s, and p_t from the nose boom are fed into the inlet computer. Each inlet has a separate control system, one of which is shown in figure 10. The outputs of each computer are commanded spike position and commanded duct pressure ratio.

Spike Position Loop

The spike position loop is used to control the inlet's throat area and contraction ratio. The schedule is primarily a function of airplane Mach number, which is derived from p_s and p_t in much the same manner as in the air-data computer. The nominal spike schedule is biased to more forward positions when deviations from nominal values of angle of attack, angle of sideslip, or normal acceleration occur.

Duct Pressure Ratio Loop

The duct pressure ratio loop is used to control the position of the terminal shock wave in the inlet. The duct pressure ratio is the ratio of a static pressure in the inlet throat, *PsD8*, to an impact pressure on the outer surface of the cowl, *PpLM*. The throat static pressure varies as a function of the terminal shock wave position. The forward bypass doors are used to move the terminal shock wave until the duct pressure ratio measured by the system matches the duct pressure ratio commanded by the inlet computer. There is a nominal duct pressure ratio schedule which varies with airplane Mach number. This schedule was derived from wind tunnel and flight tests and is intended to result in the desired shock position. The schedule is biased to a lower duct pressure ratio for deviations from nominal values of angle of attack, angle of sideslip, and normal acceleration. At a given flight condition, this lower duct pressure ratio command increases the opening of the forward bypass doors and moves the terminal shock wave farther downstream.

Restart Mode

The automatic inlet control system is equipped with an inlet unstart sensor to detect when the normal shock moves outside the inlet. When an unstart occurs, the unstarted inlet is switched to an open loop restart mode. The forward bypass doors open at maximum rate to the full open position, and the spike moves 0.381 meter forward or full forward if it is retracted less than 0.381 meter. The spike then returns slowly to the scheduled position and the bypass doors slowly close to return the duct pressure ratio to the scheduled command.

The airplane rolling and yawing motions associated with an inlet unstart can be severe (ref. 2). To reduce the severity of the unstart transient, the opposite inlet switches automatically into the restart mode at the same time as the affected inlet. This mode, which is called a crosstie, is so effective that sometimes the pilot cannot tell which inlet unstarted.

Aft Bypass Door Control System

The aft bypass doors on the YF-12 airplane are positioned by the pilot. The system consists of a commanded voltage which is nulled by position feedback from the actuator.

Manual Inlet Control System

The pilot can position the spike and forward bypass doors of each inlet manually. The primary parameter used for manual inlet control is the cockpit display of Mach number.

DIGITAL CONTROL SYSTEM

In the digital control system (fig. 11), the analog air-data computer, autopilot, autothrottle, and inlet control systems are replaced by a digital computer and an interface unit. All the signals are available for calculations, making signal integration easy. The digital system also makes it relatively easy to modify the individual systems with software changes.

At first, the existing control laws are to be programed and the systems kept separate. This will not make use of the full capability of the digital computer. The development of the advanced control laws necessary for the complete integration of the various systems is expected to be quite complex. Therefore, a large capacity, high speed computer is considered necessary for real-time computations.

CRITERIA FOR COMPUTER SELECTION

Because the primary purpose of the program is research and the objective of the research is the total integration of the systems described, the computer had to meet several criteria to insure that its capabilities were not a limiting factor in the realization of the project's goals. The computer had to have the following features: performance comparable to the state of the art in computer technology; a central processing unit with a word length of at least 16 bits; a memory capacity of 32,000 words, expandable to 65,000 words; floating point arithmetic hardware; rapid input-output processing capability; basic operational software, including an assembler, FORTRAN compiler, utility routines, diagnostics, loader, and software debugging aids; compatibility with commercial grade peripheral equipment (fig. 12); compliance with military standard MIL-E-5400 (the airborne avionics specification); go/no go selftestability; microprogramability; and compatibility with a hardware bootstrap loader.

The computer selected on the basis of these criteria is a general purpose, 16-bit digital computer with 32,000 words of memory and built-in trigonometric and hyperbolic functions. Its execution times are 1 microsecond for an addition, 6.4 microseconds for a multiplication, and 10 microseconds for a division. The interrupt scheme has three levels with 13 interrupts. There are eight independently accessible input-output channels.

INTERFACE UNIT

The interface unit is required to communicate with the digital computer through a memory interface from a dedicated block of computer-addressable memory. It must also convert aircraft signals into twos complement binary representations and convert digital computer parameters into correct aircraft representations. The interface must provide status information to the digital computer and the aircraft. The input and output signal transfers are handled by a block of computer-addressable memory in the interface unit. The signal conditioning, demodulation, multiplexing, and conversion should not introduce errors in excess of 2 percent of full scale.

Table 1 lists the input and output signals the interface must process. Spare channels not used for the conversion of the aforementioned systems are to be used later. The unit should be capable of converting all the signals shown in table 1 at a rate of 200 samples per second. Even though a high sample rate capability is not necessary for all parameters, there are some parameters with bandwidths of 20 hertz in the inlet system. In addition, the Tustin transform technique is being used where possible and a rate of 200 samples per second may be necessary for an accurate representation. Other transform techniques will be used if computer speed becomes a limiting factor. Once a parameter has been sampled it is stored in the random access memory for use by the computer. The ac signals are sampled at the peak of their respective references.

FLIGHT SYSTEM SIMULATION

Before being installed on the airplane, the digital system (hardware and software) must be verified. A complete digital system, identical to the flight system, has been interfaced with a fixed-base hybrid simulator. The hybrid simulator is programed to reproduce the aircraft and propulsion system dynamics in real time across the full flight envelope. All signals input to the digital control system are in the same form as they would appear on the airplane. This closed loop simulator is the basis for all software design and verification during the program.

