CALIBRATION YIELD IMPROVEMENT AND QUALITY CONTROL OF SMART SENSORS

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Key words: smart sensor, failure analysis, digital temperature compensation, adaptive calibration

Abstract: Concept and realization of an adaptive closed loop system for calibration of smart pressure sensors is presented. Closed loop concept enables the analysis of sensor properties and optimization of calibration procedure. System quality control mechanisms enable automatic sensor classification. Statistical data enable sensor quality information for failure analysis and quality control of calibrated sensors. System enables optimal digital temperature compensation based on sensor data acquisition and digital evaluation of sensor characteristic. Proposed digital temperature compensation reduces typical sensor temperature error after calibration to 0.05%FS, based on calibration of a lot with 34422 MAP sensors. Calibration yield was improved from 93.7% to 96.8%, achieved by adaptive evaluation of sensor properties such as offset and sensitivity. Proposed calibration system shortens the total time for calibration of smart sensors, by implementing the input testing of sensor parameters as well as final testing of the calibrated sensors, achieving calibration time of 42 seconds per sensor in system current calibration capability.

Izboljšava izplena umerjanja in nadzor kakovosti pametnih senzorjev

Kjučne besede: pametni senzor, analiza napak, digitalna temperaturna kompenzacija, adaptivno umerjanje

Izvleček: V prispevku sta predstavljeni zasnova in realizacija adaptivnega zaprtozančnega sistema za umerjanje pametnih senzorjev tlaka. Predstavljeni zaprtozančni koncept omogoča analizo lastnosti senzorjev in optimizacijo postopka umerjanja. Mehanizmi za nadzor kakovosti senzorjev omogočajo avtomatsko klasifikacijo umerjenih senzorjev. Pridobljeni statistični podatki sistema za umerjanje nudijo vpogled v kvaliteto izdelanih senzorjev, obenem pa omogočajo analizo napak umerjanja senzorjev. Sistem zagotavlja optimalno digitalno temperaturno kompenzacijo na osnovi digitalnega opisa senzorske karakteristike. Na podlagi rezultatov umerjanja serije 34422 MAP senzorjev smo dosegli tipično temperaturno napako senzorjev 0.05%FS. Izkoristek umerjanja se ob uporabi zaprtozančne strukture sistema za umerjanje poveča z 93.7% na 96.8%, kar smo dosegli z adaptivnim ovrednotenjem senzorskih lastnosti kot sta ničelna napetost in občutljivost. Predlagana izvedba skrajša čas umerjanja na 42 s na senzor pri trenutni kapaciteti sistema, kar smo dosegli z vključevanjem testnih parametrov senzorja v zaprtozančno strukturo sistema za umerjanje.

1 Introduction

Smart sensors represent an attractive approach in sensor applications due to their adaptability, achieved by means of digital signal processing. Sensor adaptability can be further turned into a major advantage by introduction of smart calibration systems.

Smart sensors are generally integrated with signal conditioning circuits. Signal conditioning circuits are needed to adjust the offset voltage and span, for compensation of temperature effects of both offset voltage and span, as well as to provide an appropriately amplified signal. The proposed approach is based on a special case of smart pressure sensors, but the developed calibration system is generally applicable for any kind of smart sensor.

In manufacturing of modern electronic devices achieving and maintaining high yield level is a challenging task, depending primarily on the capability of identifying and correcting repetitive failure mechanisms. Yield enhancement is defined as the process of improving the baseline yield for a given technology generation from R&D yield level to mature yield. Yield enhancement is one of the strategic topics of ITRS (International Technology Roadmap for Semiconductors) /1/. This iterative improvement of yield is based on yield learning process, which is a collection and application of knowledge of manufacturing process in order to improve device yield through the identification and resolution of systematic and random manufacturing events /2/. Yield improvement process will consequentially increase the number of test parameters and hence the calibration system complexity. One of advantages of increasing system complexity is the ability to integrate the input testing processes and output final testing processes into the calibration process itself, thus shortening the total time for calibration.

Several types of smart sensors with integrated signal conditioning have been presented over the past few years /3, 4/. The calibration processes and 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 /5, 6/ or off-chip trimmable potentiometers /7, 8/, to calibrate the sensor span and offset voltage and to compensate for their 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 an evaluation of the output digital values via polynomials for describing sensor characteristic, and finally converting the computed pressure values to according analog voltages /9, 10/. Mixed approach retains strictly the analog signal conversion path, while smart sensor offset and span are adjusted by setting of operational amplifiers by digital means /11/.

