DIGITAL QUARTZ PRESSURE TRANSDUCERS FOR FLIGHT APPLICATIONS

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INTRODUCTION

A series of high precision pressure transducers has been developed to meet the requirements of a variety of aerospace applications. The development of these transducers was prompted by the widespread use and increasing trend toward digital data acquisition and control systems. The design and performance goals included the requirements for a digital-type output, high accuracy, low power consumption, exceptional reliability, and small size and weight. Also, simple mathematical characterization in the processing of the output signals and general insensitivity to the environmental errors of acceleration, vibration, temperature, humidity, and electromagnetic interference, were important considerations.

The design, construction and performance of the Digiquartz® Pressure Transducers are described in the attached article [1] from Measurements and Data entitled "Digital Pressure Transducers". The object of this paper is to describe some of the past, present and future aerospace applications related to flight systems.

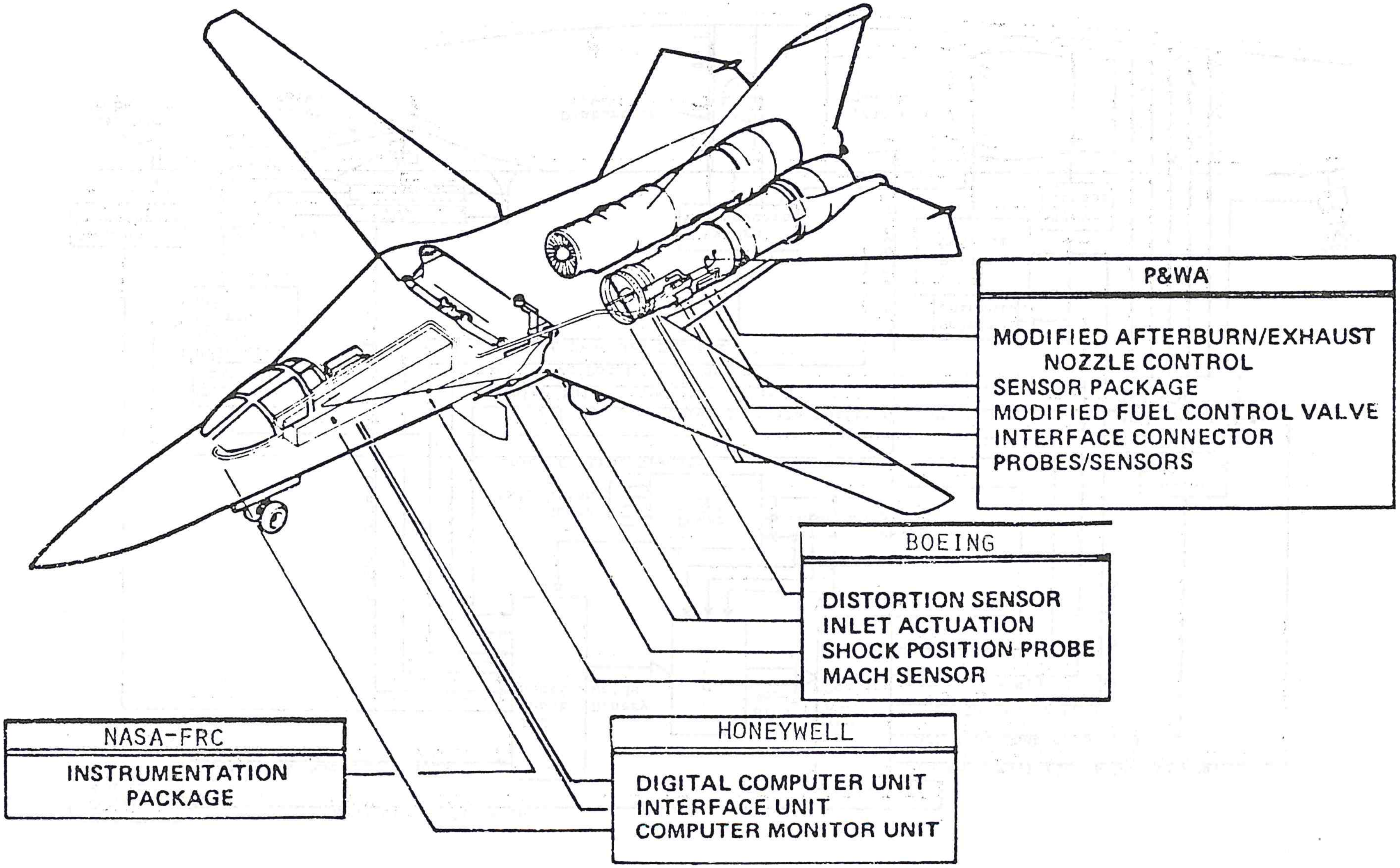
Topics to be discussed include digital electronic engine control systems, in-flight engine monitoring, flight performance benefits from improved instrumentation and control, and digital air data computer applications.

