CALIBRATION SYSTEM FOR SMART PRESSURE SENSORS

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Abstract: *A modular design of high throughput calibration system for smart pressure sensors is presented. Based on obtained results, the capacity of calibration system is 250.000 sensors per year. In addition, a novel digital thermal compensation technique is introduced, using system self-learning capability for optimization of calibration parameters. Calibration results on a run of 16568 sensors show reduction of temperature error over entire temperature range from initial 0.15%FSO/°C to 0.05%FSO/°C.*

Sistem za umerjanje tlačnih senzorjev

Kjučne besede: inteligentni senzor, digitalna temperaturna kompenzacija, umerjanje, tlačni senzor.

Izvleček: V prispevku je predstavljena modularna zasnova sistema za umerjanje tlačnih senzorjev. Na osnovi prvih testov je kapaciteta sistema 250.000 senzorjev letno. Predstavljena je izboljšana metoda digitalne temperaturne kompenzacije senzorjev preko optimizacije parametrov umerjanja na osnovi zmožnosti samostojnega učenja sistema. Rezultati umerjanja na 16568 senzorjih kažejo na zmanjšanje temperaturne napake preko celotnega uporabnega temperaturnega področja s prvotnih 0.15%FSO/°C na 0.05%FSO/°C.

1. Introduction

Smart sensors represent an attractive approach in sensor applications for industry automation due to their adaptability, achieved by means of digital signal processing. Smart sensors are generally integrated with signal conditioning circuits. Signal conditioning circuits are necessary to adjust the offset voltage and span, compensation of temperature effects on both offset voltage and span, as well as to provide an amplified signal. Several piezoresistive pressure sensors with integrated signal conditioning have been presented over the past few years /1/. Temperature compensating methods for these sensors are based either on analog, digital or mixed approaches. Analog approach usually comprises an amplifier with laser trimmable thin film resistors /2,3/ or off-chip trimmable potentiometers /4,5/, to calibrate the sensor span and offset voltage and to compensate the sensor temperature drift. Analog compensation techniques are relatively slow, inflexible and cost-ineffective. In digital approach, sampling for raw digital pressure and temperature values is first performed, followed by evaluation of the output digital values via transfer polynomials, and converting the computed pressure value to according analog voltages. Mixed approach retains strictly analog signal conversion path, while presetting the offset and span of operational amplifiers by digital means /6/.

Low cost advanced differential sensor signal conditioners /6,8/ can accommodate nearly all bridge sensor types with signal spans from 1 mV/V up to 275mV/V. Sensor's temperature dependence can be compensated by temperature sensing element, which can be either on-chip (usually an additional bridge resistor) or off-chip (thermistor, internal diode or external diode). The output can be adapted either to analog voltage output (0...5V) or current output (4...20mA) as well as digital outputs: PWM, I^2C, SPI or OWI (one-wire interface). Sensor signal conditioner can also be transformed into a simple controller by means of digital outputs which can trigger an actuator. Output resolution can be selected from 10 bits to 15 bits, with the highest sampling rate up to 3.9kHz.

The excitation of sensor comprises ratiometric voltage (externally regulated), constant voltage (on-chip) or constant current (on-chip). Sensor connection fault is detected instantaneously by comparison of the range of sensor input voltage. Variations on the common mode voltage of the sensor are monitored permanently - this enables monitoring of sensor aging. Extended temperature operation enables a wider application range in automotive industry.

However, these sensor signal conditioner features cannot be turned into an advantage without a dedicated calibration process.

Design of the actual calibration system itself is smart since the system represents a digitally-controlled closed loop, capable of self-learning. Closed loop design enables the optimization of calibration procedure parameters as well as of mentioned smart sensor properties. On the sensor level, calibration system contains orthogonalization of input quantities and full-scale output (FSO) optimization. The latter is the basis of the pre-calibration, which is performed upon entire lot of calibrated sensors. Furthermore, the system contains dedicated statistics software, which gives a detailed insight into smart sensor acquired data and calibration coefficients. The obtained statistical data provide closed loop feedback parameters, while at the same time represent the input data for failure analysis.

2. Calibration setup

Figure 1 shows a general setup of smart sensor calibration system. The setup consists of sensor calibration station, central database server and post-calibration sensor test systems. Calibration station performs the calibration procedures upon DUC (devices under calibration). Central database server gathers data from distributed databases which reside locally in every calibration station. The server performs analyses upon gathered dataset and provides the "intelligence" of the system. Finally, post-calibration sensor test subsystems provide means for evaluation of sensor properties during final testing such as thermal cycling and sensor packaging.

