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Wide-Temperature Electronically Scanned Pressure Measurement Module

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Wide-temperature electronically scanned pressure (ESP) measurement modules have been developed for wind-tunnel applications for service over a wide temperature range [50°C (122°F) to −175°C (−283°F)]. These modules are designed to account for offset voltage drift, operate without thermal protection in cryogenic temperature environments, and maintain a stable calibration for months. Conventional ESP modules cannot operate in cryogenic environments without thermal protection, for example, a heater box, which reduces available space for module installation, demands labor-intensive and time-consuming installation, and requires heavy electrical wiring that can shunt the wind-tunnel force balance. To account for force-balance shunting, separate wind-tunnel tests must be conducted to collect pressure and force-balance measurements, which devour both time and money. Because of offset voltage drift, conventional modules also require frequent test interruptions for online calibration, which can consume as much as 15% of total test time. Wide-temperature ESP modules eliminate these shortcomings while providing total uncertainty in pressure measurement less than 0.1% of full-scale output. Design, fabrication, and calibration of these modules are described. Test results from data gathered using two 16-port wide-temperature modules in the National Transonic Facility wind tunnel at NASA Langley Research Center are also provided.

Nomenclature

$a_1 \ldots a_4$	=	coefficients of fourth-order polynomial fit
H	=	percent hysteresis
N	=	percent nonrepeatability
n	=	number of measurements at nodal point
P	=	measured differential pressure
S	=	percent static error
U	=	percent total uncertainty
V_{FSO}	=	full-scale pressure voltage output
V_{fit}	=	fitted pressure voltage
V_p	=	measured pressure voltage
V_{pc}	=	corrected pressure voltage
$(V_{\mathrm{pc}})_{\mathrm{down},1}$	=	second repeated corrected pressure voltage in first measurement cycle (decreasing from full-scale pressure output toward zero)
$(V_{\mathrm{pc}})_{\mathrm{down},3}$	=	first repeated corrected pressure voltage in third measurement cycle (increasing toward full-scale pressure output from zero)
$(V_{\mathrm{pc}})_{\mathrm{down},4}$	=	first repeated corrected pressure voltage in fourth measurement cycle (increasing toward full-scale pressure output from zero)
V_{pcfit}	=	least-square, fourth-order polynomial fit of corrected pressure voltage
$(V_{\mathrm{pc}})_{\mathrm{up},1}$	=	first repeated corrected pressure voltage in first measurement cycle (increasing toward full-scale pressure output from zero)
$(V_{\mathrm{pc}})_{\mathrm{up},2}$	=	first repeated corrected pressure voltage in second measurement cycle (increasing toward full-scale pressure output from zero)
$(V_{\mathrm{pc}})_{\mathrm{up},3}$	=	second repeated corrected pressure voltage in third measurement (decreasing from full-scale pressure output toward zero)
V_{p0}	=	first measured pressure voltage in series
V_{rtd}	=	measured resistance temperature detector voltage
V_{rtd0}	=	first resistance-temperature-detector voltage in series
V_0	=	measured offset voltage

Introduction

THE technology of pressure measurements in wind tunnels has proceeded through several evolutionary stages. First, a manometer board consisted of an array of discrete pressure sensors, typically capacitive or vibrating quartz, each of which required its own connecting tube to the pressure port. Because the pressure sensors were located outside the model, all of the connecting tubes had to pass from the model across the sting to the sensor location. Later, a major improvement comprised the Scannivalve™, which multiplexed the tube pressures through a mechanical valve to a single pressure transducer, thus greatly reducing the cost of pressure measurement. Because the multiplexer, however, remained outside the model, all of the pressure tubes still had to pass across the sting. In the 1970s the introduction of the electronically scanned pressure (ESP) measurement module made it possible for the transduction from pressure to voltage, and subsequent multiplexing, to take place within the module itself. Thus only a single pair of signal leads plus another pair for module power were needed to pass from the model across the sting.

The general concept for surface-pressure measurement in wind-tunnel testing is shown in Fig. 1. Multiple pressure ports, typically 0.254 mm (0.01 in.) in diameter, are located at various measurement sites on the surface of a model. The surface pressures are communicated by means of nylon (or other) tubing to a central ESP module, which contains typically 16–64 silicon piezoresistive pressure transducers. The outputs of the transducers are multiplexed to a single pair of electrical signal wires, which transmit the output signals through the model, across the sting, and into the tunnel control room.

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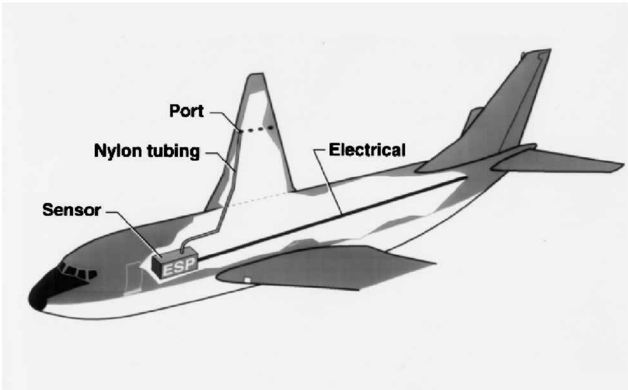

Fig. 1 Surface-pressure measurement on wind-tunnel model.

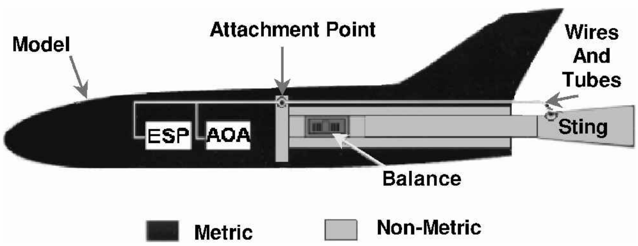

Fig. 2 Apparent strain problem.

