SMART Pressure Transducers

Combining a piezoresistive pressure sensor with a microcomputer and digital signal processing yields a transducer that is both accurate and easy to use.

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Choosing a pressure transducer for a precision measurement system (one where the total error budget is less than 1 percent) has traditionally not been a simple matter of going to a catalogue and quickly finding a device to fit the needs of the application. The task of selection was complicated by many factors, among them specifications that were often deceptive, and hidden error sources both in the transducer and in its system interface. It was necessary not merely to select a single component—the transducer—but rather to define an entire measurement system made up of many parts, each with its own error contribution. As a result, the accuracy of the pressure-measurement system could not be determined easily from the implied accuracy of the transducer but had to be determined by time-consuming analysis and testing.

Furthermore, the application often required a pressure measurement to be converted into other units for display, as when barometric pressure is used to measure the altitude of an aircraft. Such nonlinear conversions usually complicated the hardware and made it suitable for only a single function.

The SMART pressure transducers described in this article provide a systems approach to precision pressure measurement; they free the systems designer from the tasks of researching, defining and verifying transducer performance. The SMART transducers result from merging three technologies: piezoresistive sensors, the microcomputer and digital signal processing. They provide compensation for temperature effects and nonlinearities, and they offer scaling and conversion to user units, all at the transducer end of a measurement system. They are characterized by a single accuracy number that defines in-system performance. What you see is what you get: There are no hidden error sources. The key benefits of the SMART transducers are superior performance over the environmental range, excellent long-term stability, freedom from interface-induced measurement errors, the ability to multiplex digital data from several transducers onto a common pair of wires, and the ability to simultaneously output multiple parameters, such as pressure and altitude.

The Designer's Problem

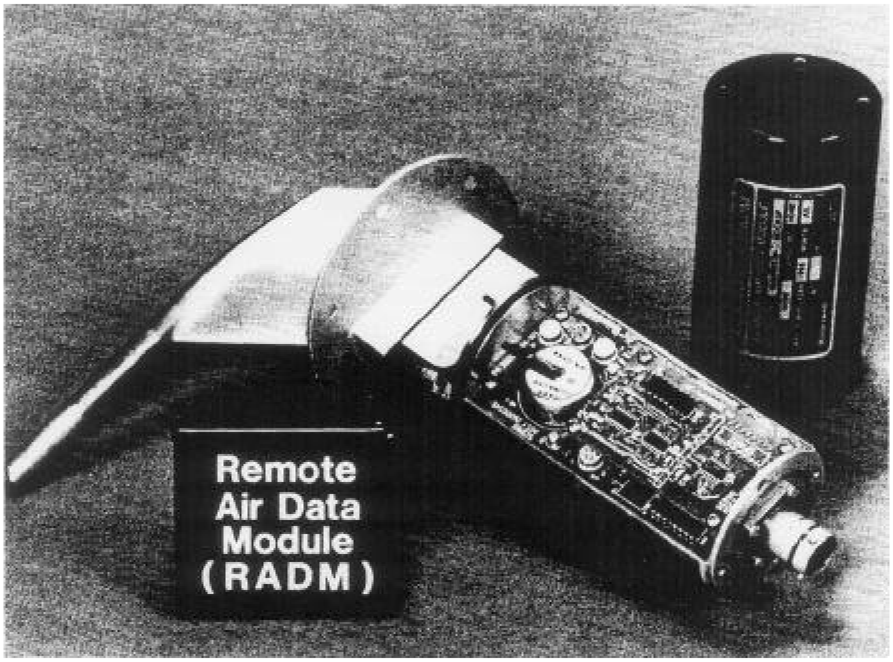
Selecting a transducer has traditionally been one of the most time-consuming tasks associated with building a pressure-measurement system. There were myriad hidden error sources and undisclosed performance specifications. A few of the many effects that had to be taken into account were: null and span shift with temperature and time, repeatability, stability, calibration accuracy and the effects of dynamic pressure and temperature changes on the accuracy of the system.

Once a transducer had been chosen, the next task was selection or design of analog signal-conditioning electronics. This part of the system was required to accomplish several functions. First, it had to amplify the sensor's low-level output and convert it to a usable format so as to overcome noise on the interface wiring. Second, it had to correct for any static or thermally induced null and span errors of the sensor. Finally, the signal-conditioning electronics often had to correct for pressure nonlinearities. It should be noted in passing that analog components used to compensate for deficiencies of the sensor and the interface electronics were themselves sources of additional thermal and long-term error.