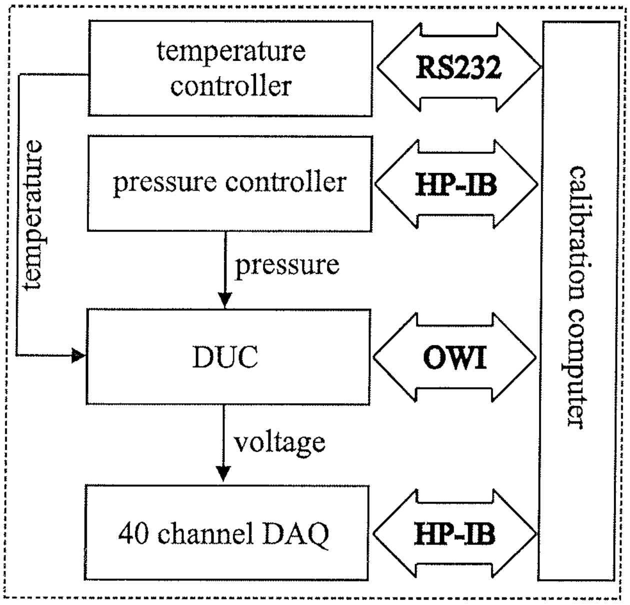

Fig. 1: Smart pressure sensor calibration system block diagram

2.1. Data acquisition

Calibration procedure starts with the acquisition of calibration points. The calibration points can be ordered into an *arbitrary* calibration scenario. Number of calibration points is chosen between 5 and 8, depending on the degree of evaluation polynomial . Chosen degree is a tradeoff between desired calibration accuracy and duration of entire acquisition. The acquisition stage of calibration procedure follows the numbered order of calibration points starting at least pressure and temperature, as shown in Figure 2.

Based on tests performed, among all 7-point calibration scenarios, the one presented in Figure 2 yields most accurate results if the middle temperature point is set at room temperature.

Calibration accuracy is depending primarily on the number of calibration points at a given temperature, while the acquisition time is primarily dependent on the temperature stabilization at a given calibration point. Calibration time

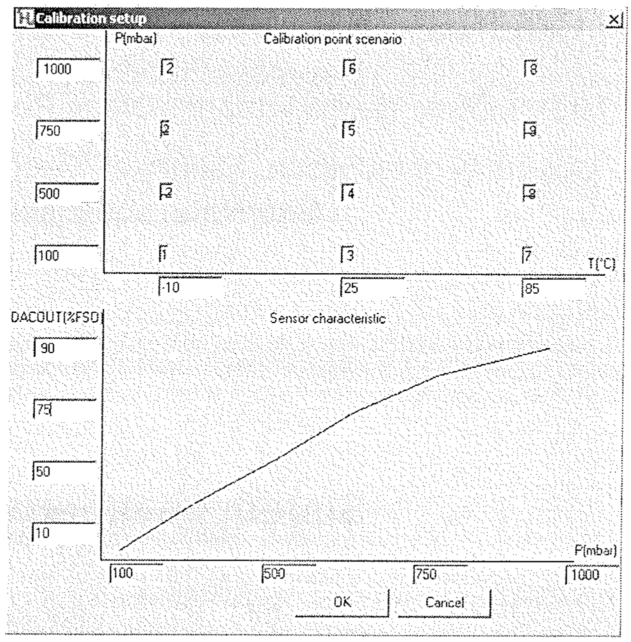

Fig. 2: Calibration scenario

can be shortened by means of zone calibration i.e. measuring entire sensor production lot at a constant temperature at all pressure points. This principle can be further enhanced by introduction of Peltier element temperature controller that was reported elsewhere /7/.

Each of calibration points consists of pressure controller set point (*p*), raw pressure sensor output (Z_P) and raw temperature sensor output (Z_{T1}) and a D/A converter output from signal conditioner (*DACOUT*).

