

# DIGITAL QUARTZ PRESSURE TRANSDUCERS FOR FLIGHT APPLICATIONS

Jerome M. Paros  
Paroscientific, Inc.

## 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<sup>1</sup> 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.

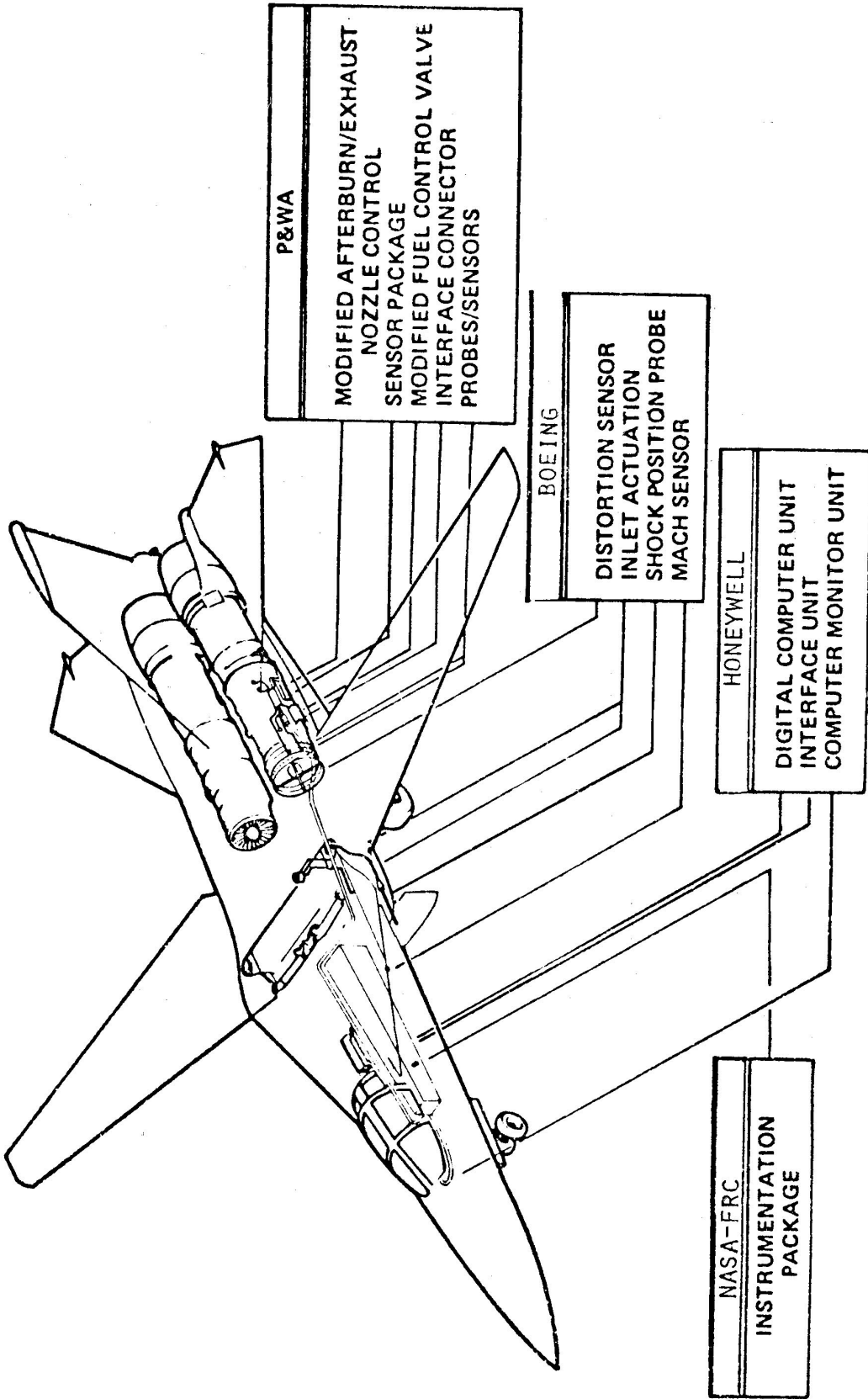
Topics to be discussed include digital electronic engine control systems, in-flight engine monitoring, flight performance benefits from improved instrumentation and control, and digital air data computer applications.