DIGITAL ELECTRONIC ENGINE CONTROL

The first flight application of the digital quartz pressure transducers was their use on an F-111 aircraft in the Integrated Propulsion Control System (IPCS).

The IPCS program was a research and development effort in which one set of hydromechanical engine and inlet controls on a supersonic airplane was replaced with a digital electronic control system. This program was sponsored by the Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio. The contract was awarded to Boeing Aerospace Company in March 1973. Major participants included Boeing, Pratt & Whitney Division of United Technologies Corporation and Honeywell Inc. Altitude cell tests were performed at NASA-Lewis Research Center and flight tests performed at NASA-Edwards Flight Research Center.

IPCS INSTALLATION ON F-111



P&WA

MODIFIED AFTERBURN/EXHAUST NOZZLE CONTROL
SENSOR PACKAGE
MODIFIED FUEL CONTROL VALVE
INTERFACE CONNECTOR
PROBES/SENSORS

BOEING

DISTORTION SENSOR
INLET ACTUATION
SHOCK POSITION PROBE
MACH SENSOR

NASA-FRC

INSTRUMENTATION PACKAGE

HONEYWELL

DIGITAL COMPUTER UNIT
INTERFACE UNIT
COMPUTER MONITOR UNIT

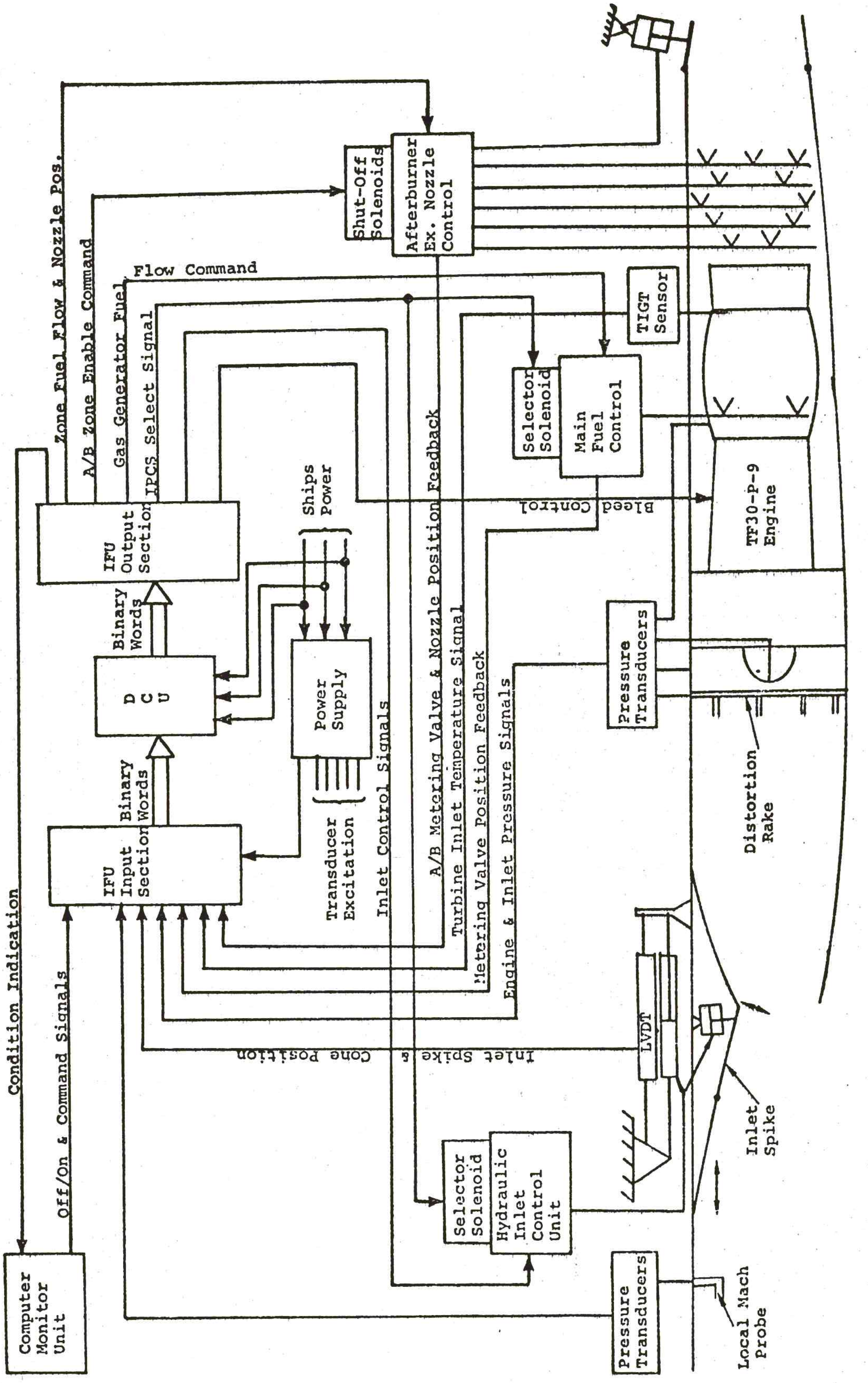

Condition Indication
Off/On & Command Signals
Computer Monitor Unit
Zone Fuel Flow & Nozzle Pos.
A/B Zone Enable Command
Gas Generator Fuel Flow Command
TPCS Select Signal
IFU Output Section
IFU Input Section
Binary Words
Binary Words
D C U
Power Supply
Ships Power
Transducer Excitation
Inlet Control Signals
A/B Metering Valve & Nozzle Position Feedback
Turbine Inlet Temperature Signal
Metering Valve Position Feedback
Engine & Inlet Pressure Signals
Inlet Spike & Cone Position
Shut-Off Solenoids
Afterburner Ex. Nozzle Control
TIGT Sensor
Selector Solenoid
Main Fuel Control
Bleed Control
TF30-P-9 Engine