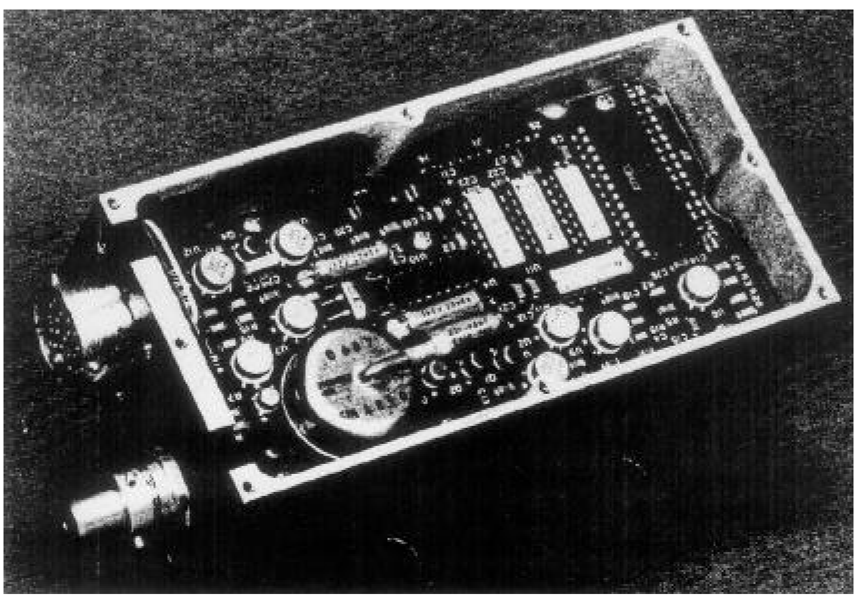
The output of the signal-conditioning stage was an analog signal, either a voltage or a current, typically 0 to 10 volts or 4 to 20 milliamperes. The voltage output mode was used most often in close-coupled systems where the transducer was supplied power independent of the output signal. The current-loop mode was used most often for applications where the transducer was located at a distance from the user system. In this mode both power and signal were transmitted over the same pair of wires; the transducer modulated its power-line current as its analog output signal.

A final task for the designer of a pressure-measurement system was to define the interface to the user system. In most applications designed in the past decade, this interface has converted the analog data-transmission format into a digital format for use either by a computer-based data-acquisition and control system or by a digital display device.

Seen from this point of view, a traditional transducer application depended not on a single component but on an entire system made up of many interdependent parts; that system is itself usually a part of a



COMPLETE PRESSURE-TRANSDUCER SYSTEM is mounted on a pitot tube that extends into the air stream flowing past a moving aircraft. The transducer is used in two applications; one is measuring the static, or ambient, pressure, and the other is monitoring the dynamic pressure associated with the aircraft's velocity. The module is now being flown aboard Boeing's next-generation-technology demonstrator aircraft.



AIR-DATA MODULE for the Aerospatiale Airbus A320 is similar to the one shown in the previous illustration but is not mounted on a pitot tube. Eight of these modules are installed in each Airbus, providing pressure measurements for the Honeywell Air Data Inertial Reference System.

larger measurement and control system. The disadvantage of this approach is the accumulation of analog error sources between the sensing element and the end system user. SMART pressure transducers overcome this disadvantage by providing all sensing, signal conditioning, compensation for thermal effects and sealing to user units at the point of measurement. The transducers then send the data to the user over a noise-resistant digital interface.

Three Examples

The development of the SMART pressure transducer has been fostered by several organizations within Honeywell: the former Commercial Aviation Division, the Defense Systems Group, the Military Avionics Division, the Industrial Controls Division, the Solid State Electronics Division, the Systems and Research Center and the Underseas Systems Division. Two of the SMART transducers developed by this collaboration are shown in the illustrations on this page.

One of the transducers is a pitot-probe-mounted remote air-data module delivered to Boeing in 1985 for flight-test usage. It is currently flying on their next-generation-technology demonstrator. An equivalent device, but not probe mounted, has been in production since 1986 for the Air Data Inertial Reference System made by Honeywell's Air Transport Systems Division for the Airbus A320. It has demonstrated transfer-standard performance typically better than ±0.01 percent full-scale total error band throughout the entire pressure and temperature environment. Another SMART transducer was developed in 1983-84 for depth sensing on the MK-46 torpedo; this application utilizes an auxiliary analog output.

Operating Principles

The solid-state sensors used in these transducers are based on the piezoresistive effect in (1-0-0) silicon.