## 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 hydro-mechanical 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



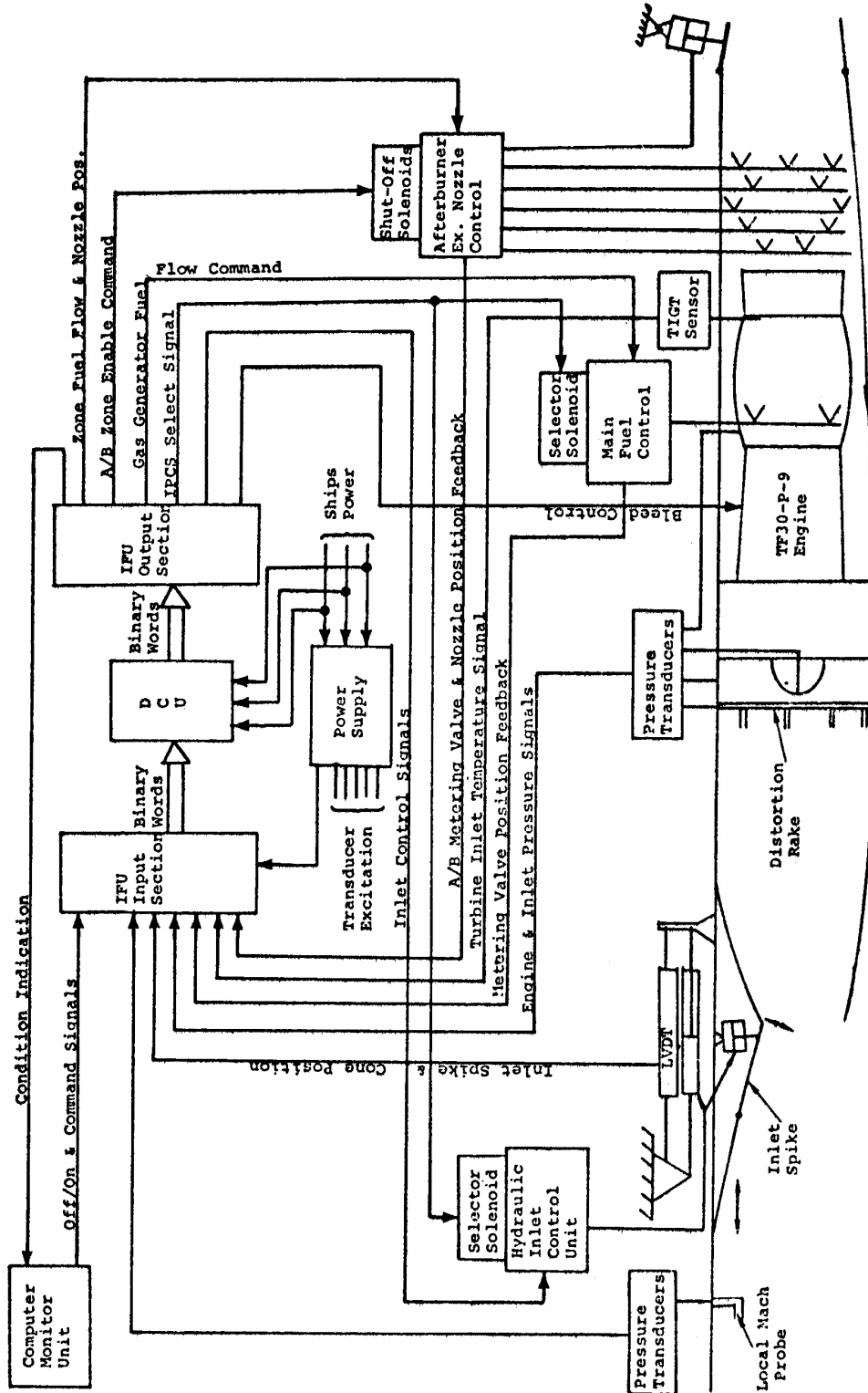


FIGURE 2

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 airframes. 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 airflow 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.

#### IN FLIGHT ENGINE PERFORMANCE MONITORING

Precise analysis of engine performance 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.