This paper will focus on the problem of adaptive calibration any quality control of smart sensors with digital temperature compensation, which is one of the most time consuming steps in sensor production. In order to advance calibration system performance, smart calibration system is conceived as a digitally controlled closed loop system capable of adaptive learning. Presented concept of calibration system is directly implemented in the iterative yield enhancement process in the production of piezoresistive pressure sensors for automotive applications. The calibration system operation and quality control is illustrated on the case of Manifold Absolute Pressure (MAP) sensors. The emphasis will be on MAP sensors, although the proposed approach can be implemented in other fields of application.

2 Calibration procedure

Main calibration procedure starts with measurement of sensor coarse gain and offset and optimization of sensor parameters to the sensor signal conditioner front end stage. After initial optimization procedure the calibration conditions are set according to calibration scenario. Raw sensor readouts of supplied reference quantities are acquired at each calibration point. After acquisition, digital description of sensor characteristic is evaluated and the results are stored back to sensor. A detailed description of calibration procedure is given in /12/. Calibration scenario defines the sequence of reference quantities, which are applied to sensors under calibration. In case of temperature compensation of pressure sensor, the reference quantities are pressure and temperature. Minimal number of calibration points is 4. This is defined by using the lowest (i.e. linear) degree of polynomial for sensor characteristic description /9, 10/ in the temperature and pressure direction. Maximal number of calibration points is primarily limited by total calibration time. In case of pressure sensors, both calibration axes consist of three calibration points, thus enabling compensation of second order nonlinearity in both directions, as depicted in Figure 1. Maximal number of calibration points for pressure sensor can cover nonlinearities up to third order in pressure direction. Actual number of calibration points is a compromise between calibration precision and total calibration time. To shorten total calibration time, the slower settling axis should be used for definition of the calibration points order. In case of MAP sensor, the temperature axis defines the calibration scenario.

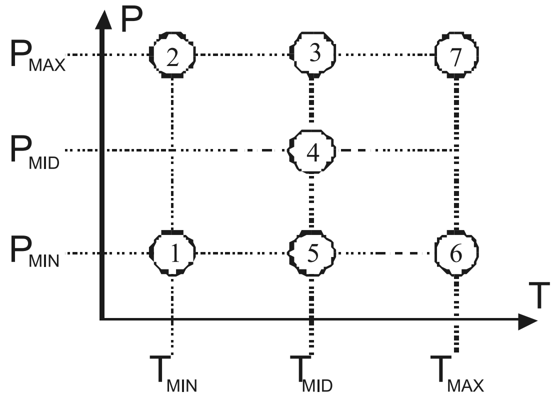

Fig. 1: Calibration scenario.

2.1 Evaluation of parameters at calibration input

Calibration scenario enables the assessment of essential input parameters to calibration procedure, which enables early fault detection on sensors before they enter actual calibration process. Input parameters comprise the properties, such as offset, sensitivity and nonlinearity of uncompensated sensing element (e.g. pressure sensor). Evaluation of such properties is essential for determination of decision criteria for adaptive concept of calibration system.

2.1.1 Pressure sensor sensitivity

Sensor sensitivity can be evaluated at three temperatures. At each temperature, sensitivity is obtained as a difference of pressure sensor voltage response, normalized to corresponding pressure change. Temperature coefficient of pressure sensor sensitivity is evaluated as a difference between sensor sensitivities at two temperature endpoints (T_{MIN} and T_{MAX} in Figure 1). Resulting difference is normalized to temperature corresponding temperature change.

2.1.2 Pressure sensor offset

Sensor offset at room temperature can be evaluated at calibration point 5 as T_{MID} in Figure 1 is normally set at room temperature. Digital sensor offset readout is transformed into voltage according to analog to digital ASIC stage parameters /9, 10/.
Temperature coefficient of sensor offset is estimated from endpoint calibration points offset values normalized to corresponding temperature difference. In presented calibration scenario the calibration endpoints for estimation of temperature coefficient are marked 1 and 6. Obtained result is recalculated to temperature response at 0°C.

2.1.3 Pressure sensor nonlinearity

Nonlinearity is calculated by using calibration points 3, 4 and 5 in Figure 1. Nonlinearity is evaluated as a difference of midpoint pressure response at calibration point 4 from ideal linear sensor response, formed by calibration points

3 and 5. Resulting difference is normalized to calibration span, defined by calibration points 3 and 5. For practical purposes, evaluation of sensor nonlinearity is performed only at room temperature.