The ESP module has served the aerospace industry well for over a quarter of a century. However, there still remain several operational problems. Because the bridge resistors are implanted in semiconducting silicon, their resistance is temperature sensitive, causing a zero drift in the output voltage. For this purpose a sliding valve that permits switching from the test pressures to a common calibration pressure applied to the sensors is built into the module. Thus a wind-tunnel test is interrupted periodically for recalibration against the zero drift.

Second, in the special case of cryogenic testing the module requires protection from the cryogenic environment, for the minimum operating temperature is specified typically as −30°C (−22°F). For this reason the module is placed inside a heater box, where the temperature is controlled to within a few degrees Celsius. Installation of the module into the heater box is labor intensive and requires the introduction of a heavy power cable across the sting and into the model.

Finally, a variety of conduits passing across the sting—heater cable, pneumatic tubes, and electrical wires—lead to an operational problem called here the "apparent strain" problem (Fig. 2). The force balance, used to measure aerodynamic forces and moments on the model, is located between the model and the sting. It is desirable that all forces and moments in the "metric" region (i.e., acting upon the model) be directed to the force balance exclusively, but the bundle of conduits across the sting transmits a small fraction of the forces and moments to the "nonmetric" region, thus shunting the force balance. As a result, to avoid errors in the force-balance measurements as a result of this shunting action it is necessary that the surface-pressure and force-balance measurements be made in separate wind-tunnel runs.

Therefore, the objective of the work described here is to develop a wide-temperature ESP module with the following features: first, stabilization of the piezoresistive bridge against zero drift; second, the capability to operate in a cryogenic environment without the need for a heater box; and finally, a reduction in the number of conduits passing across the sting, namely the small signal and power supply wires to the module and a single pneumatic tube for the reference pressure.

This paper will describe the design, fabrication, and calibration of such a wide-temperature ESP module, as well as provide experimental data gathered in the National Transonic Facility (NTF) at NASA Langley Research Center. The development of the module evolved through successive steps of trial and error, but only the successful development steps are included in this paper.

Design and Fabrication

The three most important areas in developing a wide-temperature, multiport ESP module are the selection of appropriate silicon pressure sensor dice, cryogenically compatible module packaging materials, and integrated signal conditioning circuits for use within the ESP module housing.

Appropriate silicon pressure sensor dice must have diffused impurity densities between 5×10^{19} and 2×10^{20} cm^{-3} to avoid unpredictable variations in sensor offset voltages and sensitivities caused by charge carrier "freeze-out" at temperatures below −100°C (−148°F). The two remaining areas, namely cryogenically compatible packaging and signal conditioning circuits, were investigated with primary emphasis given to module packaging concerns. Procedures and techniques for critical component bonding, such as aluminum nitride substrate to the silicon pressure sensor dice and Kovar base plate, are discussed.

Sensor Interface Cross Section

A cross section showing the interfaces from the sensor to the Kovar base plate is shown in Fig. 3. During exposure to cryogenic temperatures, a severe stress can develop across the interfaces between the pressure sensor dice, aluminum nitride substrate, and Kovar base plate. This undesirable stress might, in some cases, cause delamination of bonded components or introduce unpredictably large offset voltage variations, making pressure measurements unreliable. In wide-temperature ESP module construction silicon pressure sensors have been bonded with low-temperature solder and cryogenic adhesives with reliable bonding achieved using Hysol® 9309 adhesive sealant made by the Loctite Corp. Thermal cycle testing was performed on a completed wide-temperature module to assess bonding material integrity from room to liquid nitrogen temperatures. Procedure details and tests results are given in the subsequent sections.

Silicon Pressure Sensor Die

A silicon pressure sensor die has a built-in Wheatstone bridge with resistance elements fabricated through either the diffusion or ion implantation of boron atoms into an n-type silicon substrate. Electronic properties of the doped region (e.g., p type) are dependent upon dopant density, and the piezoresistance properties are a function of the majority charge carrier density. Charge carrier densities in silicon increase exponentially with temperature[1]; therefore, piezoresistive coefficients (sensitivity) and bridge resistances for lightly doped p-type silicon can increase up to three times higher at liquid nitrogen temperature than the values at room temperature. Offset voltages of silicon pressure sensors then vary unpredictably with temperature.

For silicon sensors with dopant densities in the range of 5×10^{19} to 2×10^{20} cm^{-3}, both sensitivity and offset voltage show

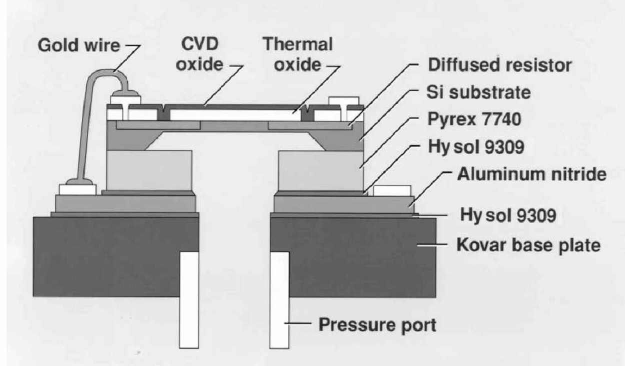

Fig. 3 Cross section of sensor interface.

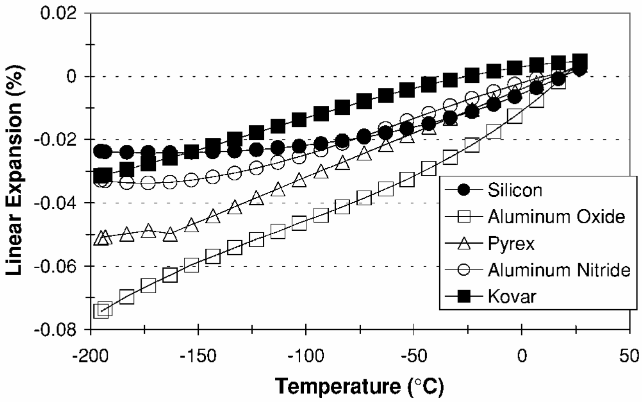

Fig. 4 Linear thermal expansions of ESP materials.

considerably less variation[2] over the temperature range of −180 to 80°C (−292 to 176°F). A dopant density of 1×10^{20} cm^{-3} is a reasonable compromise of its low-temperature stability and sensitivity. Selected silicon pressure sensor dice have dopant densities near 1×10^{20} cm^{-3}.