Pressure Transducers
Distortion Rake
LVDT
Inlet Spike
Selector Solenoid
Hydraulic Inlet Control Unit
Pressure Transducers
Local Mach Probe

FIGURE 2

The general configuration of the IPCS aircraft is shown in Figure 1. By integrating the inlet and engine controls as shown in the system schematic of Figure 2, the aircraft can operate closer to its performance limits while avoiding possible adverse interactions between engine, inlet, and air frame. Advanced sensors and a digital computer/control system provide more accurate and stable control enabling the engine to develop greater thrust and optimized performance, resulting in extended engine life, greater fuel economy, and reduced maintenance costs.

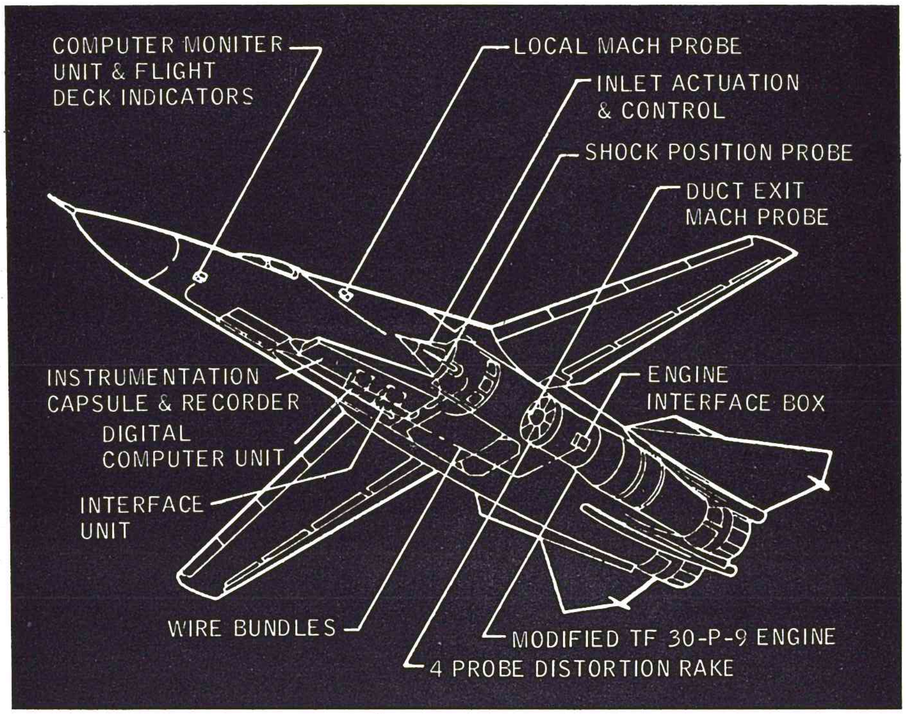
Another advantage of digital electronic control systems is their inherent flexibility. Software programming changes to the digital computer can match standard digital hardware controls with a variety of engines, inlets and air frames. Additional benefits are possible due to the ability of the digital propulsion control system to communicate directly with other digital aircraft systems such as the flight controls and air data computer.

The digital computer links the inlet and engine controls with a group of advanced sensors, including digital quartz pressure transducers used to measure inlet and output pressures as shown in Figures 3 and 4. A distortion rake supplied by NASA measures the pressure profiles at the fan face. Four digital quartz pressure transducers with ranges of 0 to 30 psia are used to measure inlet pressure and inlet distortion. The digital computer uses the output signals to control the system to accommodate the distortion in the air flow and prevent engine stall through solenoid bleed valves.