2.1.1. Sensitivity compensation algorithm

The system is able to match sensor sensitivity to the desired measurement range. The system initially presets the lowest sensitivity on all sensors and applies full-scale pressure. Sensor response is read. If the read raw pressure conversion result is within ASIC D/A converter limit interval, the sensitivity is increased by selecting higher setting of programmable gain amplifier in sensor ASIC and the output is measured again. When the gain setting is too high, the output reads maximum D/A converter output value ($FFFF_{16}$). The highest gain setting is selected, that yields the maximal output.

By measuring uncompensated pressure sensor offset and its full-scale output, the measurement range of the signal conditioner ADC is adapted resulting in its maximum bit yield. Typically 99% ADC bit yields are achieved. This reduces the importance of uncompensated pressure sensor sensitivity and offset. Low sensitivity can be improved by setting the programmable gain amplifier (*PGA*) in the signal conditioner, while shifting the entire ADC measurement range compensates high offset voltages. This enables the use of sensors whose offset can be greater than its signal, as is the case with very low-pressure sensors.

2.1.2. D/A converter thermal response adjustment

Signal conditioner's 11-bit D/A converter response features large chip-to-chip differences when used in the temperature range (typ. ±50 levels at 85°C) as can be seen from rightmost histogram bar width in Figure 3. Figure 3 shows the D/A converter readout histogram at calibration point 7 (85°C). Number of calibrated smart pressure sensors was 16568. Histogram bars on the left represent the number of sensors, which can be considered faulty due to their inadequate D/A converter response at calibration temperature.

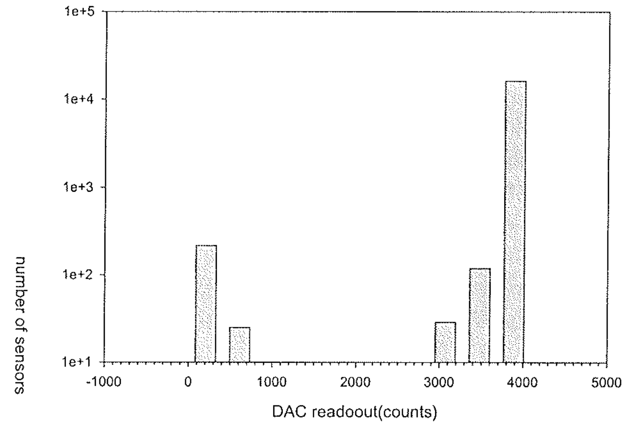

Fig. 3: Signal conditioner D/A readout at calibration point 7 (pressure=1000mbar, T=85°C)

Deviations of D/A converter's response over temperature range, shown in Figure 3, are compensated by a dedicated D/A calibration mechanism, which provides means for minimization of sensor specific errors (e.g. calibration point to calibration point errors) as well as system specific errors (e.g. signal conditioner chip to chip errors). The D/A calibration mechanism is based on the successive approximation method, where every sensor's D/A output is connected to 40-channel DAQ (data acquisition) system as indicated in Figure 1.

This arrangement of instruments forms a closed regulation loop, which tests all 11 bits in the sensor's D/A output according to successive approximation algorithm. After the desired voltage output is achieved, the result is normalized to DAC resolution and stored for further computation of calibration coefficients. This is performed in such a manner that the desired transfer characteristic is obtained at every temperature calibration setpoint.

The speed of closed regulation loop was improved with implementation of a dedicated 40 channel SAR (successive approximation register) and a precision comparator.

2.2. Orthogonalization of calibration points

Next step in calibration is the orthogonalization of acquired calibration points. Calibration points are orthogonalized along the temperature axis only, since pressure controller provides satisfactory pressure setpoint precision. Orthogonalization is included in the process of calibration points acquisition and is achieved at each setpoint by means of digital filtering, where a simple averaging filter is used to stabilize temperature within desired temperature gradient limits. The main advantage of this approach lies in the location of temperature measurement, which is located in the device under calibration (i.e. on the sensor ASIC or on the pressure sensor membrane). Since temperature controller shown in Figure 1 is left out of temperature stabilization process, this method detects faulty sensors by means of device under calibration temperature stabilization timeout, which is currently set at 20s.