Aluminum Nitride, Pyrex Circuit Boards, and Kovar Base Plate

Aluminum nitride and Pyrex® substrates are used as intermediates between the silicon pressure sensor die and Kovar base plate, which is fitted with 1.524-mm (0.06-in.)-diam stainless-steel pressure tubes welded by electron beam (see Fig. 3). Figure 4 shows the linear expansion changes of silicon, Pyrex, aluminum nitride, aluminum oxide, and Kovar as a function of temperature. (Kovar thermal expansion data were collected in house at the NASA Langley Research Center and are available via correspondence to coauthor A. J. Zuckerwar.) Linear expansion changes of silicon and Pyrex are very similar over the temperature range of −100°C (−148°F) to 100°C (212°F). At −196°C (−320.8°F) the linear expansion difference between silicon and Pyrex 7740 is approximately 0.03%. However, the linear expansion of Pyrex 7740 and aluminum nitride track very closely from −196°C (−320.8°F) to room temperature. An aluminum nitride circuit board was chosen for wide-temperature ESP module construction because of its favorable thermal conducting properties and extremely low linear expansion difference between aluminum nitride and the silicon pressure sensors bonded to Pyrex 7740. Aluminum oxide was not chosen for this particular application because of its relatively large linear expansion differences with the other materials.

Aluminum nitride and Pyrex substrates had been used as intermediates between silicon chips and Kovar base plates. These aluminum nitride substrates with 16 pressure holes having gold interconnections were tested before and after 10 thermal cycles from room to liquid nitrogen temperatures. Neither degradation of the aluminum nitride and Pyrex substrates nor electrical discontinuity of the gold leads at room and liquid nitrogen temperatures was apparent. The welding joint between the Kovar base plate and pressure port also showed no leakage both during and after thermal cycle testing.

Adhesive Sealant, Thermoplastics, and Solders

Several solders, resins, and adhesive sealants are widely available for cryogenic applications. Of these, adhesive sealants such as Crest 7450 from Lord Corporation and sheets of thermoplastic polyetheretherketon had been used previously for sensor-to-alumina and alumina-to-Kovar bonding, respectively.[3]

The maximum difference between the linear thermal expansions of Kovar and aluminum nitride is 0.015%, as shown in Fig. 4, requiring a bonding agent with some level of elongation. The manufacturer rates Crest 7450 as having an elongation factor of 1.5%, a tensile shear stress of 7000 psi at −196°C (−320.8°F), and a room temperature elongation factor of 500%. These properties make it a suitable candidate for cryogenic bonding. A pull test was conducted in the laboratory that demonstrated the material as having a 3200-psi tensile shear stress at −196°C (−320.8°F), nearly half the manufacturer's specified rating. However, sample preparation, adhesive sealant age, and manufacturing batch all appear to play roles in the level of tensile shear stress a sealant sample can withstand. In many instances pull tests of adhesive sealants bonding Pyrex to aluminum nitride could not be carried out because of premature Pyrex failure. Any failure in the module or supporting structure will show up in the response of the module itself (but the force balance reading will invariably remain intact).

Another adhesive in sheet form, American Cyanamid Company FM 1000, is a modified polyamide-epoxy unsupported adhesive film with a serviceable temperature range of −250°C (−418°F) to 95°C (203°F). It is specially developed for bonding metals, structural plastic laminates, and various composite structural plastic sandwiches. This material was used successfully for bonding the aluminum nitride substrate to the Kovar base plate. However, two disadvantages with this approach include a high curing temperature of 195°C (383°F) and cost, because the material can only be obtained in bulk quantities.

Other bonding agents such as indium and its alloys, low-temperature solders, and Ultem® by General Electric have been used with varying degrees of success under cryogenic conditions. Several other materials, such as polyamide and Hysol 9309, have been used in the aerospace industry for over a decade and were successfully tested in cryogenic conditions showing excellent results from 50°C (122°F) through −160°C (−256°F). Precise control of specimen temperature [±1°C (±1.8°F)] and tedious bonding-surface preparation for all mentioned materials are required for adequate cryogenic bonding.

Electronic Components

Electronic circuit boards used in the construction of the wide-temperature modules consist of an operational amplifier (AD524SD of Analog Devices, Inc.) and resistors. For the 16-port wide-temperature module, four eight-channel differential input multiplexers (HI-507 from Intersil Corp.) are mounted on either a Pyrex or aluminum nitride substrate with 16 pressure sensors and resistance temperature detectors (RTDs) embedded on each silicon chip. Most electronic components were individually tested before integration into a module circuit board. Approximately half of the operational amplifiers failed when exposed to liquid nitrogen temperature for the first time. These operated normally at room temperature but failed when subjected to temperatures near or below −100°C (−148°F). This failure is attributed to thermal stress and/or thermally related failure mechanisms, such as microcracks, for example.

Multiplexers in die form, however, were not thermally tested before installation onto the circuit boards for two reasons. First, small dice with 28 needlepoint contacts are difficult to handle in a cryogenic environment. Second, complementary metal oxide semiconductor devices are known to function better at cryogenic temperatures because of charge carrier freeze-out of bipolar devices.

Completed electronic circuitry boards were tested in a cryogenic chamber at −184°C (−299.2°F) and have consistently operated as an integral part of the ESP module, without any difficulties through a number of extended periods, under cryogenic temperature conditions along numerous temperature cycles. Completed modules were tested in a cryogenic chamber over the temperature range of −175°C (−283°F) to 50°C (122°F) in the laboratory. During field testing, a 16-port wide-temperature ESP module was exposed to −160°C (−256°F) over 10 times and for six runs in a Mach 0.3 wind tunnel. A completed 64-port wide-temperature module is shown in Fig. 5.