The software has been programed in modular form, with each module corresponding to an analog system on the airplane. Each of the modules is checked out on the closed loop simulator and compared to its analog counterpart. Each module checked so far has exactly reproduced the performance of the analog system it replaced when run at an adequate sample rate. The closed loop simulator is also used to determine the sample rate necessary for proper operation of the digital module. As an example, figure 13 shows time histories of various parameters in the closed loop simulation with the digital air-data system in the loop. The basic conditions are a speed of Mach 3 and an altitude of 22,100 meters, with the altitude hold mode engaged. The parameters are compared for sample rates of 3 samples per second and 15 samples per second with a static pressure fluctuation input. The figure shows a definite stepping action in the elevon and autopilot elevon command signal traces at 3 samples per second. Therefore, a sample rate greater than three was selected for air-data parameters.

INTEGRATED CONTROL LAWS

Plans for the last part of the program include the derivation and flight testing of some integrated control laws. Modern system analysis techniques are to be used for the derivation because these techniques are suited to large multivariable problems. An additional goal of the program is to evaluate the performance of reduced-state feedback controllers as compared to full-state feedback controllers, which are generally unobtainable in actual applications.

Mathematical models are necessary for the derivation of optimal control laws. Two nonlinear mathematical models—one of the propulsion system and one of the airplane's aerodynamics—have been created. These models have been verified with comparisons to flight test data (ref. 9) and are the basis for all other mathematical models to be used during the program.

Several interesting performance criteria have been proposed for development of integrated control laws. One of these criteria is the minimization of flight path and Mach number deviations during the cruise portion of the flight. A study of the longitudinal control problem by other investigators used linear quadratic regulator theory to derive the control laws. The results indicated that an autothrottle-autopilot combination was effective in maintaining Mach number and altitude simultaneously.

An example of the aircraft's response (as predicted by a mathematical model) to a step increase in temperature is shown in figure 14. The solid lines indicate the response with the presently mechanized altitude hold control laws and the dashed lines indicate the response with a partial-state feedback controller which was derived using linear quadratic regulator theory. The air-data system interprets the step increase in temperature as a step decrease in Mach number of approximately 0.03 and a step increase in pressure altitude. In the altitude hold case, the aircraft immediately dives and then goes into a lightly damped altitude oscillation. By the end of the time history the Mach number has decreased by approximately 0.45. In comparison, the partial-state feedback controller does a much better job: it uses the autothrottle to compensate for the Mach number loss and thus controls Mach number and altitude simultaneously. Upon sensing the Mach number decrease, the power lever angle is commanded to +10°, which is its full authority, thus compensating for the loss in thrust. Very little elevon is commanded as compared to the -3° commanded in the altitude hold case. The airplane's Mach number and altitude show only small deviations from their original values. Toward the end of the trace, the power lever angle is commanded to -10° to compensate for the slight overshoot in Mach number.

Because the digitized systems are single channel, a study of fail operational techniques for nonredundant sensors is of interest. A technique which uses observers to reconstruct the unavailable states is discussed in reference 10. Figure 15 shows the reconstruction of yaw rate, roll rate, bank angle, and angle of sideslip using the technique and assuming information only from roll attitude, rudder deflection, and aileron deflection signals. For this time history, the model used by the observer was not a perfect model of the actual system: some of the model coefficients were 100 percent in error. The figure indicates that it is feasible to use reconstructed signals for control purposes in the case of sensor failures. Further work is necessary to explore the use of these techniques for the stochastic case.

Two additional areas of interest are also being considered: a controller to maximize range during cruise and a controller to minimize deviations from optimal climb profiles which have been calculated *a priori*.

CONCLUDING REMARKS

Airframe/propulsion system interactions can be severe for high speed cruise airplanes. To achieve the efficiency required for future multimission aircraft, a totally integrated propulsion/flight control system will be necessary. Because of the size and complexity of the controls integration problem, digital control systems are considered necessary. Digital systems allow the flexibility and logic to minimize undesirable interactions while optimizing aircraft performance across the full flight envelope.

The NASA Dryden Flight Research Center is engaged in several programs to study digital integrated control systems. The YF-12 cooperative control program is using this technology to digitally mechanize the inlet control system, autopilot, autothrottle, and air-data computer. This digital system will allow mechanization of advanced integrated control laws for investigation of their benefits for high speed aircraft. Preliminary analytical studies indicate that an autothrottle-autopilot combination can achieve simultaneous Mach number and altitude control. These studies also indicate that observers can be used to effectively reconstruct failed sensor signals.

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3. Bentz, Charles E.; and Zeller, John R.: Integrated Propulsion Control System Program. SAE Paper 730359, Apr. 1973.
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TABLE 1.- INTERFACE UNIT SIGNAL REQUIREMENTS

(a) Inputs

Signal	Number
Autopilot synchros	5
Inlet synchros	2
Autopilot transducers (ac)	13
Inlet transducers (ac)	14
Autothrottle transducers (ac)	3
Autopilot transducers (dc)	5
Autothrottle transducers (dc)	1
Air-data transducers (dc)	3
Spare dc channels	8
Digital air-data transducers	2
Instrumentation (digital)	2
Control switches (discrete)	22
Spare discretes	16
28-volt dc power	3
	Total: 99

(b) Outputs

Signal	Number
Autopilot (ac)	4
Inlet (ac)	2
Autothrottle (ac)	2
Inlet (dc)	6
Inlet (discrete)	6
Autothrottle (discrete)	2
Mach trim (discrete)	1
Failure master (discrete)	1
Air data (digital)	3
Instrumentation (digital)	1
Synchro test	1
Spare discretes	16
	Total: 45

