THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th ST., New York, NY 10017

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TURBINE TESTING WITH HIGH-LINE, LOW DIFFERENTIAL PRESSURE MEASUREMENT

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ABSTRACT

The precise measurement of small pressure variations along and around the aerofoil stages of multi-stage machinery is error prone. This is attributable to high absolute pressures and low differential pressures. Using two high range transducers to measure pressure up and down stream of a stage, and calculating the differential by subtracting one from another introduces the error. This paper describes a method adapting low cost, low range differential pressure transducers to operate at line pressures above their burst pressure with improved accuracies. Multipoint and high-line zero calibrations, leak-checks and other troubleshooting configurations as well as a safe mode are possible.

INTRODUCTION

Calculating the slight difference between any two sensors at high pressures introduces an error based on the sensors used. The operation of pressure transducers over a small percentage of their range yields a larger error than transducers of similar full scale accuracy used over its entire range. Through the use of a patch panel architecture and on-line calibration techniques, a single differential pressure sensor operating at an elevated reference pressure can be fitted to an application where the measurement is distributed over the sensor's full range. As an example, when a 50 psi transducer is used to measure a ±50 psi differential at a line pressure of 300 psi, a 0.08 psid resolution is made possible. It would require two 400 psia absolute sensors with a ±0.013% level of uncertainty to match the resolution of the differential sensor's reading.

Shown in Fig. 1 is an example of the high-line method. Elevated reference pressures are supplied from the compressor and measured by an absolute secondary pressure standard with an uncertainty of ±0.01% F.S. Switching patch panels are pneumatically tied to the calibration and reference inputs of a pressure scanner. Scanners contain an array of pressure sensors and calibration valves designed to operate in four modes of test. Precautions must be followed to minimize the risk of damage to the low pressure sensor during the high-line scenario.

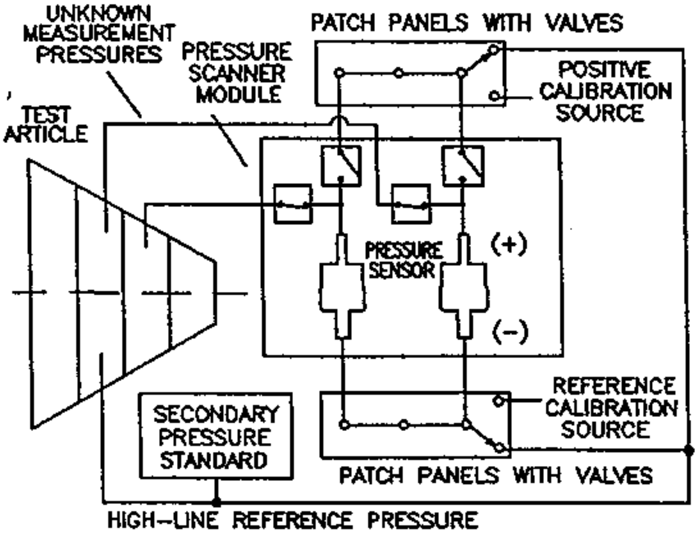

Figure 1 High-Line Test Example

PRESSURE SENSOR DESCRIPTION

The piezoresistive pressure sensor design contains a balanced Wheatstone bridge diffused into a silicon diaphragm acting as a barrier between the positive and negative side. Pressure changes the physical dimension of the diaphragm and bridge resistance, creating a condition that can be measured electronically. A trimmed resistor network added to the base of the sensor provides temperature correction over a range of 0° C to 59° C with a maximum thermal error of ±0.25% F.S.(Brysek, 1988) Measurement pressure, termed Px, is routed to the positive sensing side of the diaphragm with reference pressure directed to the opposite or negative side. Conventional testing methods subject the reference side to barometric or a known low pressure. An absolute pressure sensor has a sealed vacuum on the reference side.

Presented at the International Gas Turbine & Aeroengine Congress & Exhibition
Orlando, Florida — June 2-June 5, 1997

In high-line, low differential applications, pressures higher than the normal sensor value are introduced to both sides of the sensing diaphragm. A high-line zero shift is experienced when an equal high pressure applied to both sides of the sensor, Table 1. Strains greater than the original design levels are experienced in the casing of the transducer. These forces are coupled into the pressure sensing element causing the change in the zero output. The zero point can be recalibrated to correct the shift with only slight span errors. The key to this correction is switching and balancing the pressure differential across the transducer without large pressure transients.