Calibration

Calibration System Setup

The system used to calibrate the wide-temperature ESP modules, shown in Fig. 6, is broken down into five areas: 1) cryogenic high-pressure calibration chamber, 2) measurement and control of internal chamber temperature, 3) pressure supply for reference and calibration, 4) liquid nitrogen supply for cooling, and 5) data acquisition system.

Table 1 Accuracies of instruments used during calibration

Device	Measurement	Accuracy
PSI System 8400	Air pressure scanning	±0.1% full-scale output
	High-pressure accuracy	±0.02% full-scale output
	Pressure calibration	±0.02% full-scale output
Mensor PCS 400	Reference pressure calibration	±0.025% full-scale output (including linearity, hysteresis, repeatability, and temperature after zeroing at the operating temperature)
West 5010	Thermocouple input	±0.1% of span

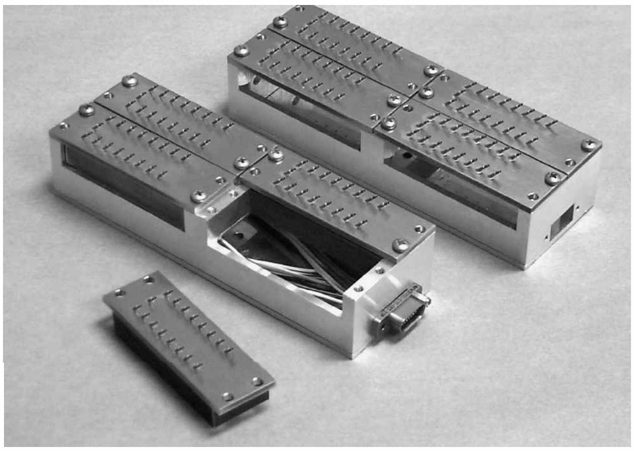

Fig. 5 Sixty-four-port wide-temperature ESP modules.

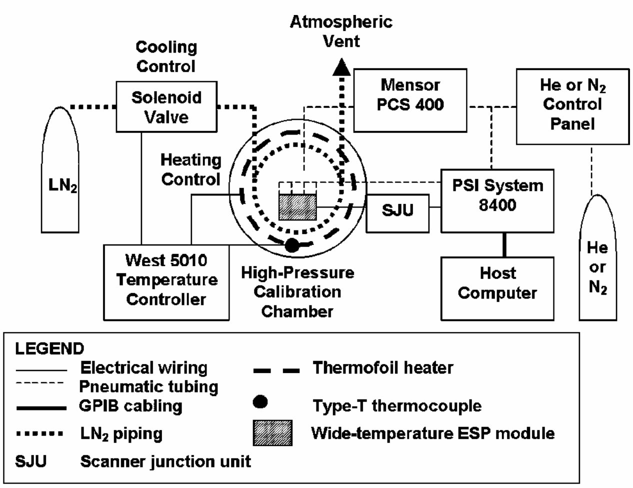

Fig. 6 Calibration system of the wide-temperature ESP module.

The devices used during calibration include the Pressure Systems, Inc. (PSI), System 8400, PCS 400 by Mensor Corp., and West Instruments, Ltd., model 5010. Accuracies of these devices are shown in Table 1.

Cryogenic High-Pressure Calibration Chamber

The cryogenic high-pressure chamber, Fig. 7, is rated for reference pressures as high as eight atmospheres and temperatures as low as −180°C (−292°F). This allows for accurate simulation of conditions encountered in the NTF cryogenic wind tunnel at the NASA Langley Research Center. The chamber is constructed of schedule-40 seamless stainless-steel pipe with chamber length of 0.6096 m (2 ft) and diameter of 0.2032 m (8 in.). Two 0.2032-m

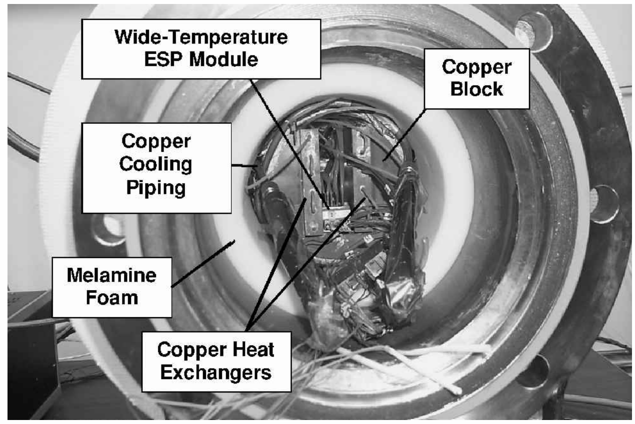

Fig. 7 Calibration chamber.

(8-in.)-diam flanges constructed of 150 working-class schedule-40 slip-steel seal the ends of the chamber. The rear-sealing flange contains several wire feedthroughs allowing passage for thermocouple and low-voltage instrumentation wires, copper tubing, and gas lines into the chamber. Thermocouple and instrumentation wires are necessary for temperature measurement and power supply for amplifiers, multiplexers, and RTDs located on the module's circuit board.

A 0.1016-m (4-in.)-diam copper cylinder block is fitted into the chamber for cooling and heating of the ESP module. The copper block transmits heat between the module and external cooling and heating sources. A rectangular piece, roughly equal to the size of the module's cross section, is cut out along the entire length of the block. The test module sits within this cutout along with two rectangular copper heat exchangers along either side. Helium or nitrogen gas, which is used for chamber pressurization and module calibration, flows through passageways drilled though the heat exchangers. This aids in equalizing the temperature of the incoming gas to that of the internal chamber, reducing the burden on temperature control. EG&G Wakefield Engineering 120-Series thermal compound provides a light bond and increases heat transfer between the outer surface of the module and the surface of the copper block cutout on which the module sits.