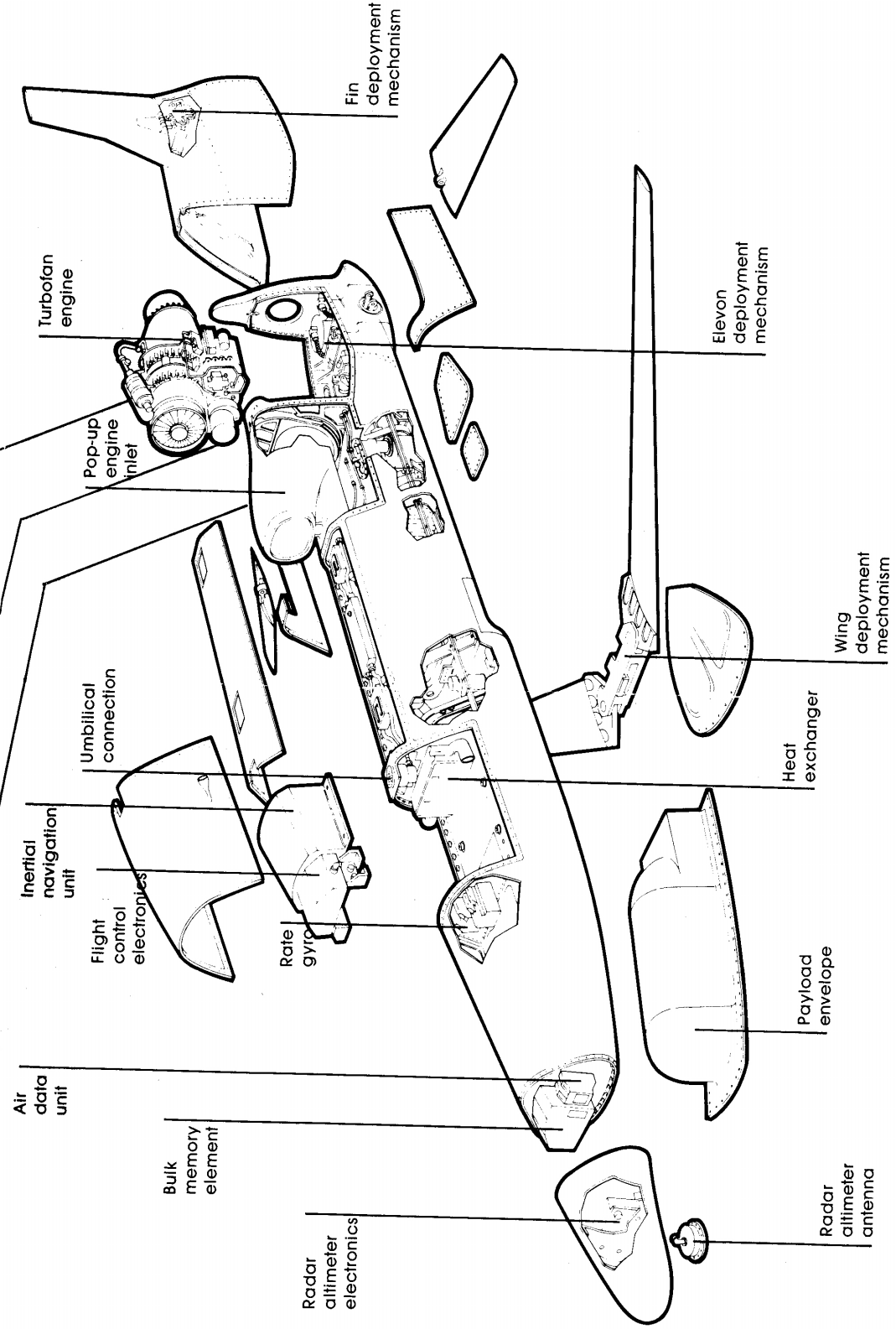
The requirements imposed on the pressure transducers included a digital-type output, high accuracy, fast response time, small size and weight, and the ability to perform well under the severe environmental conditions of shock, vibration, and temperature associated with this missile.

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 rise in the price of jet engine fuel, both aircraft manufacturers and users have reviewed methods of improving fuel conservation. An article published by the Boeing Commercial Aircraft Company has examined possible areas of improvement including reduced aerodynamic drag, and improved instrumentation such as mach meter 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 mach meter 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



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 mach meters were examined. This is shown in Table 1 where an assumed error in mach meter of 0.01 mach low (i.e. reading 0.84 mach when the airplane was in fact flying 0.85 mach). If the mach meter 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, or 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 mach meter reading for the 747 airplane is over \$45,000, \$90,000 and \$135,000 per year based on the assumed mach meter 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**

<u>747 Aircraft</u>		<u>FUEL BURN PENALTY</u>		<u>COST OF FUEL BURN/YR</u>		
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
<u>727 Aircraft</u>		<u>FUEL BURN PENALTY</u>		<u>COST OF FUEL BURN/YR</u>		
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 turbine 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 diffuser nozzle pressure, exhaust gas temperature, and RPM. These engine performance charts are obtained from sea level test runs on static testing.

It is felt that significant savings in fuel consumption can be achieved 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 force balance 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 users.

## 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. Averaging longer or using a higher frequency clock can obtain higher resolution. 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.

A second characteristic of the transducer, which makes it highly desirable 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 straightforward, 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 that 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. 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.

## ACKNOWLEDGEMENTS

The author wishes to thank the following people and organizations for their contributions:

G.W.N. Lampard and C. Carlin of The Boeing Company's IPCS Program and the USAF Aero Propulsion Laboratory, Air Force Systems Command, Wright Patterson AFB, Ohio. The digital pressure transducers for the ALCM Program were provided under Contract # F 33657-72-C-0923 to the Boeing Company as sponsored by the AGM-86A Program Office, Deputy for Air Launched Strategic Missiles, Aeronautical Systems Division, United States Air Force, Wright-Patterson Air Force Base. Also greatly appreciated is the material supplied by J. Codomo of ELDEC Corporation, and G. Hedrick and H. Sandberg of Harowe Systems.