Two transducers are located at the local mach probe to measure static and total pressure. Two 0 to 30 psia transducers measure static and total pressures at the duct exit. These transducer measurements feed into the computer controlling the spike and the cone on the variable inlet of this supersonic airplane.

The flight test phase of the IPCS program was successfully completed in March, of 1976. Some conclusions that can be drawn from the IPCS program are that more precise control of a propulsion system is desirable and possible, but depends upon the availability of precise measurements made with accurate, reliable, and compatible sensors.

Transducers with high reliability and outstanding performance are paramount requirements for aircraft control applications; however, significant design and analysis benefits can result from proper engine instrumentation and in-flight performance monitoring.



F-111 Inlet Installation

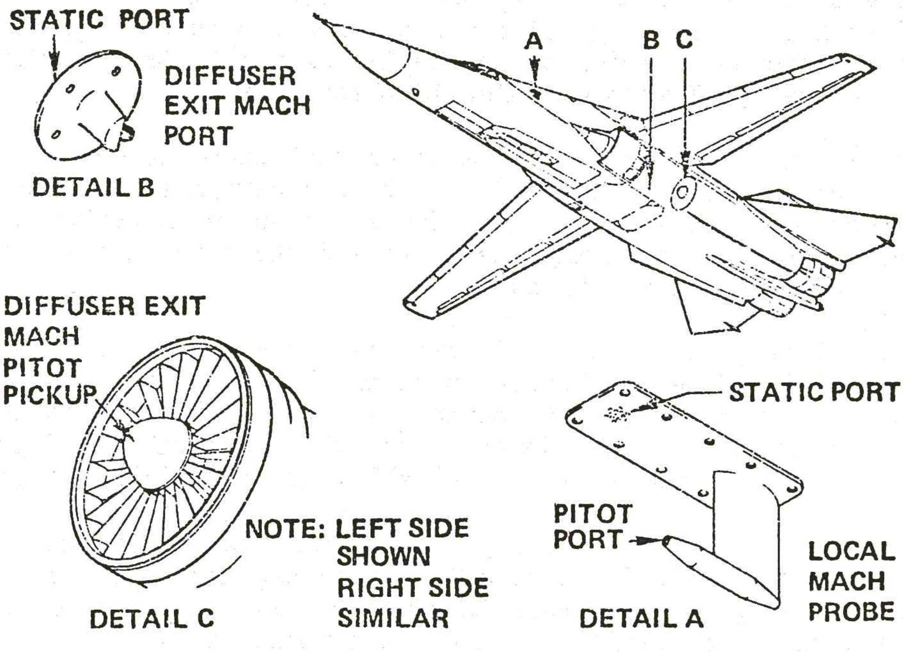


FIGURE 3

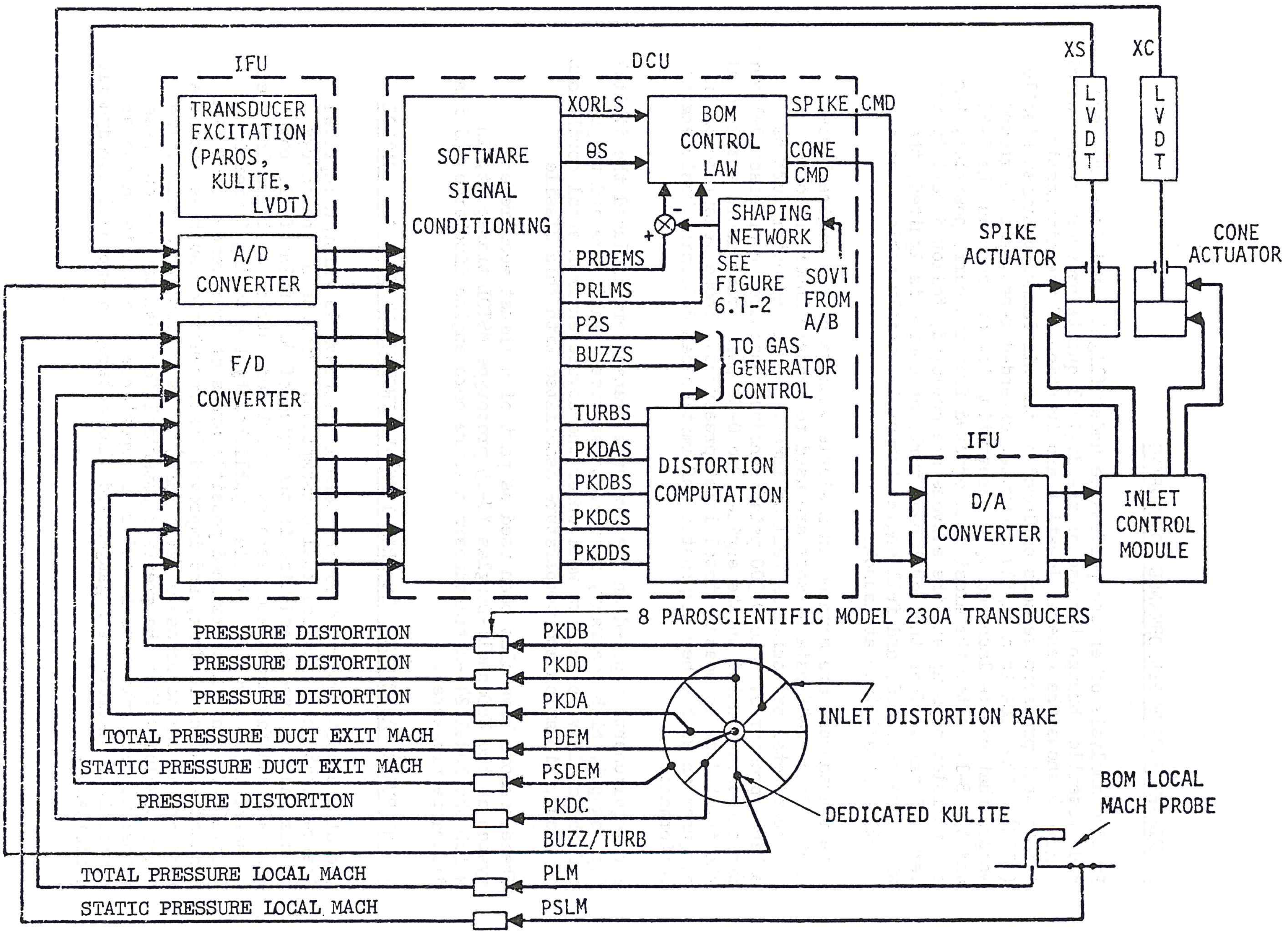

XS
XC
IFU
DCU
TRANSDUCER EXCITATION (PAROS, KULITE, LVDT)
A/D CONVERTER
F/D CONVERTER
SOFTWARE SIGNAL CONDITIONING
XORLS
θS
BOM CONTROL LAW
SPIKE CMD
CONE CMD
L V D T
L V D T
SHAPING NETWORK
SEE FIGURE 6.1-2
SOVI FROM A/B
PRDEMS
PRLMS
P2S
BUZZS