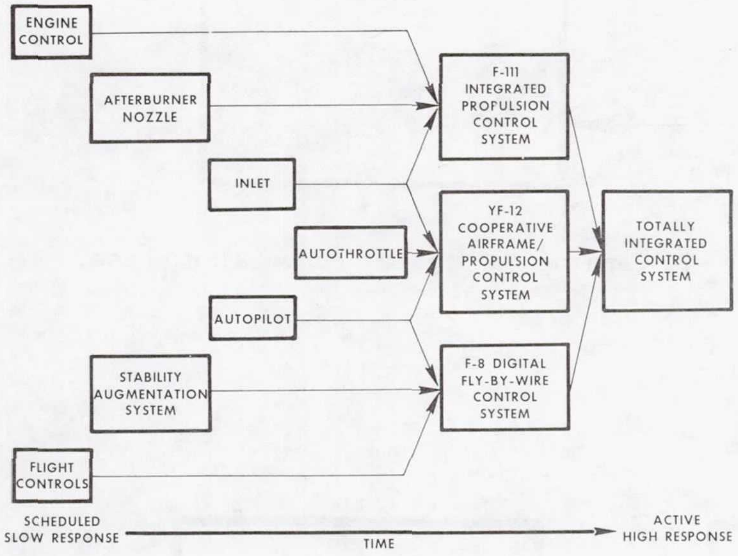
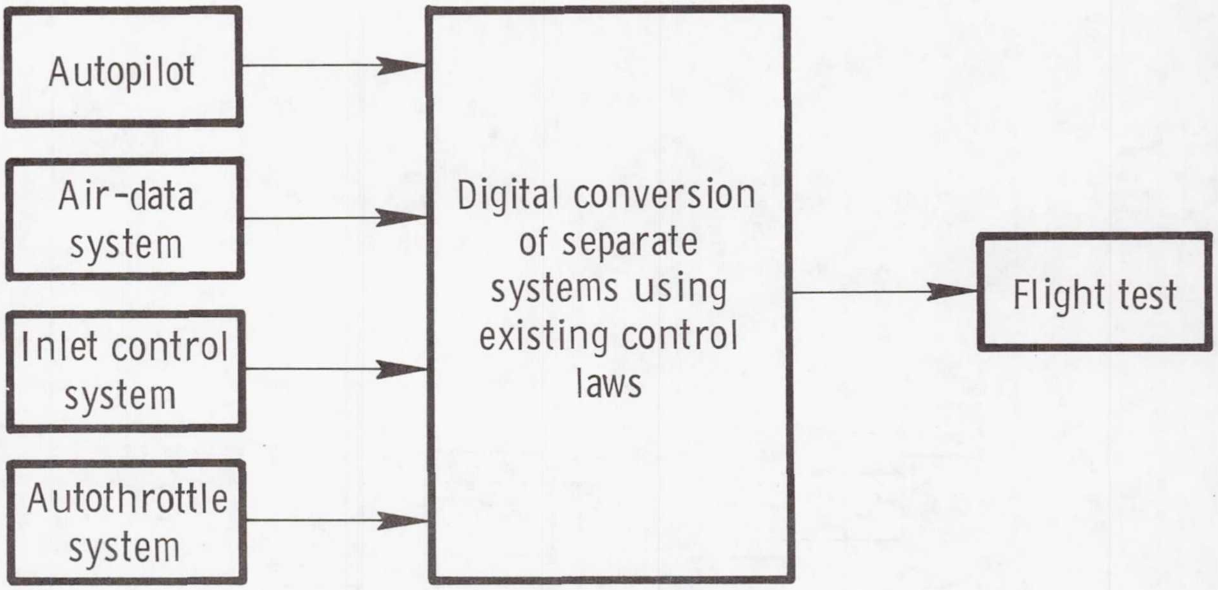
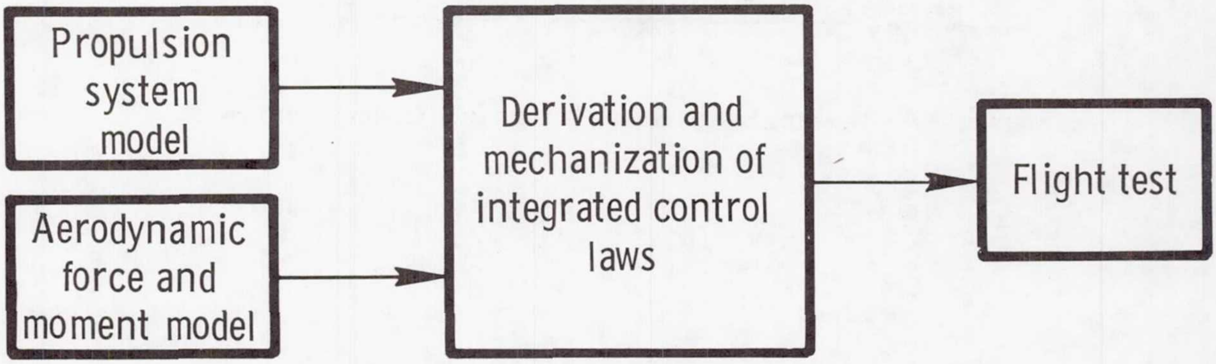


Figure 1.- Evolution of propulsion and flight controls.



(a) Analog to digital conversion phase.



(b) Integrated control law phase.

Figure 2.- Digital integrated airframe/propulsion control program.