PRESSURE RANGE	MAX REF BOTH SIDES	PERCENT MAX REF APPLIED				
		0%	25%	50%	75%	100%
2.5 PSID	40 PSIA	.01	.04	.07	.10	.14
5 PSID	100 PSIA	.01	.03	.05	.07	.10
15 PSID	100 PSIA	.01	.02	.03	.06	.07
50 PSID	250 PSIA	−.02	−.11	−.26	−.32	−.47
100 PSID	250 PSIA	0.0	−.17	−.34	−.39	−.55

Table 1 Zero Shift

PRESSURE SCANNER MODULE DESCRIPTION

The conventional electronic pressure scanner module consists of remotely piloted calibration valves close coupled to 16 sensors, a multiplexer, and an instrument amplifier. A PC based data acquisition system and an automated pressure calibration system with NIST traceable secondary standards are used to achieve an uncertainty of ±0.06% F.S. In 1994, an intelligent pressure scanner, the Digital Sensor Array, became commercially available. The DSA integrates RAM, 16 bit A/D converter, and microprocessor to achieve an accuracy of ±0.05% F.S. for 6 months. Sensors are characterized using 9 pressures in 10 temperature planes. A three dimensional look up table is generated and stored within the module's memory. Each sensor is driven with a constant current excitation source and temperature is monitored through changes in the voltage feedback of this supply. When an unknown pressure is introduced, the pressure-temperature look up table is used.(Matthews, 1995)(Greener, 1996)

The module's internal calibration valve supports 4 pneumatic configurations, read, calibrate, purge, and isolate mode. The normal configuration, no control pressure, is the read mode. In calibrate mode, the sensor must be isolated from the Px input and subjected to a calibration source, Fig. 2. Control pressure of 90 PSI is applied to CTL1 and CTL2 to close the normally open isolate valve and open the normally closed calibrate valve. To clean or purge the Px lines, calibrate mode is established with the calibration line open to atmosphere while CTLPRG is applied to release the purge source. By isolating the sensor from the purge path and allowing a vent path to the sensor, purge pressures much greater than the range of the sensor may be used without fear of damage. The isolate mode also supports sensor leak checks. The small volume trapped at each sensor can be monitored for decay.

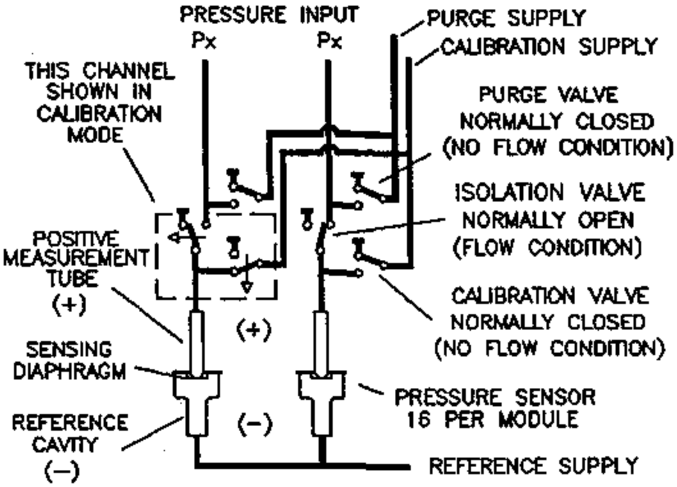

Figure 2 Pressure Scanner Logic Diagram

PATCH PANEL OPERATION

The patented patch panel can convert up to 16 modules for high-line use, Fig. 3.(Chalpin, 1994 patent). The possible configurations of the patch panel and scanner module are high-line differential read, Fig. 4, high-line zero calibration, Fig. 5, Multipoint calibration and ambient referenced testing, Fig. 6. The normal state of the patch panel and modules is high-line, low differential read. In this mode each scanner module's CAL and REF line is supplied with the elevated reference pressure, LINE REF. Since the module's calibration valve has normally closed valves on the CAL line at each sensor, switching to calibrate mode applies the LINE REF pressure to both the positive side as well as the negative side of the sensor, allowing a high-line zero calibration. Zero calibration coefficients are updated by the data system before the modules are returned to the read mode to resume differential testing. Switching the normally closed valve to support the zero calibration displaces an internal volume of 0.0105 cu.in. at the sensing diaphragm, resulting in a small pressure transients within the range of the sensor. If the CAL to REF short were to take place at the patch panel, away from the module and sensors, a pneumatic race and a large pressure differential would occur before equalization. Should a sizeable change in the reference level occur during the course of a test, as in a large change in engine speed, another high-line zero calibration is performed. Should a severe change in pressure occur, safe mode is established by switching to high-line zero mode, reducing the risk of sensor damage.