2.1.4 Temperature sensor response

Temperature sensor response is evaluated at three different temperatures (T_{MIN}, T_{MID} and T_{MAX}). Acquired data can be used for calibration of auxiliary temperature measurement channel calibration. Temperature sensor offset, sensitivity and nonlinearity can be evaluated from data acquired at calibration points 1, 5 and 6 in Figure 1. Validity of temperature sensor response can be checked at calibration points 2, 3 and 7 in Figure 1.

2.1.5 Insertion of excess test points

In order to avoid additional final testing procedures, further test points can be inserted into calibration scenario, depicted in Figure 1. Raw sensor response is acquired at test points. Acquired data is not used in calculation process of sensor characteristic parameters. Test points are inserted along a faster settling axis. In case of proposed calibration scenario in Figure 1, this is the pressure axis.

Introduction of additional test points imposes a lesser delay in comparison to time required for separate final testing procedure. Moreover, by introduction of additional test points, a more accurate, instant evaluation of total calibration error can be performed immediately after calibration. Total calibration error is essential figure of calibration process quality and gives a direct insight to sensor classification.

2.2 Evaluation of parameters at calibration output

Calibration output parameters are directly related to compensation of unwanted dependencies. In case of presented MAP pressure sensor this is the temperature compensation. Temperature error is evaluated at every calibration point immediately after evaluation of calibration coefficients. It is calculated by calibration computer as a difference between output of ideal characteristic of MAP sensor and the ASIC simulation of sensor characteristic. Total temperature error comprises RSS (root square of sum of squares) of temperature errors, calculated at every calibration point. Total calibration error is comprised of RSS sum of total temperature error and the combined standard uncertainty for output analog stage, if the sensor features analog output.

The ASIC features 16 bit integer arithmetic, therefore a rounding error, which occurs during coefficients calculation, is further minimized by evaluation of total temperature error on all rounding combinations. Rounding combination of calibration coefficients, that yields minimal temperature error at each calibration point is written to ASIC.

2.3 Failure analysis

Failure analysis is used for detection of cause of calibration failure upon calibrated sensors as well as establishing the system related calibration failures. The failure analysis can be used instead of separate input control to calibration process. Therefore, failure analysis procedures must distinguish between system causes of failure and sensor failures and signal conditioner failures. Furthermore, sensor failure causes may be introduced during manufacturing process or are a direct consequence of failed sensor. Sensor related failures can be divided into several categories:

2.3.1 Sensor related causes of failure

Inadequate response of pressure sensor response failure is determined prior to calibration process. It is evaluated by calculating the sensitivity of sensor - if the sensitivity is zero, or out of sensitivity validity interval, then this error is signaled and the sensor is discarded. Excess nonlinearity is determined by calculating the difference of midpoint pressure response and the midpoint derived from ideal linear sensor characteristic, passing through endpoints. If the nonlinearity exceeds more than 2%, the error is signaled.

2.3.2 ASIC related causes of failure

Inadequate response of temperature sensor response can represent a cause of calibration failure. In case of presented MAP sensor calibration, this type of error is attributed to signal conditioner circuit, since the temperature sensor (diode) is located within ASIC.

Another type of calibration failure can be attributed to calibration polynomial coefficient clamping, when the solution of calibration coefficients exceeds the interval of 16 bit integer values. This error can be found after acquisition of raw sensor values, when the sensor characteristic is evaluated.

2.3.3 Calibration system related causes of failure

Inadequate temperature stabilization error can be determined by comparing orthogonality of temperature calibration points. Whenever the corresponding temperature calibration points differ more than 10%, this error is signaled.

Calibration of sensor output stage failure can be detected by comparing the analog to digital values at corresponding calibration points, which have the same output response. If the output values differ more than 10%, this error is signaled. This is a system cause of failure, because the process of output calibration was interrupted.

The sensor output value must not be clamped to maximum at any calibration point. If an error stays clamped to maximum, this can be attributed to signal conditioner failure. However, this error may also indicate improper sensor connection.