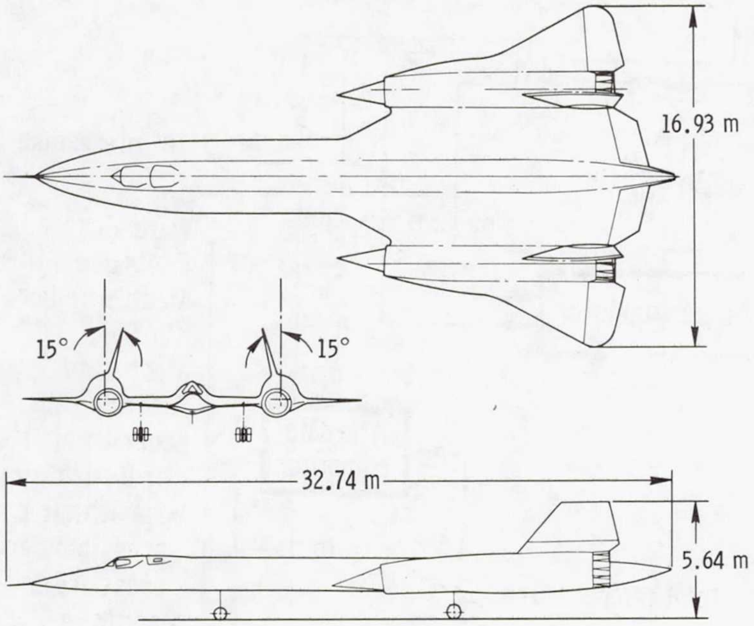


Figure 3.- Three-view drawing of YF-12 airplane.

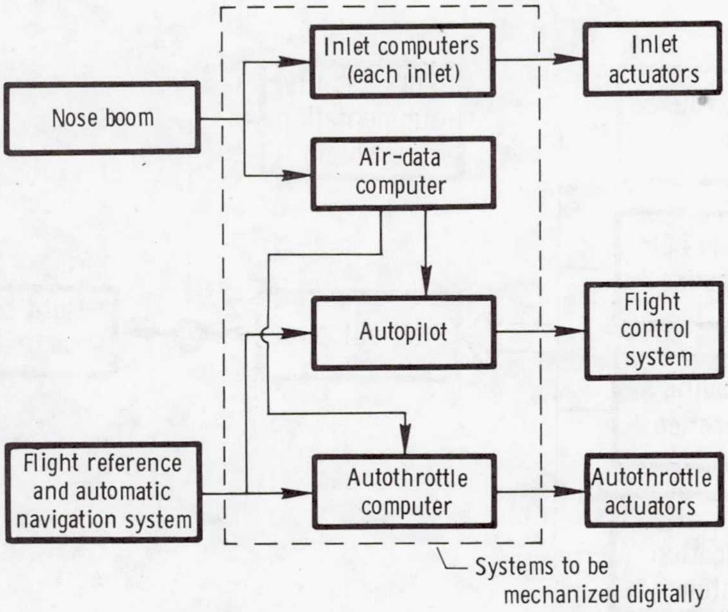


Figure 4.- Existing analog control systems.

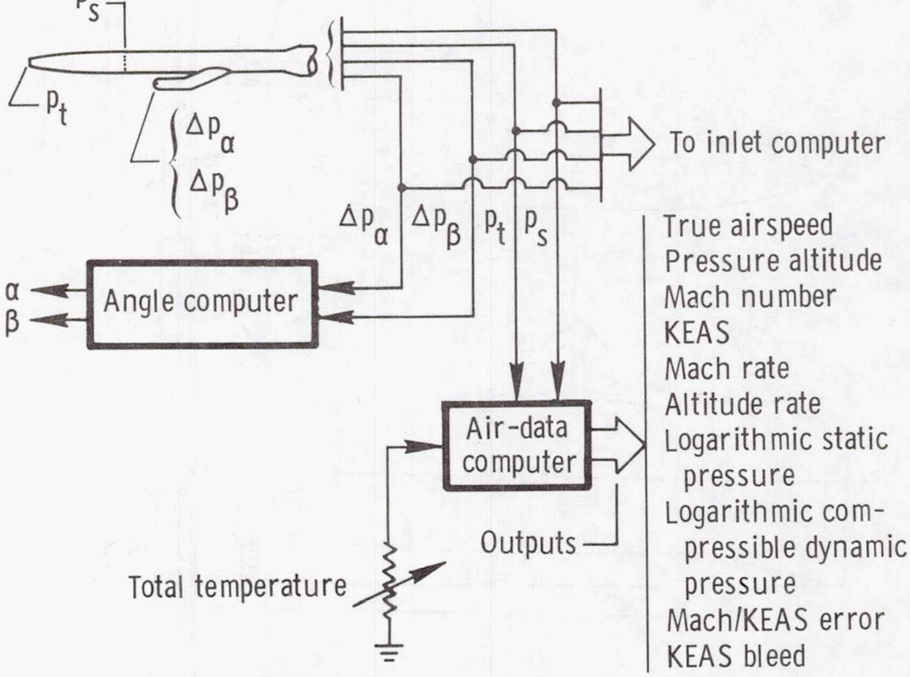


Figure 5.- Air-data system.