Copper cooling piping of 6.35-mm (0.25-in.) diam is wound over the circumference of the block along its entire length. Liquid nitrogen, which enters and exits the chamber through feedthroughs constructed in the rear flange, flows through the piping and cools the copper block. Thermofoil™ heaters from Minco Products, Inc., are pasted over the copper piping to provide heat to the block. The air gap between the copper piping and the outer surface of the copper block is filled with 120-Series thermal compound to improve heat transfer. An insulation material, melamine foam, is fitted along the inner surface of the chamber, including the front and rear flanges, to reduce heat transfer between the copper block and the inner walls of the chamber; this lowers the total temperature attainable at the module. Insulation is also form fitted over the entire outer surface of the chamber, reducing heat flow between the chamber and the outside environment.

Measurement and Control of Internal Chamber Temperature

A West Instruments, Ltd., Model 5010 temperature controller and two solid-state relays (Model CSD2410 from Crydom Corp.) provide measurement and control of internal chamber temperature (Fig. 6). Temperature measurements are taken within the copper block near the module, which ensures that calibration will be made at the desired set temperature. The West 5010 is a single-loop industrial controller equipped with one universal input and two universal outputs. The first output is connected to the heat relay that triggers the Thermofoil heaters, whereas the second connects to the cooling relay that activates a 40-psi cryogenic series solenoid valve (ASCO Valve, Inc.) governing liquid nitrogen flow into the chamber. A type-T thermocouple element with a copper/constantine junction, which supplies temperature measurement near the module, is connected to the universal input.

Pressure Supply for Reference and Calibration

Supply gas, which is necessary for calibration and reference pressure, is routed through a pressure control panel to the calibration chamber, via the Mensor PCS 400 pressure controller and PSI System 8400 data acquisition system. Helium is currently being used as the supply gas for calibration; however, nitrogen gas can also be used. The supply panel consists of a 160-psi TESCOM Corp. gas regulator, a 150-psi relief valve, and a manually operated valve. Gas flows through the regulator, relief valve, and manual valve before exiting through a 1-m (3.281-ft)-long, 6.35-mm (0.25-in.)-diam stainless-steel tube. A T-fitting, at the end of this tube, simultaneously directs gas to the System 8400 and PCS 400. The System 8400 provides regulated calibration pressure to the ESP module, whereas the PCS 400 regulates the reference pressure within the calibration chamber.

Liquid Nitrogen Supply for Cooling

Liquid nitrogen is supplied to the calibration chamber through the solenoid valve from a 270-L liquid nitrogen dewar fitted with a 50-psi relief valve. A 105-psi rupture disk and 75-psi relief valve are attached to 19.05-mm (0.75-in.)-diam liquid nitrogen supply piping ahead of the solenoid valve. Fluid flows from the dewar, through the solenoid valve, and into the copper cooling piping within the chamber. Liquid nitrogen exits the chamber and is vented outside the laboratory into the atmosphere through a conventional piping system.

Data Acquisition System

Data acquisition is provided by a system consisting of a desktop personal computer and the System 8400. The personal computer supplies commands to the System 8400 and stores measured data, whereas the System 8400 supplies calibration pressures and measures output voltages from the ESP module. The desktop IBM-compatible personal computer consists of a 100 Mz, 486-based microprocessor with 8 MB of memory running the Microsoft® DOS® operating system. The System 8400 is a commercially available, highly modular analog-to-digital data acquisition system that supports electronic scanner and pressure standards.[4] Its main components consist of a system processor (SP), pressure calibration unit (PCU), and scanner digitizer unit (SDU). The personal computer connects to the SP through a general purpose interface bus cable via a National Instruments IEEE488/GPIB card installed in the desktop computer. High-level commands are issued from the personal computer to the SP through programming script written in Microsoft compiled QuickBasic®, providing commands for various functions on the System 8400.

The SP contains a 32-bit microprocessor capable of parallel processing, VersaModule Eurocard Bus, and comprehensive firmware, which provides for a high-speed environment and supplies all data reduction and control functions for the System 8400. The PCU is a digitally controlled, pneumatic calibration source and pressure measurement device. The SDU, a high-speed (50-KHz) 16-bit digital converter, reads and digitizes transducer voltages from the ESP module. Each ESP module is connected to a scanner junction unit, which interfaces the module(s) to the System 8400.

Calibration Matrix

Calibration of the wide-temperature ESP module is conducted inside the cryogenic high-pressure chamber simulating NTF environments using combinations of liquid nitrogen flow, Thermofoil heaters, and various chamber reference pressures. Measurements are taken at each of three reference pressures and 10 temperatures. Reference pressure conditions are 1, 3, and 8 atm, and temperature conditions are 50, 25, −25, −50, −75, −100, −125, −150, and −175°C (122 to −283°F). Calibration performed at a specific temperature and reference pressure is referred to here as a "nodal point."

There are a total of 30 unique calibration nodal points for which differential calibration pressures, with a specified step size, are applied to the module over two complete cycles. For example, in the case of a module with a pressure range of ±2.5 psid differential pressure is applied to the module in 0.5-psid increments from 0 to 2.5 psid for two complete cycles and 0 to −2.5 psid for another two complete cycles. This data collection procedure produces two repeated measurement points at the maximum and minimum applied pressure extremes and four repeated points for all other applied pressures with the exception of the 0-psid point, which has five repeated measurements. The data collection cycle at a typical nodal point is shown in Fig. 8.