The amplitude of the bridge's output signal is a function of pressure and temperature, as shown in the upper illustration on page 77. The strong temperature dependence of this "raw" sensor output is unfortunate. The most apparent component of the temperature dependence is essentially due to a "softening" of the sensor diaphragm with increasing temperature. To correct for such repeatable temperature-dependent errors, an on-die temperature-sensitive resistor is provided. The temperature measured by this resistor is then used by a modeling algorithm to compensate for temperature-dependent error sources within the sensor.

Basis of Sensor Design

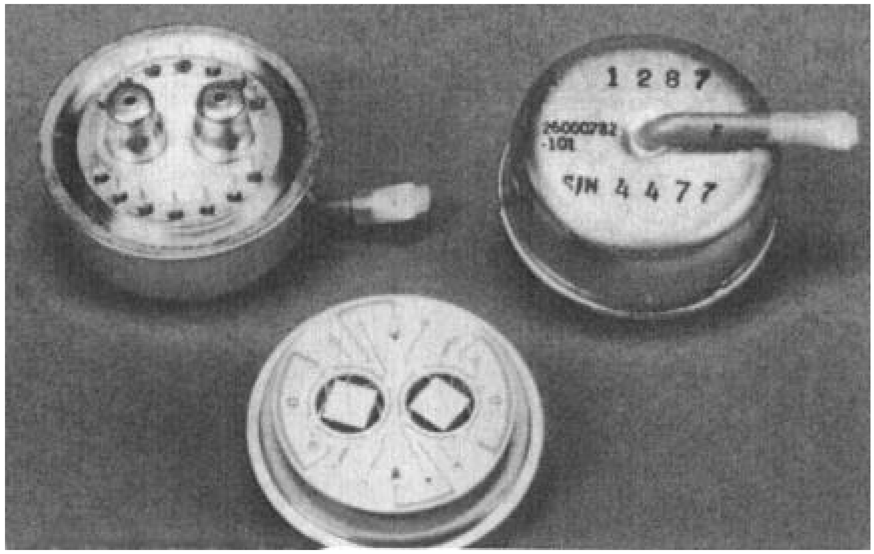
Long-term stability was our key design goal for the sensors used in SMART transducers. It was therefore essential that we not encumber the sensor die with mechanical and electrical contrivances to attempt to compensate for temperature effects and pressure nonlinearities.

The only absolute demands on the sensor are that it yields highly repeatable and stable results. Hence the sensor can be made very simple, and the corrections can be made in the digital modeling algorithm. This simplicity yields improved reliability, repeatability and stability, and it reduces thermal hysteresis and sensor cost. The result is an uncompensated, loose-tolerance but stable sensor.

An example of such a sensor is shown in the illustration above. This sensor is used in Honeywell's air-data and engine-pressure-ratio products for many civil and military applications, including airliners such as the Boeing 727, 737 and 747, the McDonnell-Douglas MD-80 series and DC-10, and the Airbus A320 and Fokker 100, which will be entering service soon.

Modes of Measurement

For this reason high-performance true differential piezoresistive sensors are not generally available, although many attempts have been made to passivate the active side of the die with silicone gel or other means in order to obtain a true differential measurement. Our sensor overcomes the differential-sensor-stability problem by providing a "quasi-differential" measurement capability.



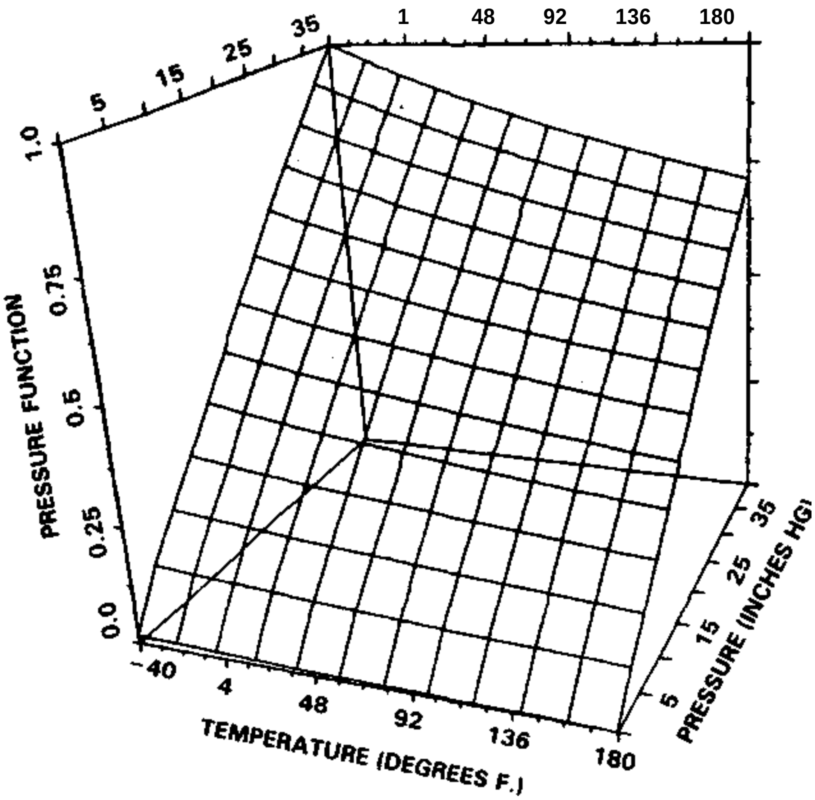
QUASI-DIFFERENTIAL SENSOR for air-data applications measures two absolute pressures with high precision in order to synthesize a differential measurement. Mounting the two sensors in the same housing, so that hey share the same reference vacuum, eliminates a potential source of error, namely differences in the residual pressures of two independent reference-vacuum chambers.