Multi-point calibration is restricted to engine idle or static conditions due to possible trapped high reference pressure in the patch lines. To support this type of calibration, the patch panel must first be switched with 24VDC. The modules are then placed in calibrate mode to apply precise CAL and REF pressures to the sensors. Sensors of the same pressure range can have two different high-line references when two patch panel arrays are used. They will be reunited for a multipoint calibration with a common 24VDC signal and common calibration sources. All unused module locations on the patch panel must be capped when not in use.

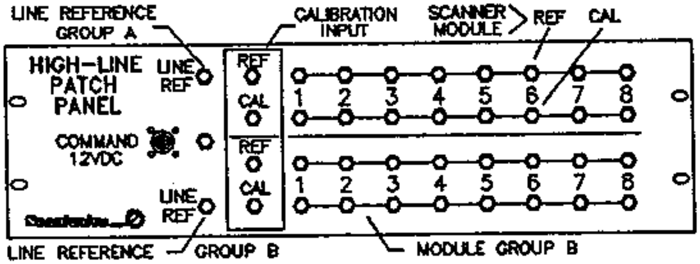

Figure 3 Patch Panel Front View

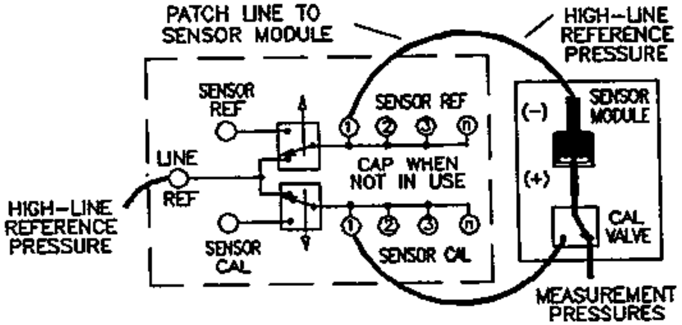

Figure 4 High-Line Low Differential Readings

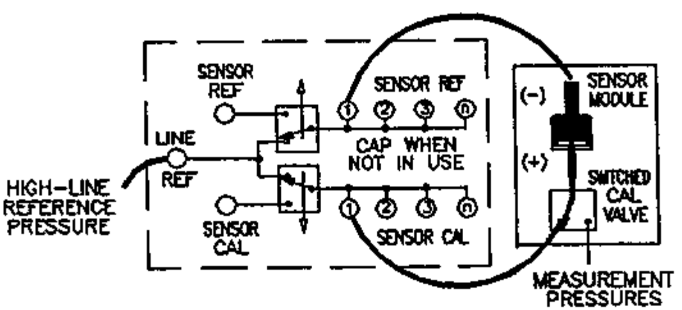

Figure 5 High-Line Zero Calibration

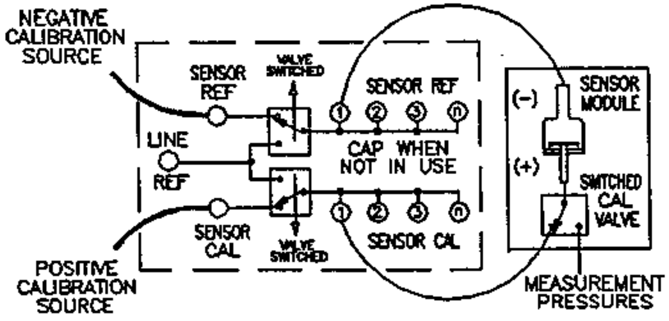

Figure 6 Multi-point Calibration

TEST SETUP

The purpose of the acceptance test was to observe sensor accuracy while operating close to the maximum allowable over-pressure limits of the reference cavity. Also, the zero shift was examined before and after a high-line zero calibration.

The measurement system under test contained 5 calibration control units (CCU), 1040 pressure sensors, and other necessary support equipment. The CCU supplied calibration pressure to the scanners and measured external pressures with an uncertainty of ±0.01% F.S. with redundant secondary standards. Calibration, ambient, and high-line reference pressure was measured and recorded. A high flow I/P servo valve regulated pressure for positive and negative calibrations. The CCU also switched high-line patch panels.