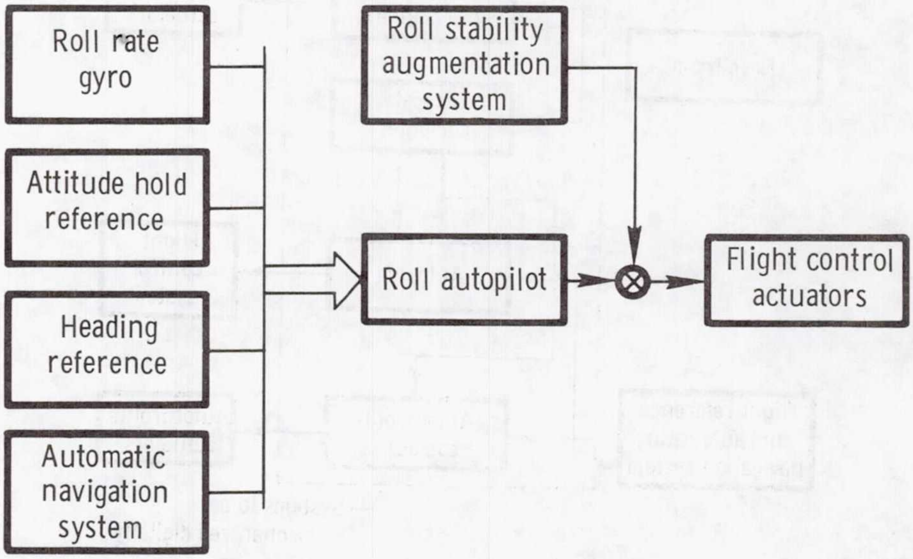


Figure 6.- Roll autopilot schematic.

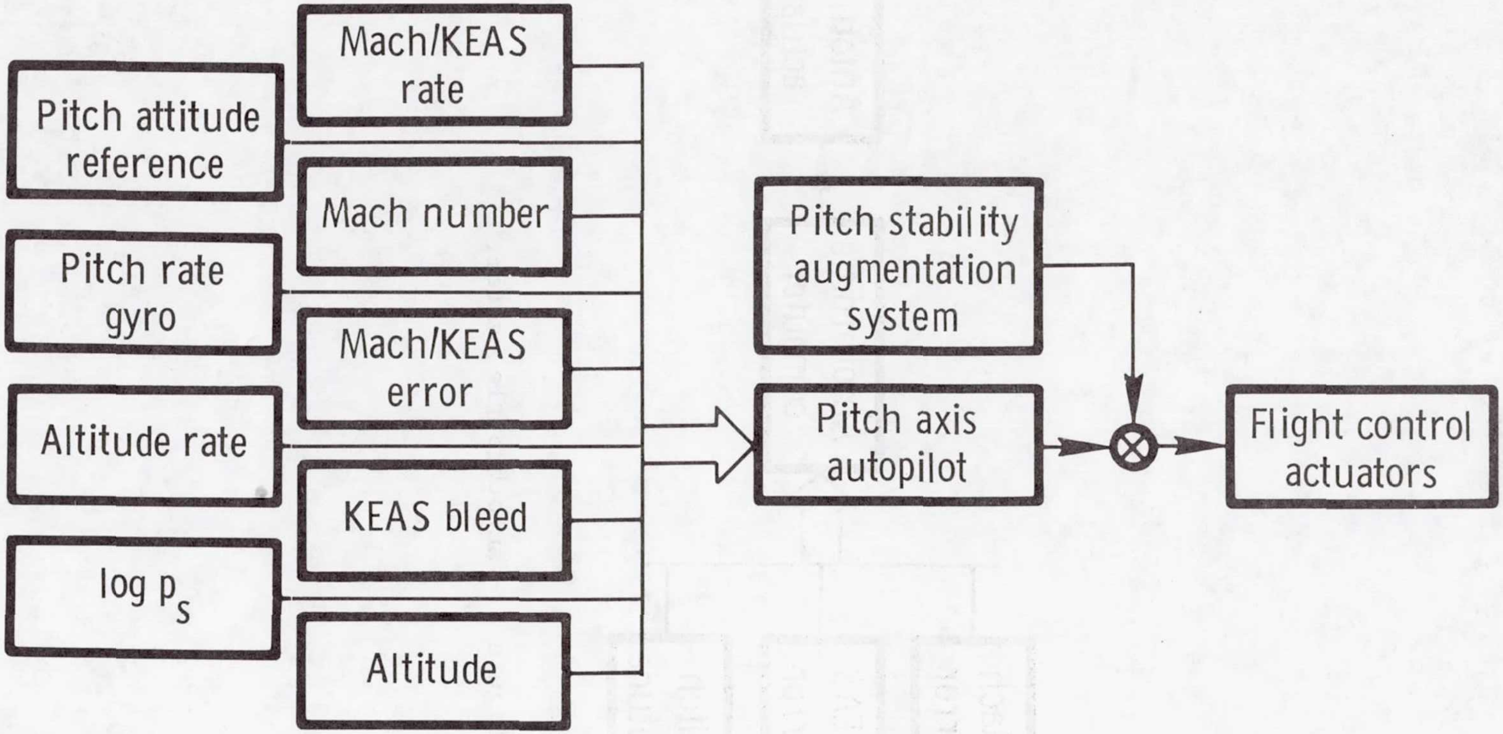


Figure 7.- Pitch axis autopilot schematic.