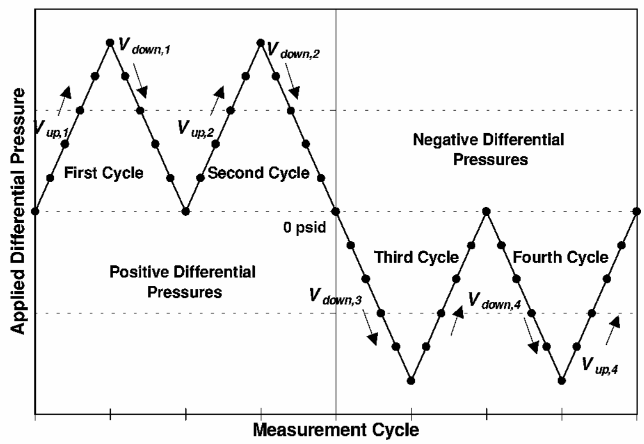

Fig. 8 Typical data collection cycle at a nodal point.

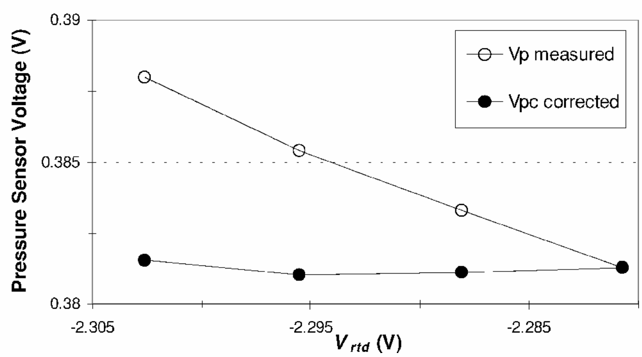

Fig. 9 V_p and V_{pc} for sensor 10 of the 16-port wide-temperature ESP module at a calibration step pressure of 0.5 psid, temperature of −175°C, and reference pressure of 8 atm.

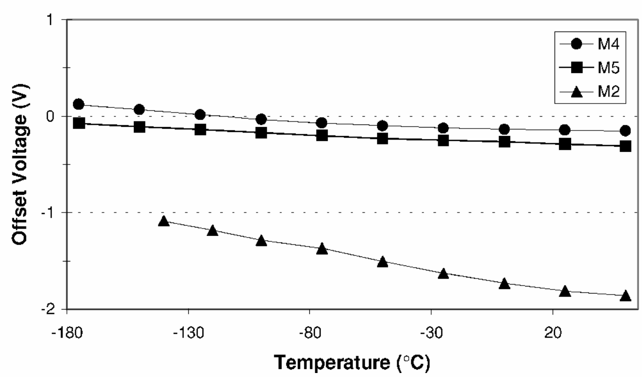

Fig. 10 Typical variation in corrected offset voltage for a single pressure port of the 16-port M2 and M4 and 64-port M5 at 1-atm reference pressure.

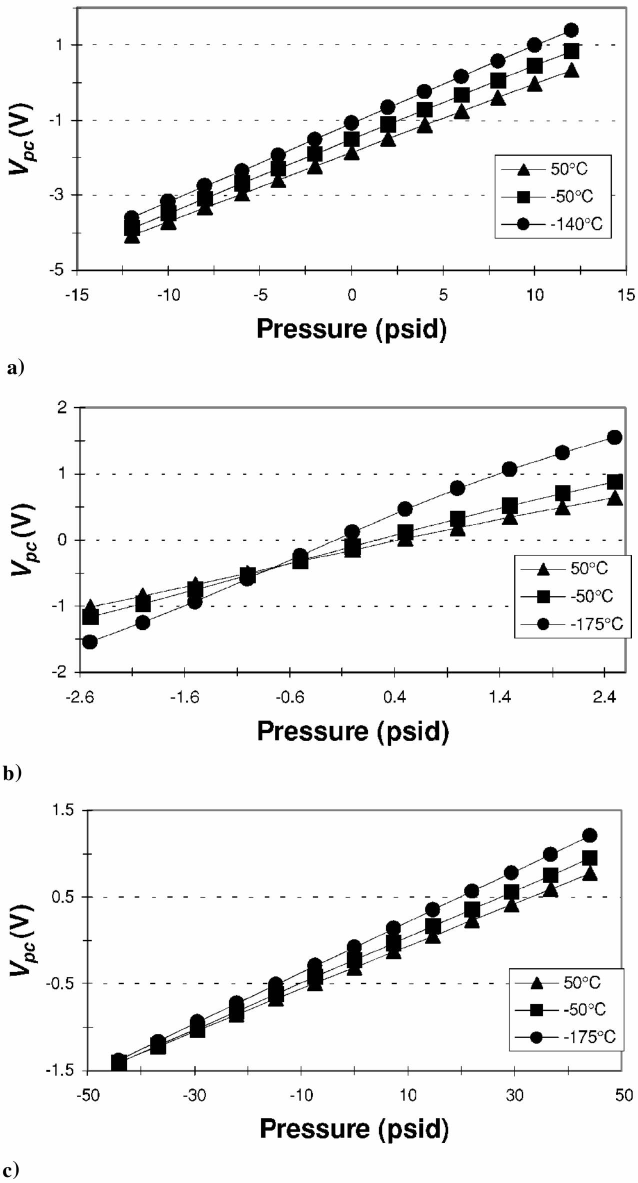

Fig. 11 Typical corrected output voltage response for a single pressure port: a) 16-port module M2 at 1-atm reference pressure, b) 16-port module M4 at 1-atm reference pressure, and c) 64-port module M5 at 8-atm reference pressure.