2.3. Calculation of calibration coefficients

Pressure sensor's signal conditioner uses two-dimensional rational polynomial for pressure calculation /8/, which enables correction of nonlinearities up to the third order.

$$Y=\frac{Z_P+c_0+2^{-(R-1)}c_4 Z_{T1}+2^{-2(R-1)}c_5 Z_{T1}^2}{c_1+2^{-(R-1)}c_6 Z_{T1}+2^{-2(R-1)}c_7 Z_{T1}^2}$$
$$p=Y(1-2^{-15}c_2-2^{-15}c_3)+2^{-15}c_2 Y^2+2^{-15}c_3 Y^3 \qquad (2.1)$$

Where c_0 through c_7 are calibration coefficients of pressure sensor, p is the normalized DAC output resulting from successive approximation algorithm, described in section 2.1. The value of p is in interval [0..1). Z_P is an offset corrected raw A/D readout from pressure sensor and Z_{T1} is a chip-offset corrected raw A/D readout from temperature sensor. Note that the actual temperature and pressure set points have only indirect significance to further calibration process, since the calculation polynomial not dependent on them. More important is the temperature and pressure stability at the desired calibration setpoint.

The resulting pressure output of the sensor can be adapted to various orders of calibration, ranging from linear to third-order nonlinearity calibration. Hence, a wide variety of algorithms are implemented into calibration coefficients calculation.

If c_2 and c_3 coefficient (2^{nd} and 3^{rd} order nonlinearity) are set to zero, the remaining coefficients can be determined by solving a system of linear equations. However, this system is resolved by computing a Vandermonde matrix, which is generally ill conditioned. This can lead to large deviations from sensor characteristic. Generally, a sensor characteristic using the equation is evaluated by full set of coefficients or at least with c_3 set to zero. In this case a set of nonlinear equations must be resolved. This can be achieved by implementing several iterative methods such as Newton-Raphson, Wegstein and Broyden /9/. Special attention has been devoted to use of Broyden method, since it does not include calculation of Jacobian matrix at each iteration. The latter can be singular, which can fail the progress of iterations.

Both approaches have been combined into automatic algorithm for determination of a complete set of coefficients. Initial guess, prerequisite for later iterations, can be evaluated by setting c_2 and c_3 to zero. This yields an exact first-order solution, which serves as initial guess input into Broyden algorithm. The higher order nonlinearities (c_2 and c_3) have generally small values (or high for bad sensor). If a Broyden algorithm yields c_2 and c_3 coefficients zero, an exact solution is used. Calculation is evaluated versus all calibration points and a combined standard uncertainty is calculated according to RSS (square root of the sum-of-the-squares) method. In order to avoid large deviations from sensor characteristic, the Vandermonde system is solved and resulting coefficients are validated against preset sensor type limits, which are stored in the database.

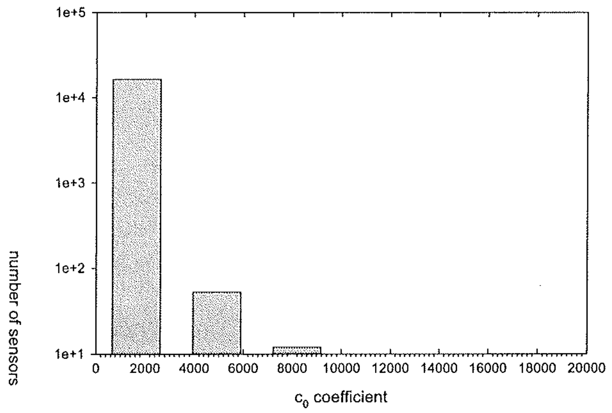

Fig. 4: Coefficient c_0 limit distribution

2.4. Validation of calibration coefficients

A test lot of sensors is calibrated repeatedly, until sufficient amount of data is gathered. Each of coefficients c_0 through c_7 are then plotted into corresponding histogram. Figure 4 shows the distribution of c_0 coefficient value for 16568 sensors. Coefficient validity interval in Figure 4 is initially set at 16-bit integer range, so the entire dataset is plotted. After calibration of test-lot, the interval is subsequently narrowed to [0..3000] as shown in Figure 4. The validity interval could be narrowed more, but as validity criteria for all coefficients (c_0..c_7) are superimposed, this is more than sufficient. This iterative evaluation of coefficients was implemented into an algorithm for automatic setting of calibration limits, which represents the basis of system self-learning. Human intervention is required only until a sufficient amount of sensors are calibrated. During that initial phase system is learning what criteria denote a good sensor. After that, the system autonomously makes more and more sharp distinctions between good and bad sensors.