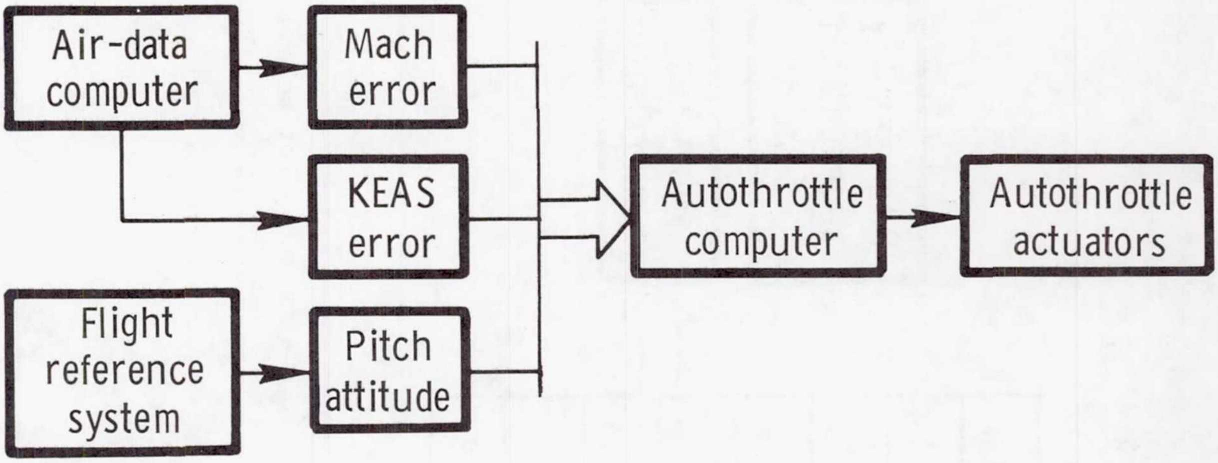


Figure 8.- Autothrottle system.

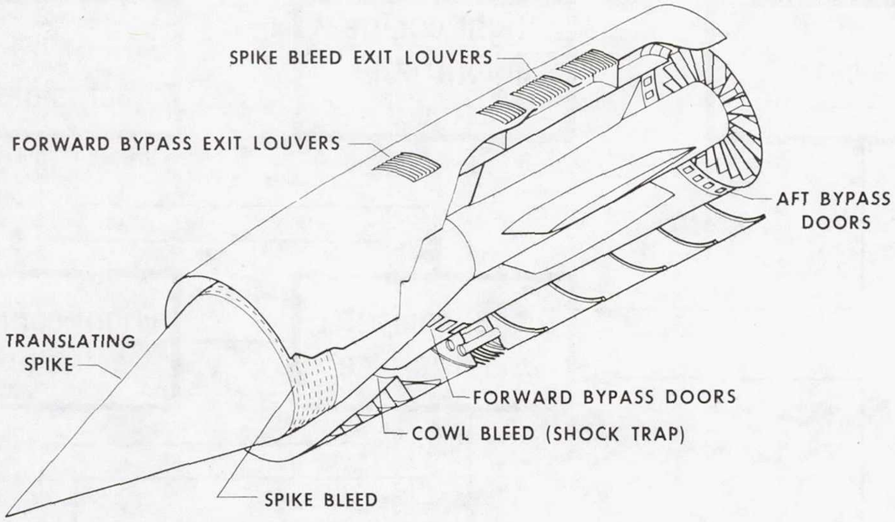


Figure 9.- Inlet system.

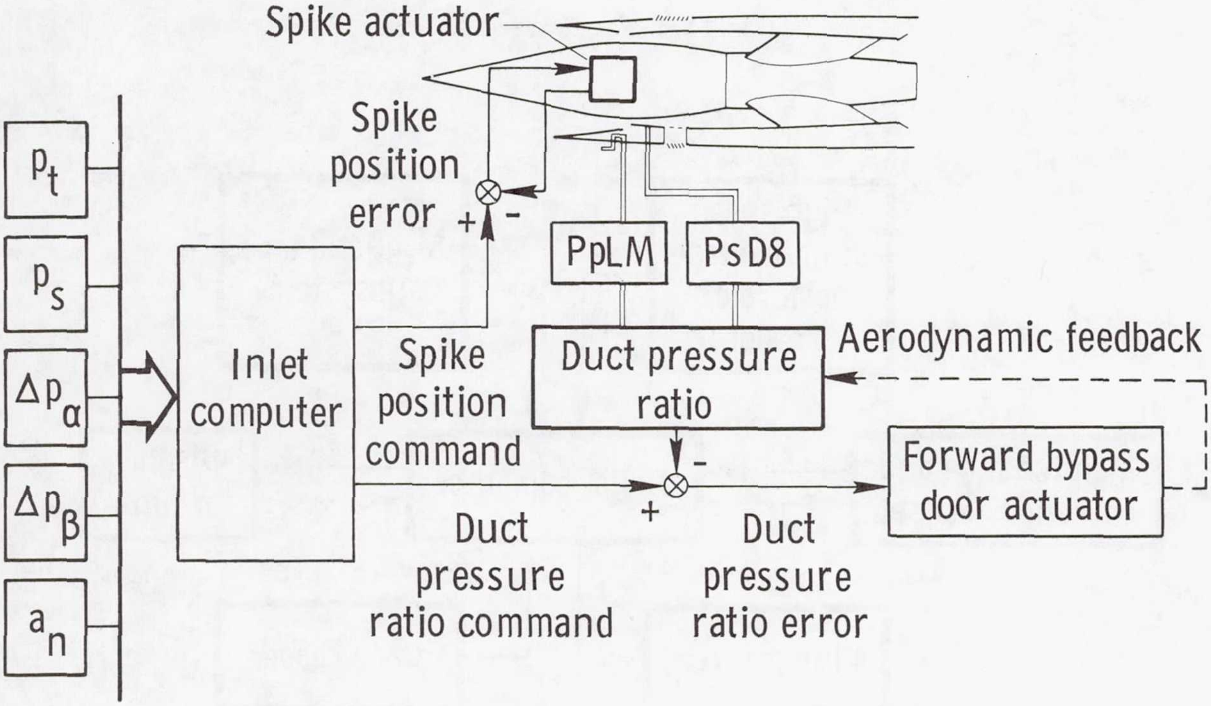


Figure 10.- Inlet control system.