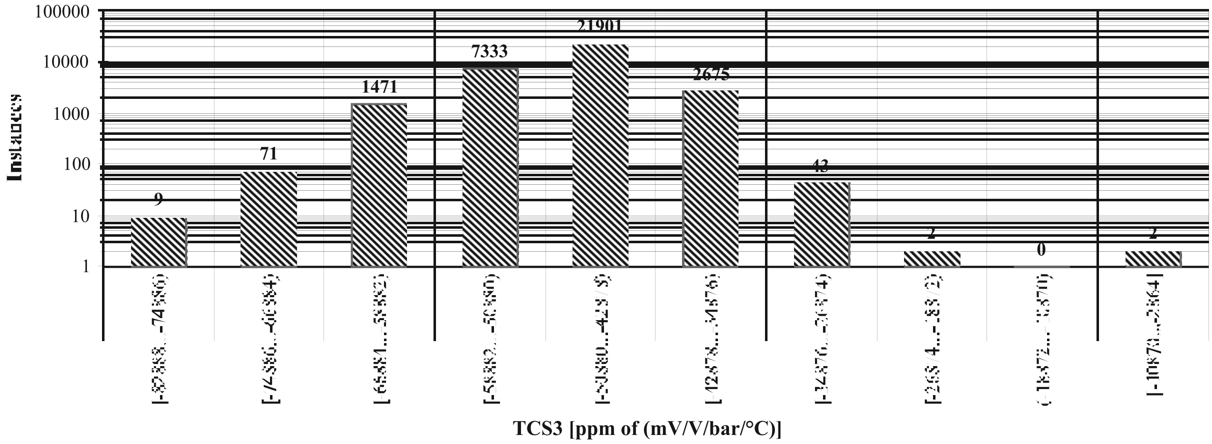

Fig. 2: Input temperature coefficient of sensitivity.

3 Results

Presented results are based on 34422 calibrated manifold absolute pressure sensors. Results comprise analysis of operation of two calibration systems. Input sensor properties investigation is presented on ZMD31020 signal conditioner /9/. Output properties analysis and failure analysis was performed on ZMD31050 signal conditioner /10/.

3.1 Input properties of calibrated sensors

Based on described statistical analysis of sensor properties a histogram, which sets the sensor validity interval was plot. The input temperature coefficient of pressure sensitivity at calibration point 3 in Figure 1 is in the range of /-8% ... -0.2%/, which represents a insurmountable span of temperature coefficients, if analog calibration was to be made upon such sensors.

Average value of input temperature coefficient of pressure sensitivity in the histogram, depicted in the Figure 2 is -4.9% (mV/V/bar). Standard deviation from this value is 0.51% of (mV/V/bar). Sensors, based on analog signal conditioners with operational amplifiers /7/, can compensate temperature coefficient of sensitivity up to 0.2%/°C. The latter clearly demonstrates the advantage of the digital temperature compensation based signal conditioners. Input temperature coefficient of offset voltage is depicted in Figure 3. Again, the plotted histogram depicts large variations for temperature coefficient of offset voltage. Analog calibration system could not calibrate the sensor with temperature coefficient of offset voltage in the range of 1mV/°C.

3.2 Output properties of calibrated sensors

In case of calibration of ZMD31050 based MAP sensors, further 11 test points were introduced to calibration scenario. Output temperature error histograms were evaluated at 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% of power supply voltage pressure response at 85°C and 20°C upon a set of 5828 sensors. From initial 5828 sensors, 366 were evaluated as bad. Among them were 182 sensors, lacking the results from testing at 20°C. Calculated histograms are a clear demonstration of effectiveness of digital temperature compensation. The histogram in Figure 4 depicts the magnitude of temperature error in test point 1 (T=85°C, P=17kPa, V_{OUT}=5%VCC). Presented result was subtracted with an ideal value and