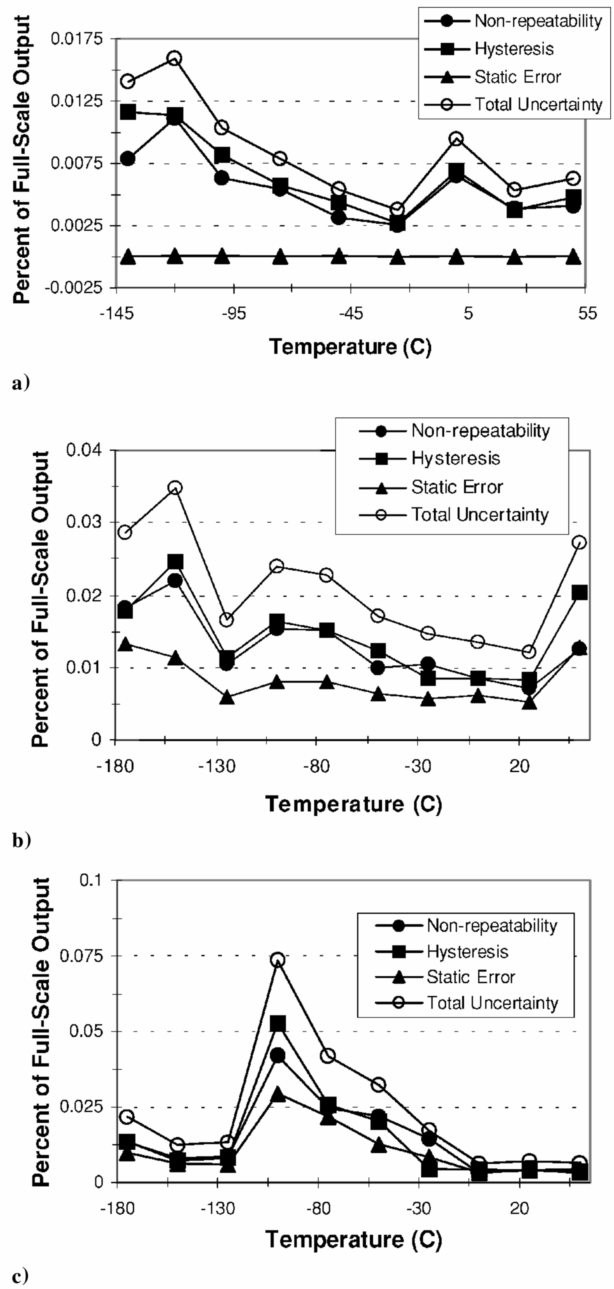

Fig. 12 Typical uncertainties for a single pressure port: a) 16-port module M2 at 1-atm reference pressure, b) 16-port module M4 at 1-atm reference pressure, and c) 64-port module M5 at 8-atm reference pressure.

Uncertainty Analysis

At each nodal point uncertainty analysis is conducted for each port of the wide-temperature module, which includes analysis of nonrepeatability, hysteresis, and static error of measured bridge voltages. During the measurement of differential step pressures at a nodal point, internal chamber temperature drifts and must be corrected for. Before an uncertainty analysis is conducted, a corrected pressure voltage V_{pc} is defined to remove temperature influences on measured pressured voltage V_p for each calibration step pressure. Reference pressure, however, does not exhibit excessive drift during measurement at a nodal point and, therefore, does not influence V_p to an appreciable extent requiring correction. Measured pressure voltage corrected to constant conditions is used in the following uncertainty analysis.[5]

Based on the data collection procedure at a single nodal point (just described), each step pressure measurement point [between 0 psid and full-scale pressure output (FSO)] is repeated four times. Measured pressure voltage V_p is corrected to a common temperature based on the measured temperature voltage V_{rtd} obtained at the same step pressure. Each grouping of repeated measurements is modeled by a linear fit using the equation

$$(V_p/V_{p0}) - 1 = S(V_{\mathrm{rtd0}} - V_{\mathrm{rtd}}) \tag{1}$$

Once S has been determined from the fit, V_{pc} for the given step pressure at a nodal point is found by

$$V_{pc} = V_p/[1 - S(V_{\mathrm{rtd0}} - V_{\mathrm{rtd}})] \tag{2}$$

All calculated values of V_{pc} for a step pressure grouping are averaged to a single value that is used for pressure calibration coefficient determination. Unaveraged values of V_{pc} are used in the uncertainty calculation. Typically, this correction removes the linear variation of V_p with temperature shown in Fig. 9. Equations in the following sections are written for positive pressure, for example, measurement cycles 1 and 2, also apply to negative pressures, for example, measurement cycles 3 and 4.

Table 2 Test set I: Q-probe Check-Standard Test 115; test set II: seal pressure test within the arc sector

Port	Run	Wide-temperature ESP modules: Port pressure, psid	Wide-temperature ESP modules: Port temperature, °C	Reference pressure, atm	Conventional ESP module: corresponding port pressure, psid
			Test set I		
14	24	8.08	122.51	2.49	8.03
14	26	8.04	121.60	2.49	8.03
14	29	5.33	−50.50	2.40	5.33
14	31	5.31	−51.56	2.40	5.29
			Test set II		
1	22	0.0238	50.13	1.68	——
8	22	0.0346	49.57	1.68	——
16	22	0.00112	49.58	1.68	——
1	30	0.00602	47.83	2.95	——
8	30	0.0151	47.45	2.95	——
16	30	0.00339	47.47	2.95	——
1	40	0.00223	48.74	3.32	——
8	40	0.0117	48.24	3.32	——
16	40	−0.0109	48.29	3.32	——

Nonrepeatability Analysis

Nonrepeatability is a measure of the module's ability to reproduce readings under equivalent, consecutively applied conditions. Readings are made at repeated points along the same measurement direction, either increasing from zero or decreasing from full scale. Percent nonrepeatability is found as follows:

$$N = \{100[(V_{pc})_{up,1} - (V_{pc})_{up,2}]/V_{FSO}\}\% \tag{3}$$

The mean overall differential pressures at a nodal point, excluding zero differential pressure data, are computed to be the percent nonrepeatability.

Hysteresis Analysis

The maximum difference between output readings under equivalent conditions at points along different directions of the measurement cycle is hysteresis, which is found as follows:

$$H = \{100[(V_{pc})_{up,1} - (V_{pc})_{down,1}]/V_{FSO}\}\% \tag{4}$$

The mean overall differential pressures at a nodal point, excluding zero differential pressure data, are computed to be the percent hysteresis.