The conditions of test were stable and a random selection of pressure sensors from each range was used. Multi-point positive and negative calibrations were first performed on all the sensors in the system. With the scanners held in calibrate mode, a deadweight pressure with rated accuracy of 0.01% of reading was applied to LINE REF and REF(-) calibration source on the patch panel. In this configuration the deadweight pressure was applied to both sides of the sensor. High-line zero shifts were recorded and corrected. Next, the CCU was set to match the applied deadweight pressure, and the patch panel was switched. Known differential pressures were applied by regulating CCU output on the positive side of the sensors. The applied test points were the line pressure plus and minus 20%, 40%, 50%, 60%, 80%,and 100% of the sensor range. Ramp up, ramp down, and spot checks were performed. After reaching stability at each setpoint, sensor differential readings, CCU output, and ambient pressure readings were recorded. The absolute line reference pressure was calculated by adding the ambient pressure reading to the deadweight setting.

DATA ANALYSIS

The following test steps and equations were used as part of the acceptance test procedure.

1. Calculate absolute "Sensor Error $_j$" for every measured channel$_j$:

$$\text{Sensor Error}_j\,[\text{psi}] = P_{SENSOR\,j} - [P_{CCU(i)} - (P_{DH} + P_{CCU(1)})] \quad (1)$$

2. Calculate "Sensor Error" relative to fullscale of sensor range :

$$\text{Sensor Error}_j\,[\%\ \text{F.S.}] = 100 * \text{Sensor Error}_j\,[\text{psi}] / \text{Sensor Range} \quad (2)$$

3. Calculate Average of Errors for every data set :
   Set 1 channel 1-43
   Set 2 channel 22-64

4. Calculate standard deviation for every data set expressed in [psi] and [% F.S.].

5. Calculate the difference between same channels (duplicate readings) of both data sets (channel 22-43) defined as stability.
6. Determine maximum and minimum value of each data set expressed in [psi] and [% F.S.] and record channel number.
7. Calculate spread of data as the difference between Maximum and Minimum expressed in [% F.S.].
8. Calculate the difference between the CCU setpoint and the CCU actual value and express in [% F.S. CCU] and [% F.S. Sensor]. If the [% F.S. CCU] deviation is greater than 0.01%, the test point was unstable or the operator read a false value. This condition occurred 5 times out of a possible 63.
9. Determine number of occurrence of a limit condition (Min or Max) on every channel. Examine all channels with more than 2 limit conditions for faulty sensors.

Error Analysis

The absolute and relative error analysis followed the equations below:

Absolute Sensor Error :

$$d(\text{Sensor Error})_{abs} = |dP_{SENSOR}| + |dPccu| + |dP_{DH}| + |dP_{CCU(1)}| \quad (3)$$

Relative Sensor Error :

$$d(\text{Sensor Error})_{rms} = (|dP_{SENSOR}|^2 + |dP_{CCU}|^2 + |dP_{DH}|^2 + |dP_{CCU(1)}|^2)^{0.5} \quad (4)$$

The largest deviation from the average of the readings was taken as the accuracy measure for the sensors group. The absolute value of the maximum deviation around the average of a sensor range group is shown in Figs. 7-11. The ambient conditions of the test are indicated. All channels performed within the limits except for the 15 psi range. This range was retesting in a later application without outstanding error. A joint histogram for the sensor readings for all the setpoints together is shown in Fig. 12. The histogram based deviation values were used to determine the standard deviation for the two datasets, and to calculate 3σ of 0.01 % F.S. shown in Fig. 9 as an additional limit.

Continued tests have been conducted on a reinforced sensor housing design. The over pressure limit was increased from 250 psi to 500 psi on 50 and 100 psi sensors. High-line zero corrections maintained a 0.08% F.S. accuracy on the test batch. A more expensive version of the sensor capable of withstanding 1000 psi on the sensor base pins was available, but not used due to its availability and increased cost

Field testing has demonstrated large fluctuations in measurement and line reference pressures. Resolution can be greatly refined with multiple sensors measuring the same differential. An example of this multi-read approach employed at BMW Rolls-Royce used 500 psi, 100 psi, 50 psi, and 15 psi sensors to measure a single differential pressure. The system has shown an ability to measure the slow transients found during engine runup and rundown maneuvers and the relative behavior between measurement points during pressure surge conditions. (Chalpin and Labanei, 1994)