2.5 Storage into database

Smart sensor's database record consists of 39 fields, which can be divided into several groups. Calibration setup related information, describing record number, timestamp of calibration and ISO63 date code for a lot as well as sensor position in calibration system and calibration identification number. Smart sensor calibration settings are ASIC configuration word, calibration validity interval and calibration coefficients c_0..c_7. Calibration point related settings such as values of raw pressure and temperature sensor response and results of D/A converter calibration. The contents of records enable complete traceability of calibrated sensors and statistical processing of calibration effectiveness.

3. Measurements and results

The calibration procedure has been implemented upon a series of 16568 automotive sensors. Temperature selectivity with typical lower and upper sensor error bands are presented in Figures 5, 6 and 7, each corresponding to selected temperatures -10°C, 25°C and 85°C, respectively. Results are plot within minimum and maximum admissible temperature error bands according to /9/. Temperature error is calculated as a normalized difference between ideal MAP sensor response and the calibrated response. Typical temperature selectivity of raw pressure sensor 0.15%FSO/°C has been reduced to 0.05%FSO/°C with the use of digital temperature compensation. Raw, uncompensated sensors without signal conditioner and digital temperature compensation have temperature selectivity typically 2.5%FSO/°C, around -10°C.

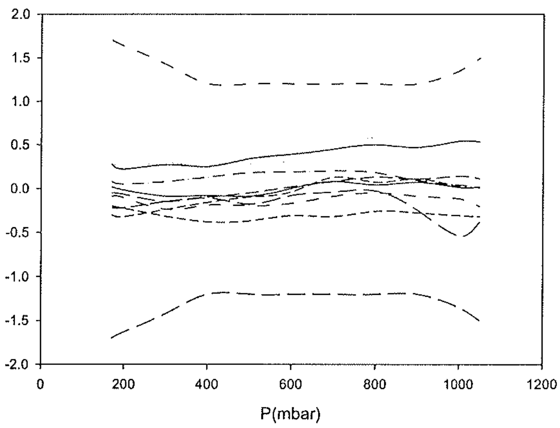

Fig. 5: Temperature selectivity at -10°C

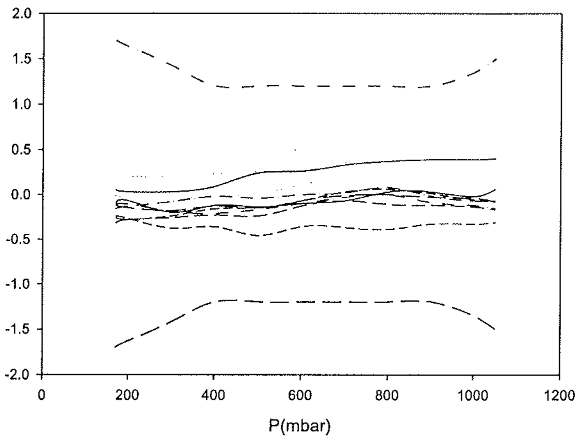

Fig. 6: Temperature selectivity at 25°C

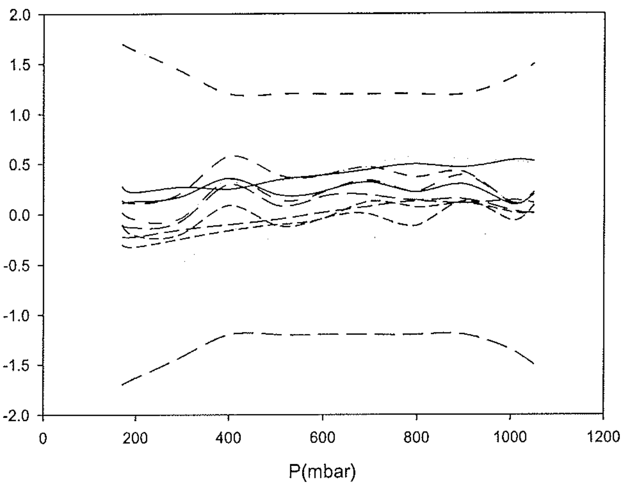

Fig. 7: Temperature selectivity at 85°C

4. Conclusion

Smart pressure sensor calibration system has been designed, fabricated and tested. Sensor calibration setup and calibration software have been tested on a production lot consisting of 16568 Manifold Absolute Pressure sensors. Calibration results show significant improvements in sensor temperature response, achieved by means of digital temperature compensation approach presented in this paper.

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