The sensor is a dual-channel absolute device which was designed originally for high-performance primary air-data applications (providing altitude, airspeed, Mach and other pressure-related information to the pilot, autopilot, and other systems on aircraft). It is discussed in detail in Reference 1.

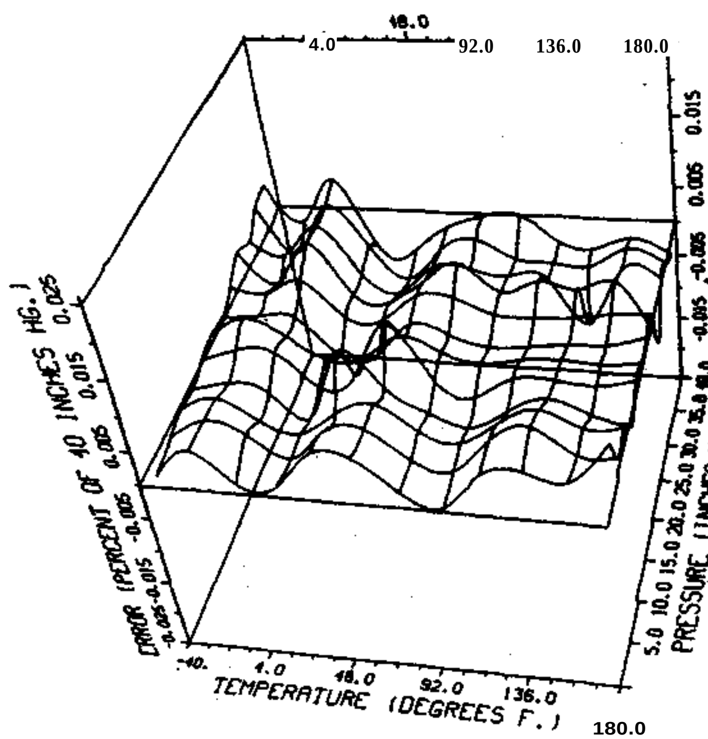
In the air-data application two pressures need to be known precisely. The absolute ambient pressure is needed to monitor altitude, and a differential measurement of the dynamic pressure due to the aircraft's movement through the air provides the information needed to calculate airspeed; both pressures enter into the determination of Mach number. The quasi-differential sensor provides the ability to measure two absolute pressures precisely. Because both sensing elements are enclosed in the same reference vacuum chamber, there is no reference-vacuum difference between them; a precision differential measurement is made by subtracting one absolute pressure measurement from the other.

The idea of subtracting two absolute pressures to synthesize a differential measurement is not new. It had often been done with separate pressure sensors, each having its own independent reference-vacuum error. Using the Solid State Electronics Division's tiny piezoresistive sensor technology allowed two absolute sensors to be integrated within the same package and to share the same reference vacuum. Any reference-vacuum error then becomes a common-mode error, which disappears from the differential measurement.

The advantage of the single reference vacuum can be explained as follows: P_1 and P_2 are the input pressures to be measured, and V_1 and V_2 are the pressures in the corresponding reference-vacuum chambers (a vacuum is never perfect).



UNCOMPENSATED OUTPUT of the sensor depends strongly on temperature as well as pressure. The fact that the surface of the graph slopes downward to the right indicates that the sensor becomes less sensitive to pressure as the temperature increases. There is also a slight nonlinearity in the response of the sensor to pressure at a fixed temperature.