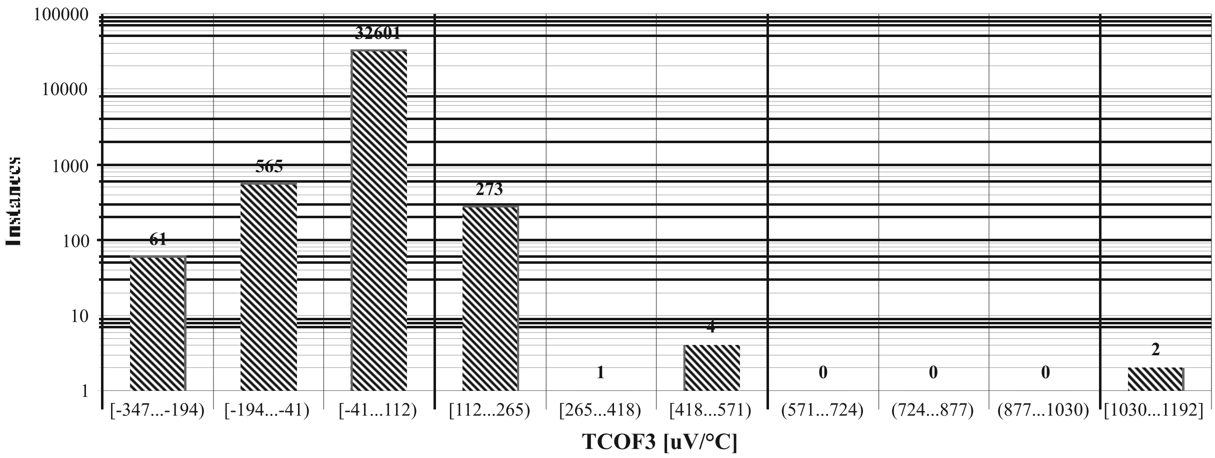

Fig. 3: Input temperature coefficient of offset voltage.

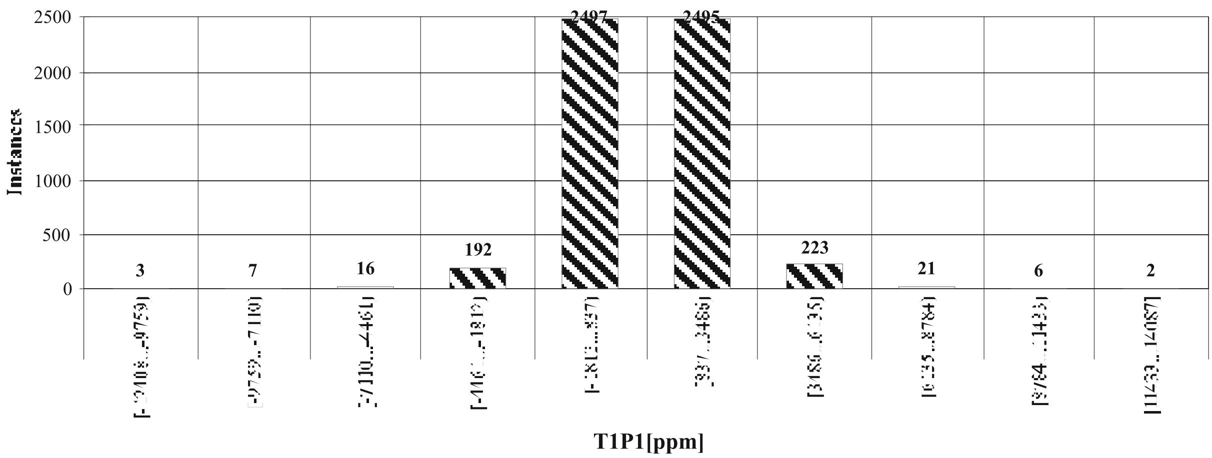

Fig. 4: Temperature error at test point 1.

the resulting error was normalized in ppm. The data in the Figure 4 shows temperature error in the range of /-0.2% … 0.38%/ for 5075 sensors out of 5462 total, whereas the admissible range of temperature errors lies within ±1.7%.

Mean histogram value, representing a typical calibration temperature error is 0.086%. The standard deviation from this value is 0.16%. Similar histogram was evaluated at test point 11 (T=20°C, P=105kPa, V_{OUT}=95%V_{CC}) and the resulting temperature error is depicted in Figure 5. Mean histogram value is now 0.15%, while the standard deviance is 0.19%.

If remaining 184 sensors (366-182) bad sensors are further analyzed, the output stage failure is noted on 82 sensors, which can be attributed to faulty connection of the sensor output, because the sensor output stays the same on every test point. The same cause of error can be attributed to faulty output stage – fault in signal conditioner. The actual cause can be determined with combined insight into calibration database. Remaining 102 sensors were calibrated with temperature error out of MAP sensor specification. One of them (ID=58800) was rejected by calibration process due to inadequate pressure response. Upon analysis of calibration database upon these 101 sensors, it becomes apparent that most of the tested sensors passed the calibration, but failed the test. This indicates a change in sensor properties during packaging step of production. The tests were performed after thermal cycling, therefore the failure was introduced during packaging phase of sensor production. Packaging after calibration was performed in case of MAP sensors based upon ZMD31020 signal conditioner. Temperature error values are summarized in the Table 1. First column summarizes the test pressure points, second column lists the maximum error margin in parts per million and the next two columns summarize the typical temperature error at temperatures 85°C and 20°C. For each pressure test point, a temperature error histogram was statistically evaluated by calculating first four statistical moments. Table 1 lists the temperature error average and its standard deviation (ó).