TO GAS GENERATOR CONTROL
TURBS
PKDAS
PKDBS
PKDCS
PKDDS
DISTORTION COMPUTATION
SPIKE ACTUATOR
CONE ACTUATOR
IFU
D/A CONVERTER
INLET CONTROL MODULE
8 PAROSCIENTIFIC MODEL 230A TRANSDUCERS
PRESSURE DISTORTION
PKDB
PRESSURE DISTORTION
PKDD
PRESSURE DISTORTION
PKDA
TOTAL PRESSURE DUCT EXIT MACH
PDEM
STATIC PRESSURE DUCT EXIT MACH
PSDEM
PRESSURE DISTORTION
PKDC
BUZZ/TURB
TOTAL PRESSURE LOCAL MACH
PLM
STATIC PRESSURE LOCAL MACH
PSLM
INLET DISTORTION RAKE
DEDICATED KULITE
BOM LOCAL MACH PROBE

FIGURE 4

IN FLIGHT ENGINE PERFORMANCE MONITORING

Precise analysis of engine perfomance under flight conditions has been made possible through the use of the digital quartz pressure transducers. Figure 5 shows the general location and function of the diagnostic flight test pressure sensors employed on the Air Launched Cruise Missile (ALCM). The ALCM is a highly accurate, extended range, air to ground weapon that can be launched by a penetrating bomber such as the B-52 and the B-1. After the missile is ejected from its carry position, the engine inlet pops up and the elevons are deployed, followed next by the vertical tail. Then the low bypass turbofan engine is ignited, the wings are unfolded, and full engine thrust is rapidly achieved as a function of altitude at launch.