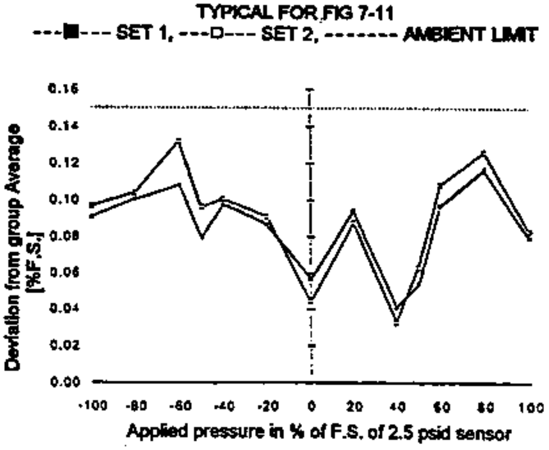

Figure 7 Deviation of 2.5 psid sensors from group average

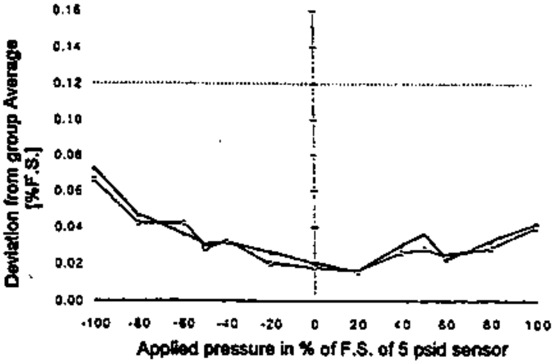

Figure 8 Deviation of 5 psid sensors from group average

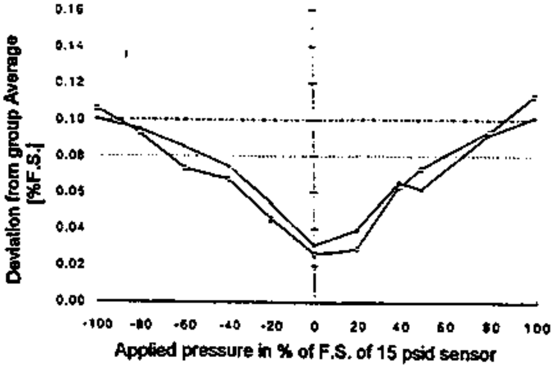

Figure 9 Deviation of 15 psid sensors from group average

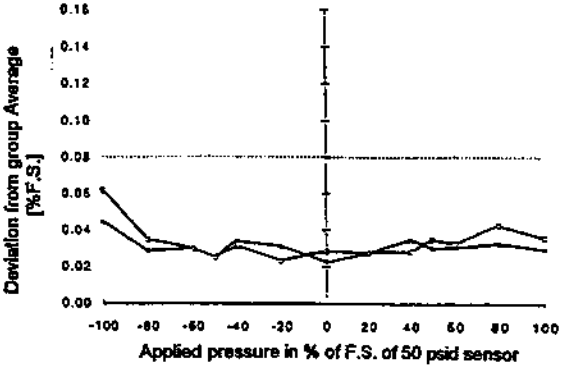

Figure 10 Deviation of 50 psid sensors from group average

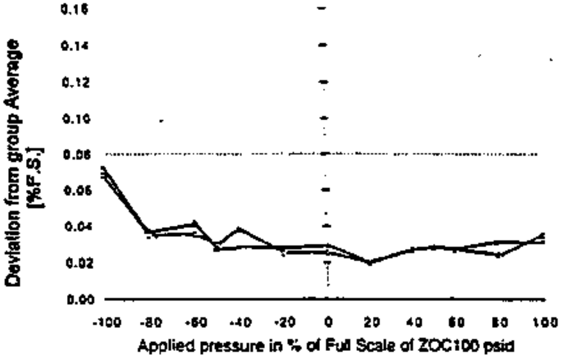

Figure 11 Deviation of 100 psid sensors from group average

Figure 12 Error distribution of 15 psid sensors

CONCLUSION

Examples of the measurement system described in this paper have demonstrated high reliability and safety in the engine test industry. Adapting equipment for use with elevated line pressures can optimize test results. Through a patching architecture, patch panel valves, and sensor calibration valves, the basic function of read, calibrate, and purge have been retained. A high-line zero correction has been found to be essential and has been made possible by minimizing the change in volume during its application. This technique typically improved differential pressure measurement accuracy in high line pressure applications by a factor of 6 over an ambient referenced approach. A 0.08%F.S. level of uncertainty has been demonstrated .

ACKNOWLEDGEMENT

The author wishes to acknowledge all those involved at the Scanivalve Corp for their help and input.

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