Results from Table 1 can be interpreted as a figure of quality of calibrated sensors for MAP sensor application.

Next, the analysis of maximal sensor temperature error was performed on all tested temperatures. Resulting maximal

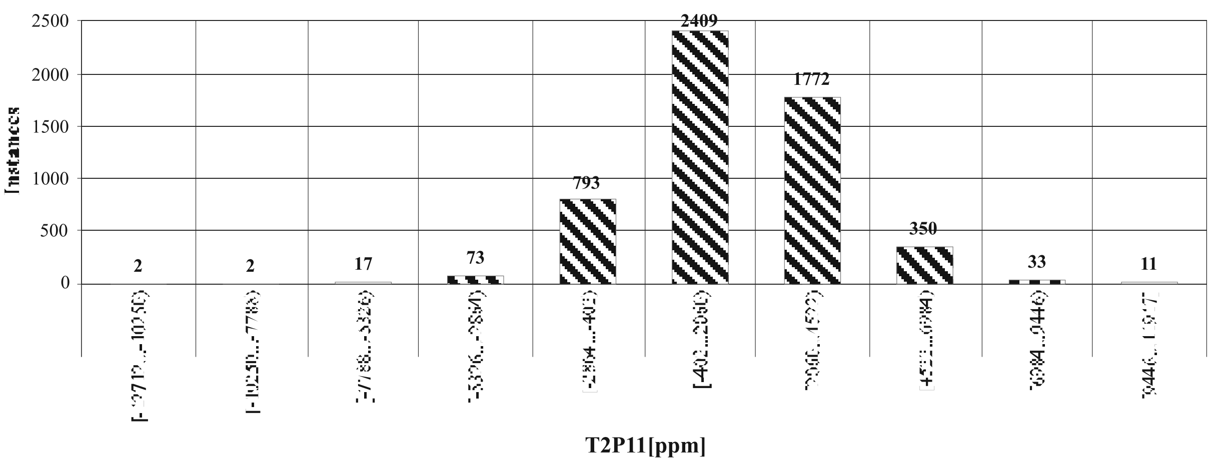

Fig. 5: Temperature error at test point 11.

Table 1: Temperature error for MAP sensors.

P (kPa)	error limit (ppm)	error @ 85°C		error @ 20°C	
		avg. (ppm)	σ (ppm)	avg. (ppm)	σ (ppm)
17	±17000	861	1686	2527	2048
20	±16300	548	1461	2067	2075
30	±14200	-294	1497	2087	2124
40	±12000	-707	1613	1898	2013
50	±12000	-1076	1559	1621	1960
60	±12000	-895	1508	1832	1935
70	±12000	-560	1480	2167	1904
80	±12000	-538	1433	2146	1891
90	±12000	-729	1436	1899	1923
100	±13500	-848	1451	1639	1960
105	±15000	-876	1449	1535	1996

errors were divided into 10 bins and the result was evaluated in the histogram. Resulting histogram is summarized in Table 2. The histogram depicts sensor classification in ten classes. The majority (5189 of 5462) of sensors are well within 0.7% limit of temperature error.

Important is, that classification can be performed on each and every calibrated sensor. Because of complete sensor traceability, we are able to identify the class and quality for each calibrated sensor. The calibration yield upon 5462 sensors is 98.1%.

Table 2: Classification of calibrated sensors.

Class	Limit (ppm)		Sensors
	upper	lower	
1	767	2239	992
2	2239	3711	2190
3	3711	5183	1477
4	5183	6655	530
5	6655	8127	182
6	8127	9599	44
7	9599	11071	24
8	11071	12543	16
9	12543	14015	4
10	14015	15490	3

The cause of failed sensors is attributed to change of sensor properties after calibration during packaging process. This was counter measured by performing the packaging process prior to calibration and performing the calibration as a last step of production process. Advanced signal conditioners (ZMD31050) enable calibration of packaged sensors by one-wire communication. The change of sensor properties can also be monitored by the signal conditioner itself. Advanced signal conditioner ZMD31050 measures not only the differential sensor voltage, but also the common mode voltage. This voltage changes if a single bridge resistor value changes. The change is compared to limits, measured during calibration. When the common mode falls out of stored limits, an alarm is signaled and sensor output is disabled, making sensor unusable. The calibration yield was further improved by discarding the faulty sensors during sensor pretesting phase.