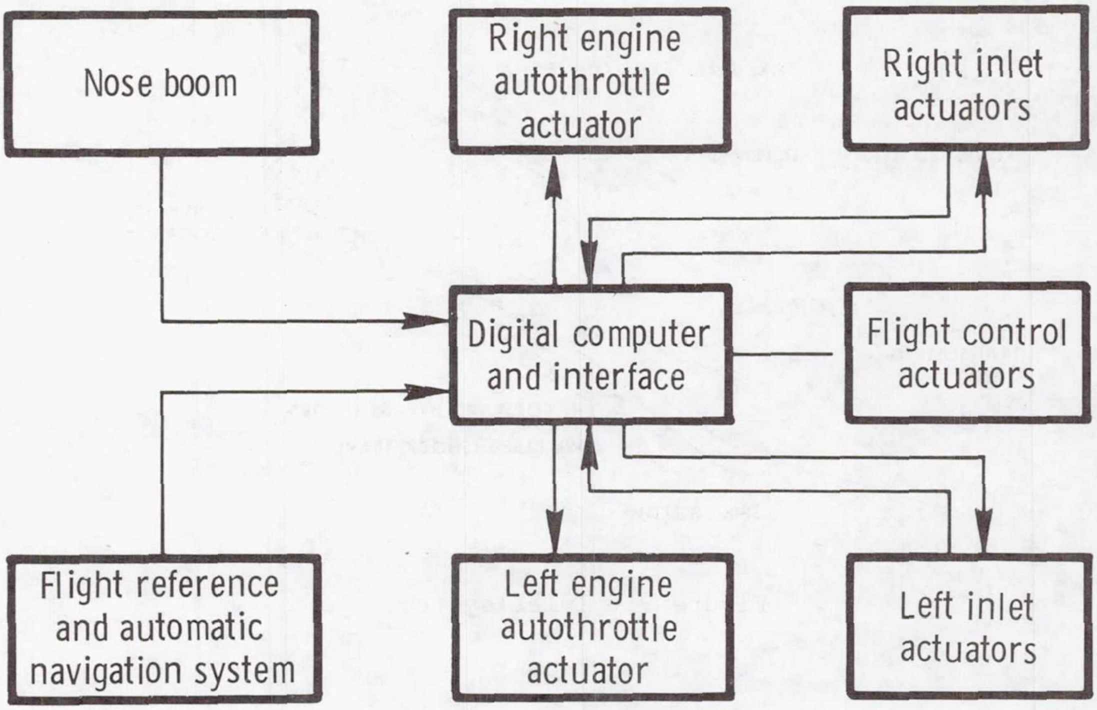


Figure 11.- Digital control system.

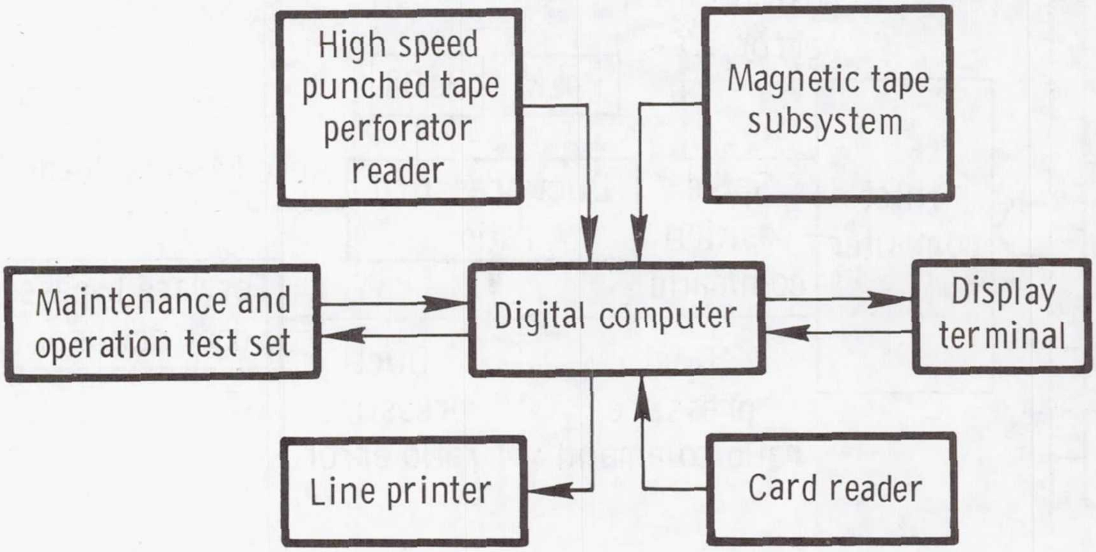


Figure 12.- Computer and peripheral equipment.