Static Error Analysis

Static error is defined as the rms deviation of fitted from actual measurement data. In this case V_{pc} is fitted to P using a fourth-order polynomial resulting in a least-square fit given by

$$V_{pc} - V_0 = a_1 P + a_2 P^2 + a_3 P^3 + a_4 P^4 \tag{5}$$

Two sets of coefficients for $a_1 \ldots a_4$ are found for both positive and negative P, respectively. Percent static error is found by

$$S = \frac{100\sqrt{\sum_n (V_{pc} - V_{pcfit})^2}}{n(V_{FSO})}\% \tag{6}$$

The mean overall differential pressures at a nodal point, excluding zero differential pressure data, are computed to be the percent static error.

Total Uncertainty Analysis

Total uncertainty is defined as the square root of the sum of the squares of the nonrepeatability, hysteresis, and static error (in percent) given by

$$U = \sqrt{N^2 + H^2 + S^2}\% \tag{7}$$

Laboratory Calibration Data

Calibration data were gathered for a 16-port ±15-psid module designated as the M2, a 16-port ±2.5-psid module designated as the M4, and a 64-port ±45-psid module designated as the M5. All three modules are supplied with 5-V excitation across each pressure sensor. Sample calibration data are provided in the following sections, showing offset pressure voltage response of the modules as a function of temperature, output pressure voltage response to applied differential pressures, and uncertainties in pressure measurement (discussed in the preceding section). Sample wind-tunnel data taken with modules M2 and M4 in the NTF wind tunnel are also provided.

Offset Voltage

Typically, offset bridge voltages for the wide-temperature modules vary less than 1 V over the full temperature range at 1, 3, and 8 atm. Figure 10 shows the typical variation in offset voltages for the M2, M4, and M5 wide-temperature modules. Voltages vary smoothly over the entire temperature range with no abrupt changes to suggest electronic component failure caused by thermal stress and/or thermally related failure mechanisms at the lower temperatures.

Output Response

Output pressure voltage varies linearly over the full pressure range for the M2, M4, and M5 modules. Response linearity is retained through the entire temperature range (Fig. 11). Pressure response, however, varies as a function of temperature for each module; this is evident in the changes in the offset voltages and response slopes. RTDs located on each sensor die account for this by providing continuous temperature measurements. An algorithm that uses these temperature measurements, along with reference pressure, to interpolate pressure from measured voltage using the pressure response slope between appropriate nodal point conditions was developed. Slopes are fitted by least squares to multiorder polynomials and arranged in "look-up" tables by nodal point, which are then used by the interpolation algorithm to calculate the differential pressure at the port.

Bridge Voltage Uncertainties

Total uncertainty in pressure measurement for the M2, M4, and M5 does not exceed 0.1% FSO over the full temperature ranges of the modules. Typical values for a single port for nonrepeatability, hysteresis, static error, and total uncertainty are shown in Fig. 12. Each uncertainty element contributing to the total uncertainty is comparable in magnitude over the entire temperature range. Static error provides the least contribution to the total uncertainties, whereas hysteresis appears to be the greatest contributor. Differences between total uncertainties at maximum and minimum temperatures are comparable in magnitude indicating good performance from temperatures exceeding room temperature to cryogenic conditions.

Wind-Tunnel Experimental Data

The 16-port M2 and M4 modules were installed for two separate tests in the National Transonic Facility at Langley Research Center. The ±15-psid M2 was installed to measure wall surface pressures, along with a conventional ESP module, during Q-probe Check-Standard Test 115. Pressure taps of both the wide-temperature and conventional ESP modules were located near each other for pressure measurement comparison purposes. The ±2.5-psid M4 was installed permanently in the arc sector of the NTF to measure seal pressures between the model and sting. The seal pressures are typically low, seldom reaching a differential level as high as 2.5 psi.

Table 2 shows the pressures and temperatures measured with the two modules. Each run corresponds to a different tunnel condition, for example, temperature, dynamic pressure, Reynolds number, etc. Port pressures measured with M2 module are consistent with those measured with the conventional module, the ports being located in close proximity to one another. This holds from temperatures exceeding room temperature to cryogenic conditions. Comparison pressure testing could not be conducted with the M2 module because of limited available space within the arc sector of the NTF. However, measured data matched anticipated results because pressures within this confined area remain relatively constant at low pressures during various testing conditions.

Conclusions

Multiport wide-temperature sensors have been developed at the NASA Langley Research Center to address some of the practical problems of current state-of-the-art electronically scanned pressure modules, namely, stabilization against zero drift, elimination of the heater box, and relief of the apparent strain problem across the sting. Modules are built using commercially available parts, which were chosen specifically for cryogenic operation, saving a considerable amount of design and construction costs. These cryogenically compatible components include aluminum nitride bonded to Kovar and lightly doped silicon pressure sensor die via adhesives such as Hysol 9309 and polyetheretherketon The modules have sustained numerous exposures to cryogenic temperatures providing reliable calibration and field test data. Total uncertainties in pressure measurement for the 16-port modules M2 and M4 and 64-port M5 modules are less than 0.1% full-scale output during unprotected exposure to temperatures ranging from 50 to −175°C (122 to −283°F).

A major benefit of the wide-temperature modules over conventional modules is the elimination of online calibration during experimental testing. These modules need only be calibrated once in the laboratory before a test. For instance, a wind-tunnel test need not be interrupted for calibration against the zero drift because temperature sensors located on each pressure port allow continuous update of the pressure calibration coefficients. The wide-temperature modules also provide real-time temperature readings at each port, a feature not available in existing ESP modules. Module functionality can be verified before, during, and after field testing via the use of check readings to compare port temperature and pressure measurements with those of an independent pressure transducer and thermocouple. This assures the user of the validity of the wide-temperature module's measurements and allows a check for any failure in the system. Also with the elimination of the heater box, the amount of wiring across the sting balance is reduced, diminishing the effects of the apparent strain problem. This removes the need to conduct separate wind-tunnel tests for balance and pressure measurements, which reduces effort, time, and cost.

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