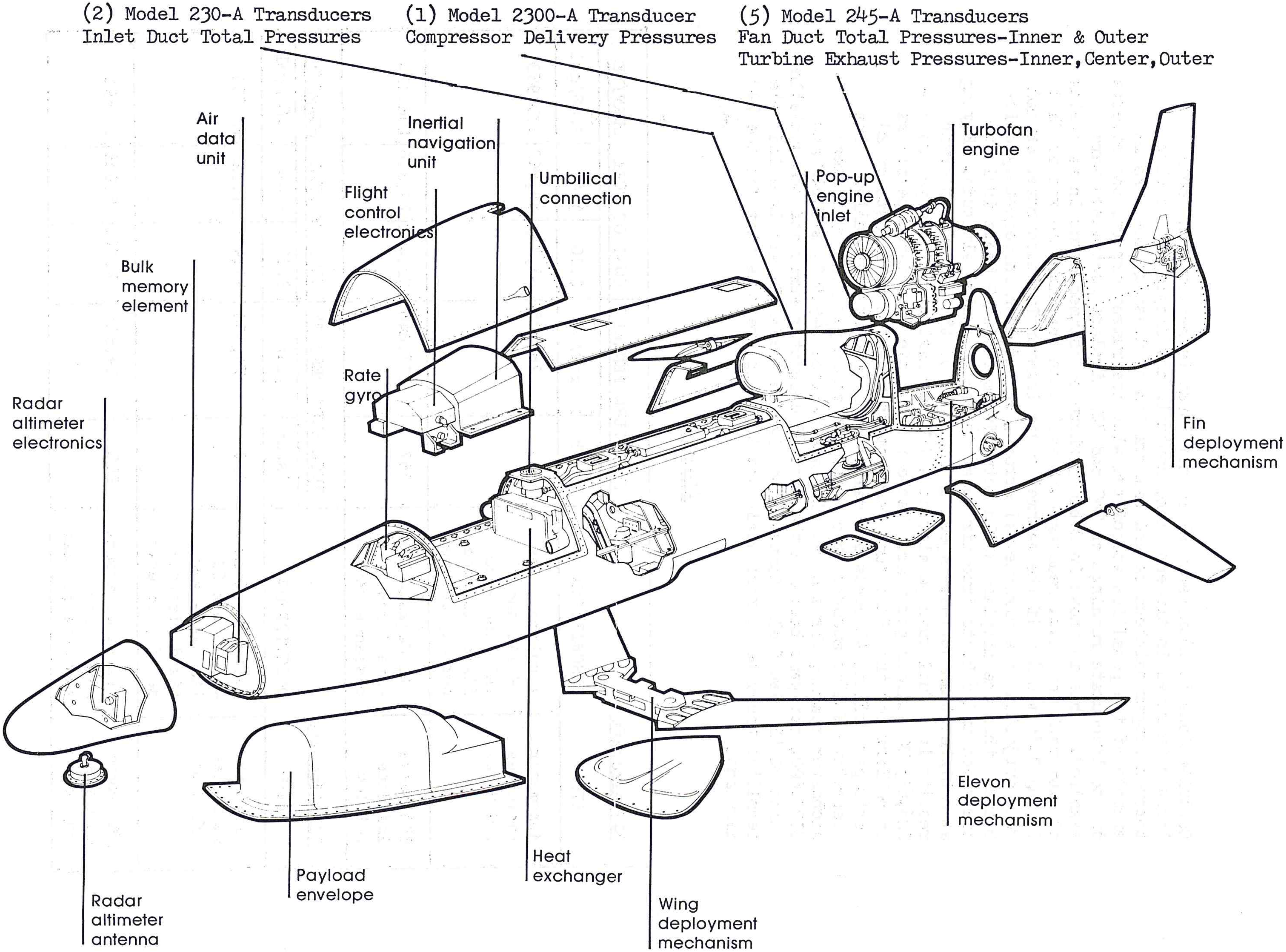
Five transducers are mounted in a single package on the engine bypass duct. These 0-45 psia sensors are used to measure inner and outer fan duct total pressures as well as inner, center and outer turbine exhaust pressures. One 0-300 psia transducer measures compressor delivery pressures as mounted on the engine. Two 0-30 psia transducers are used at the inlet duct to measure total inlet pressures. These measurements in conjunction with other diagnostic information can determine basic engine performance.

The requirements imposed on the pressure transducers included the digital-type output, high accuracy, fast response time, small size and weight, and the ability to perform well under the severe environmental conditions of shock, vibration and temperature associated with this missile.

These sensors have also been used as part of a thrust measurement system on the McDonnell-Douglas YC-15 prototype MSTOL transport, in which the Model 245-A transducers measure core engine discharge and fan discharge pressures.

FLIGHT PERFORMANCE BENEFITS FROM IMPROVED INSTRUMENTATION AND CONTROL

One of the most important flight benefits achievable through improved instrumentation is reduced fuel consumption. Because of the energy crisis and the associated rise in the price of jet engine fuel, both aircraft manufacturers and users have reviewed methods of improving fuel conservation. A recent article [2] published by the Boeing Commercial Aircraft Company, has examined possible areas of improvement including reduced aerodynamic drag, and improved instrumentation such as machmeter reading and engine pressure ratio (EPR) transmission and display. The study concluded that the greatest potential for fuel savings on these commercial aircraft were in order of importance, inaccurate machmeter correction, improved EPR gauges and flow meters,and improved aerodynamic performance.