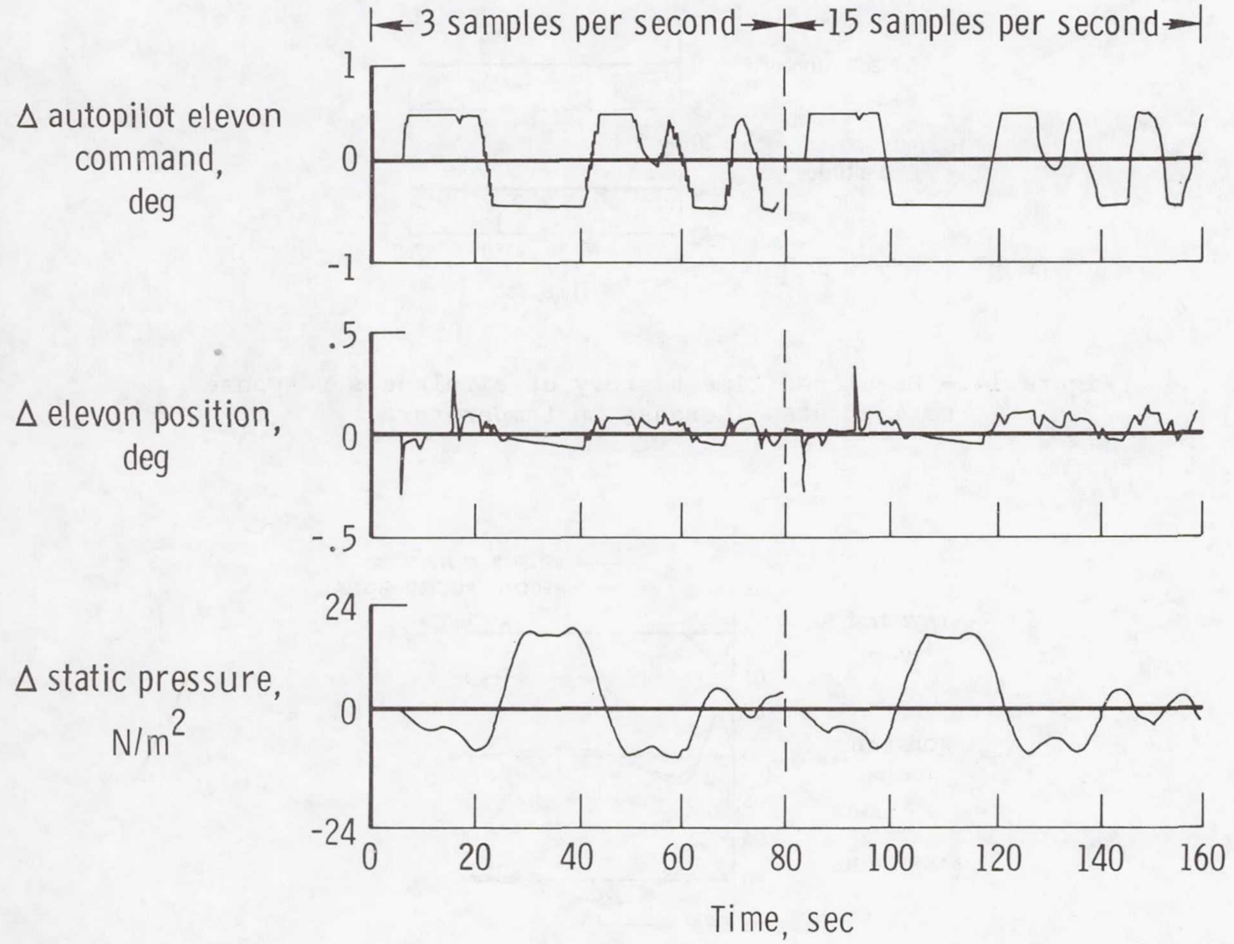


Figure 13.- Effect of sample rate on digital system response.

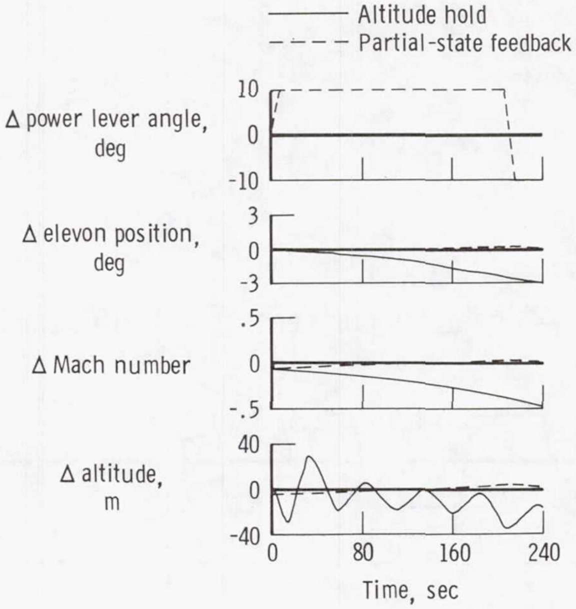


Figure 14.- Predicted time history of airplane's response to 4^{o} C step increase in temperature.

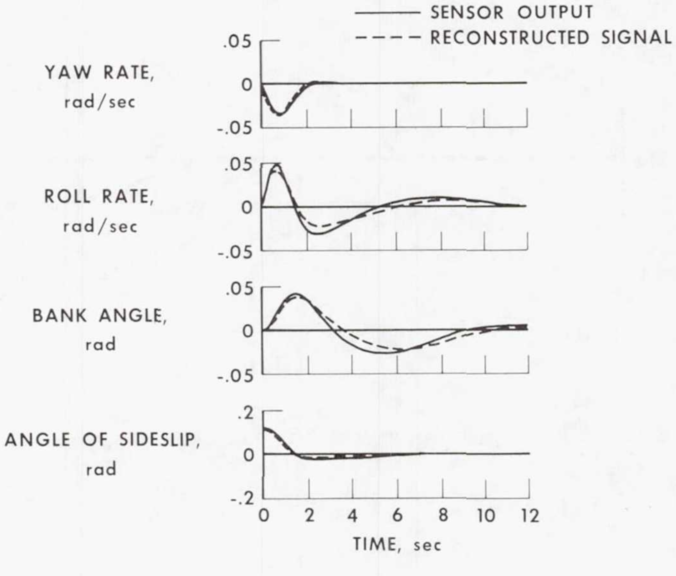


Figure 15.- Comparison of reconstructed signals and actual sensor outputs.