3.3 Demonstration of adaptivity concept

The adaptivity of the system is based upon determining the limits of all system parameters, which define the criteria for quality of calibrated sensors. The result from criteria adaptation is the calibration interval for a given sensor property, based on sensors which comply with predefined output response.

The limit optimization process is performed upon every sensor that enters the calibration process. Primary acquired sensor parameters are obtained directly from acquisition – raw pressure and temperature sensor readouts. The raw values are recalculated to analog measured quantity according to preamplifier settings, including sensor offset compensation and preamplifier gain.

An illustrative case of sensor limit adaptation is presented when a new sensor enter the calibration process. After initial acquisition of raw values the new sensor response is evaluated and its response is inserted in the histogram, which depicts the raw sensor readouts at the first calibration point (17kPa, -20°C). Entering sensor was assigned identification number (ID=31326).

From the histogram on Figure 6, it is obvious, that the tested sensor extremely deviates in raw response from all other sensors. However, an automated analysis must establish other sensor properties in order to determine whether a given sensor will enter a full calibration process or not. Sole evaluation of the magnitude of raw pressure response is not sufficient for final estimation, because the sensors at the input can be e.g. from different manufacturers and their responses may vary. The calibration system is designed to adapt also to new type of sensor with different input properties. The system needs to find the explanation for this raw pressure response. If several pressure points are scanned, the sensor properties can be evaluated (sensitivity, offset and nonlinearity). First, the sensor sensitivity is calculated as a difference of two pressure responses. If the sensor readout is approximately ten times larger than normal, then the sensitivity should be in proportion with raw readouts. Otherwise, the sensor response can be considered inadequate – this indicates failure in offset or gain optimization process. The system calculates the sensor sensitivity and depicts the result in the histogram for comparison with other sensors. The resulting histogram is depicted in the Figure 7. The sensitivity was evaluated in the range between 300 and 338, which is in proportion with sensor readouts.

Therefore, further analysis is performed and sensor nonlinearity is evaluated and the results are depicted in the Figure 8. When the sensor nonlinearity is compared to other sensors in histogram, it becomes obvious, that the sen-

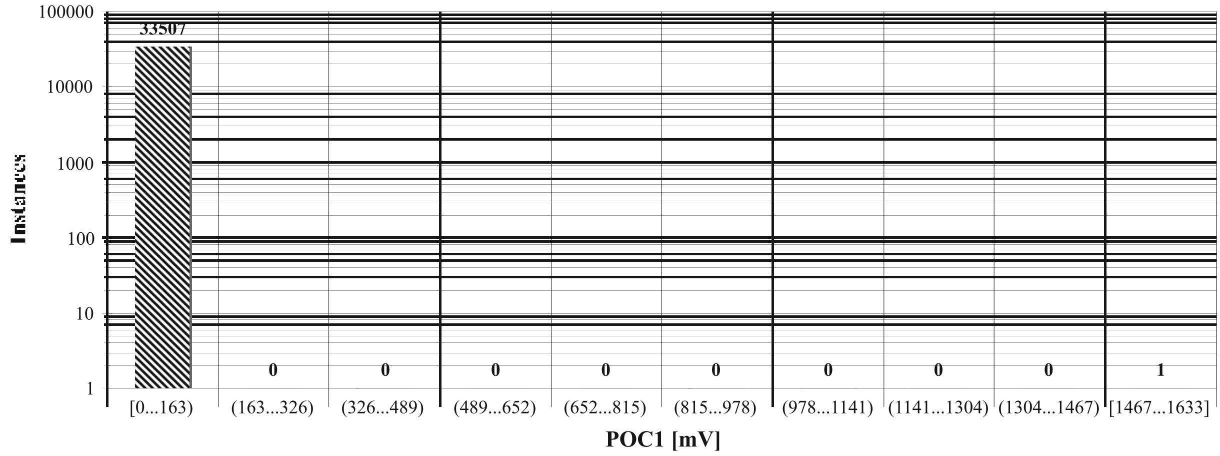

Fig. 6: Raw pressure sensor response at calibration point 1.