ACCURACY OF THE TRANSDUCER is vastly improved by an algorithmic process called modeling that compensates for temperature-dependent errors and nonlinearities in the "raw" sensor data. The vertical scale in this illustration is magnified 2,000 times in order to make slight departures from the ideal sensor response visible. The graph indicates that for all combinations of pressure and temperature measured the transducer is accurate to within ±0.01 percent.

The conventional two-pressure differential-pressure synthesis then takes the following form:

$$(P_1 - V_1) \sim (P_2 - V_2) = (P_1 - P_2) + (V_2 - V_1)$$

In contrast, the quasi-differential pressure measurement involves only a single, common reference vacuum *V:*

$$(P_1 - V) - (P_2 - V) = (P_1 - P_2)$$

Thus by utilizing a common reference vacuum for the two absolute pressure measurements, no reference-vacuum error source corrupts the quasi-differential pressure measurement.

High-pressure piezoresistive pressure sensors (for applications above 2,000 p.s.i.) generally require a different approach in order to keep the sensor small and yet endure the high level of stress imposed by the environment. This method causes a slight performance degradation, but it allows cost-effective high-pressure sensors to be used reliably over the long term.

Digital Signal Processing

The microcomputer used in the SMART transducer enables a simple sensor element, fabricated only to loose tolerances, to make high-precision measurements. Through the process called modeling, the repeatable error sources of each sensor arid its associated analog-to-digital conversion electronics are measured and systematically compensated for by an algorithm. The microcomputer also formats the output data, performs continuous self tests of transducer functions, provides serial communications and performs any addition scaling or limit functions defined by the user.

Calibration by modeling allows us to produce a device that uses no precision components and requires no analog calibration adjustments. The modeling algorithm's ability to correct for pressure nonlinearities and fixed and temperature-dependent error sources results in exceptional performance, reliability and long-term stability.

The illustrations on page 77 compare the normalized "raw" sensor performance before modeling with the accuracy of the system after modeling. As a result of compensation by digital modeling alone all points are accurate to within ±0.01 percent of full scale. This level of performance is what the end user is able to realize with the SMART transducer system. Because modeling is simply an algorithmic function, it is also able to transform one parameter into another. For example, the modeling algorithm can incorporate the nonlinear relation between barometric pressure and altitude.

Other manipulations of the digital data can also be undertaken when necessary. For example, the dynamic behavior of the transducer—its response to changes in pressure—can be shaped by digital filtering algorithms. Or, for control systems, the microcomputer could calculate and output derivative and integral functions in addition to the baseline proportional function; indeed, the output function could even be a weighted composite of all these terms.

Digital Communications and Control

The presence of a microcomputer within the transducer has allowed us to add a number of other features that enhance both performance and convenience and are not available in traditional analog transducers.

Communication between the transducer and the using system is one area where digital technology has conspicuous advantages.

The transducer can easily be configured to output its data in a standard serial communications protocol such as RS-423 (the default), RS-422, RS-232C or ARINC 429 (for air-data modules). Signals from a number of transducers can be multiplexed on a single pair of wires using some of these formats. Multiple communications formats can be accommodated simultaneously, as is done in air-data modules that provide a bidirectional RS-423 channel and an ARINC 429 unidirectional output. Bidirectional communication allows the user to control and monitor (via internal built-in-test features) the operation of the transducer. This facility allows automated calibration verification and adjustment without removal of the transducer. Other output formats, even analog (as previously noted) can also be provided for interface with existing systems.

Another important advantage of the digital input-output link is its insensitivity to interface-induced noise. In an analog interface, filtering to reduce aliasing can degrade the overall system dynamic performance. The digital interface used with the SMART transducer allows standard error-detection and correction techniques, such as parity checking and data reconstruction, to be utilized. This insures a high-integrity data link between the transducer and the user. Very little extraneous noise is then superimposed on the resulting pressure measurement.

Conclusions

Perhaps the best way of summarizing the benefits of the SMART transducer is to consider the meaning of the acronym "SMART." The transducers are:

- Simple to use: The digital interface relieves the system designer of the time-consuming task of transducer research and design.
- Maintainable: Much of the transducer's functionality is governed by firmware, which allows it to be controlled, tested and adjusted through a digital data link.
- Accurate: The user has only a single accuracy specification to understand. The specified accuracy of the transducer is sure to be fully realized when the transducer is integrated into the system.
- Reliable: The simplicity and stability of the digital mechanization ensures it.
- Trainable: The microcomputer can be programmed to scale and limit output data in accordance with a field-inserted function.

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Reference

1. DuPuis, Paul, "A Novel Primary Air Data Quality Pressure Transducer," *Proceedings of the National Aerospace Electronics Conference*, 1985.