(2) Model 230-A Transducers
Inlet Duct Total Pressures
(1) Model 2300-A Transducer
Compressor Delivery Pressures
(5) Model 245-A Transducers
Fan Duct Total Pressures-Inner & Outer
Turbine Exhaust Pressures-Inner, Center, Outer
Air data unit
Inertial navigation unit
Turbofan engine
Umbilical connection
Pop-up engine inlet
Flight control electronics
Bulk memory element
Rate gyro
Radar altimeter electronics
Fin deployment mechanism
Elevon deployment mechanism
Heat exchanger
Payload envelope
Radar altimeter antenna
Wing deployment mechanism

Contributions to improved fuel economy must be achieved not only through improved instrumentation, controls and displays, but also through proper maintenance and calibration of these devices. As an example of the penalties associated with instrument errors, the effects due to inaccurate readings on 747 and 727 airplane machmeters were examined. This is shown in Table 1 where an assumed error in machmeter of 0.01 mach low (i.e. reading 0.84 mach when the airplane was in fact flying 0.85 mach). If the machmeter was inherently inaccurate, or had been subjected to environmental errors, or had been inadequately calibrated, then the airplane would actually be flying 4 knots indicated air speed and 6 knots true air speed faster at cruise altitude. Flying at a higher than optimum speed as a result of the instrument error results in a fuel burn penalty on a 747 aircraft of 717 lbs per hour - 226,655 US gallons per year. Table 1 shows the associated penalties in dollars for the added fuel consumption based on fuel costs of 20 cents per gallon, 40 cents per gallon, and 60 cents per gallon. The respective dollar amounts which could be saved per year by correct machmeter reading for the 747 airplane is over $45,000, $90,000 and $135,000, per year based on the assumed machmeter error and the variable costs of the jet fuel. Comparative figures for a 727 airplane indicate penalties would be approximately one third as great as that for the 747 airplane.

TABLE 1

747 Aircraft		FUEL BURN PENALTY		COST OF FUEL BURN/YR		
ITEM	DESCRIPTION	lbs/hr	gal/yr	$.20	$.40	$.60/gal
Machmeter indicates .01 M low	Airplane flies 4K IAS and 6K IAS fast-same fixed distance per day covered	717	226,655	45,331	90,662	135,993
EPR Gages indicate .01 low	All Gages, assume same fixed distance per day	567	177,040	35,408	70,816	106,224
727 Aircraft		FUEL BURN PENALTY		COST OF FUEL BURN/YR		
ITEM	DESCRIPTION	lbs/hr	gal/yr	$.20	$.40	$.60/gal
Machmeter indicates .01 M low	Airplane flies 4K IAS and 6K IAS fast-same fixed distance per day covered	310	79,550	15,910	31,820	47,730
EPR Gages indicates .01 low	All gages, assume same fixed distance per day	156	39,820	7,964	15,928	23,892

The second major instrument error affecting fuel consumption is due to inadequate engine pressure ratio (EPR) gauges. Aircraft tubine engines are used to generate the propulsive energy by imparting momentum to a gas. The gas used by turbine engines is a mixture of products of combustion and air raised to a high energy level by the process of combustion. The basic turbine engine consists of a compressor, burner, turbine and nozzle. The combination of compressor, burner and turbine is referred to as the gas generator. This term is used to describe the function of accepting air at a low energy level and producing a new gas (air plus products of combustion) at a high energy level. The gas generator thus provides the high energy gas to the nozzle and results in the propulsive force or thrust used to propel the aircraft. The cockpit instrument used to display to the pilot a measure of how much thrust the engine is producing is the EPR indicator. The sensing device of engine pressure ratio is the EPR transmitter.

Pratt & Whitney Aircraft Division of United Technologies Corporation has used engine pressure ratio (EPR) as the primary thrust setting indicator for their engines. Studies were made to select the thrust setting parameter for the high bypass ratio JT9D engine. Parameters under consideration included overall engine pressure ratio (Pt 7/ Pt 2), low rotor speed (N1), fan pressure ratio (Pt 2.5/Pt 2), and pressure ratio based on turbine interstage pressure (Pt 6/Pt 2). The studies concluded that the most accurate thrust setting parameters were EPR and Pt6/Pt2. Although comparable in accuracy to EPR, Pt6/Pt2 was eliminated to avoid placing pressure sensors in the turbine section of the engine.

The use of fan speed (N1) for thrust indication has been advocated because of increased measurement accuracy and reliability. The study concluded that EPR is a better thrust setting parameter than N1 even with a factor of 6 accuracy degradation, because the rate of change of thrust is significantly greater for a given change in N1 than it is with the same change in EPR, especially at altitude conditions. Other factors influencing the choice of EPR over N1 included the sensitivity of fan speed to airflow shifts experienced during the life of an engine and the high shifts in the N1 versus thrust relationship due to incorporation of engineering changes in production. EPR has been shown to be a safer parameter to use in terms of engine deterioration and turbine temperature abuse, particularly for climb.

The indicated EPR is based upon the use of the engine manufacturers performance charts modified by in-flight measurements of diffuzer nozzle pressure, exhaust gas temperature, and RPM. These engine performance charts are obtained from sea level test runs on static testing.

Extrapolation predicted performance at various altitudes and air A total air temperature - engine pressure ratio limit (TAT - system displays the actual chart performance limits for various environmental pressures, temperatures and mach number but has no direct relationship to the indicated EPR. It is felt that significant savings in fuel consumption can be effected through the development of a new EPR system consisting of a solid state EPR transmitter and the appropriate cockpit indicators. Fuel burn penalties associated with EPR gauges indicating 0.01 low are shown in Table 1 for two types of commercial aircraft.

Past attempts at implementing a solid state EPR transmitter have failed because the transducers available could not meet the specified accuracy under difficult environmental conditions. As a consequence several types of forcebalance EPR transmitters have been used as the primary turbine engine power setting parameter. The advantages of using the digital quartz pressure transducers as EPR transmitters include not only the fuel savings associated with improved accuracy, but also a savings in size, weight, cost, reliability and maintainability.

Improvements in instruments to measure and display mach number and the power setting parameters of thrust through improved EPR transmitters and indicators, can result in significant flight performance benefits to both the airplane manufacturer and the airplane user.

DIGITAL AIR DATA APPLICATIONS

The key elements in modern air data systems/computers are the pressure transducers. Advances in the sensor field can now be combined with the latest microprocessor and digital logic circuitry to yield more accurate and reliable air data systems. The digital quartz pressure transducers are particularly well suited to meet air data requirements for a variety of reasons.

It is important that the output signal be compatible with the digital computer. The digital-type output of the quartz crystal pressure sensor is simple to process and characterize. The nominal frequency excursion is from 40 KHz to 36 KHz for zero to full scale pressure inputs. The most common way of processing the output is to let the signal gate a high frequency clock for a number of cycles and to measure the average period output. Using a 10 MHz counting clock and averaging for 1,000 periods (approximately 25 milliseconds) yields a pressure resolution of 0.003% Full Scale. Higher resolution can be obtained by averaging longer or using a higher frequency clock. A resolution of 0.01 inch of altitude change at sea level is achievable.

A second order polynomial expression is sufficient to linearize the quartz crystal sensor output to within the accuracy of most primary pressure standards. Only (3) coefficients are required to convert the period to linear pressure. The calibration storage requirements, as well as the processing, are therefore greatly reduced over other transducers whose outputs are more complex functions and higher order polynomials. Indeed, the output processing is so simple that a small, hand-held calculator has been adapted to serve as a portable readout device for these transducers. A short program on this calculator can yield both pressure and altitude information.

A second characteristic of the transducer which makes it highly desireable for an air data computer is its very low uncompensated temperature coefficient. Due to this very low intrinsic temperature coefficient, temperature compensation in the computer is straight-forward, requiring both a minimum of storage and computer time. Further, the stability and accuracy of the transducer's temperature sensor are significantly less critical. Errors due to rapid changes in ambient temperature are minimized because of the "vacuum bottle" environment around the quartz crystal sensor. The transducer has well known and repeatable temperature characteristics which are dependent upon the materials of construction and the orientation of the crystallographic axes. Quartz crystals are used as frequency standards because of their low temperature sensitivity, remarkable elastic properties, and long term stability.

Another important design feature is a counter-balance acceleration compensation arrangement which makes the transducer insensitive to orientation, acceleration, and vibration.

Since the quartz crystal sensing element works in an ultra-high vacuum, it must be isolated from the outside elements. This construction eliminates errors due to variations in density and humidity in the applied pressure media. The calibration is the same for dry air, moist air, nitrogen,etc. Indeed, these transducers have been used extensively in the oceanographic field to measure water levels. The mechanical isolation protects the sensor from contaminants and also prevents acoustical coupling with the sensed medium; therefore, the external tubing and volume has no effect on the calibration.

By using opposed bellows, the transducer can be configured as a differential pressure transducer. There are significant advantages in using this type of sensor for airspeed measurements since improved accuracy results in using only the airspeed related, differential pressure inputs.

In summary,the digital quartz crystal pressure transducers have the accuracy, stability and other operational characteristics necessary for air data computer applications. The simplicity of processing the output easily permits the use of a microprocessor rather than the more complicated and costly CPU's. The sensors are small, lightweight, and insensitive to acceleration, shock and vibration. They are not significantly affected by the affects of temperature, EMI, humidity, density or contamination.

REFERENCES

1. Paros, Jerome M., Digital Pressure Transducers, Measurements & Data, Issue 56, volume 10, No. 2 March-April, 1976, pp. 74-79.

2. The Boeing Commercial Airplane Company, Fuel Conservation Through Airplane Maintenance, Boeing Airliner, April, 1976.

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