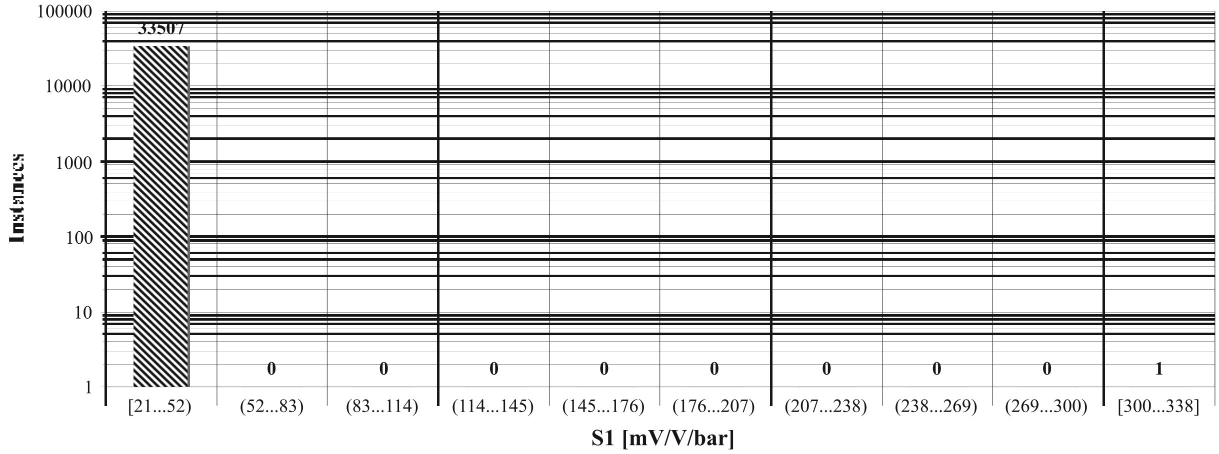

Fig. 7: Sensitivity at calibration point 1.

sor is highly nonlinear (55.8%). Therefore, the sensor is discarded from further calibration process.

The sequence of high sensitivity and excess nonlinearity failures implies that a pressure sensor was not designed for calibration on a high pressure range: A low pressure sensor was exhibited to calibration on a high pressure range. Such a low pressure sensor exhibits larger sensitivity but also nonlinear response, when exposed to overpressure.

Sensors such with nonlinearity can be calibrated, but not with the seven point calibration scenario, which was used during calibration process of manifold absolute pressure

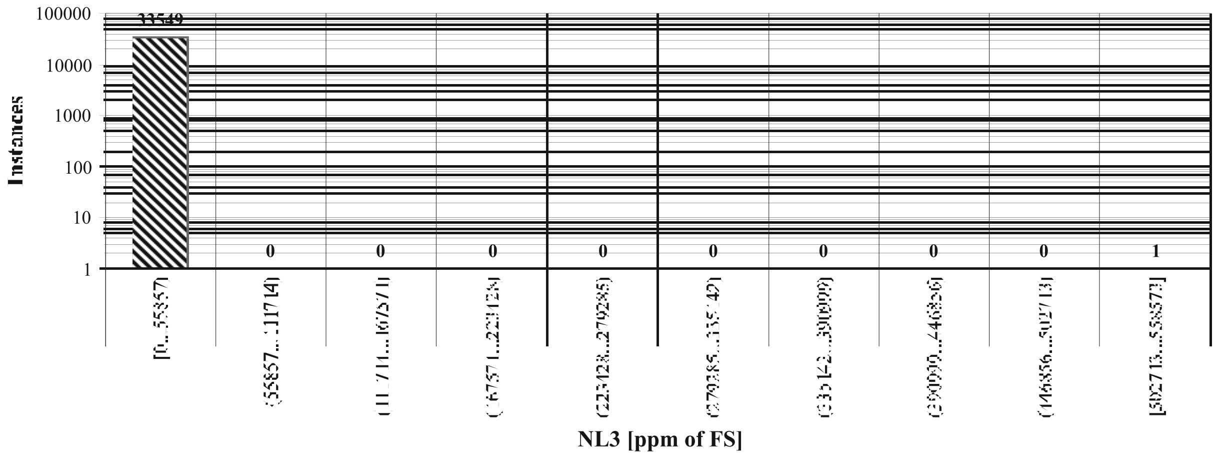

Fig. 8: Nonlinearity at calibration point 1.

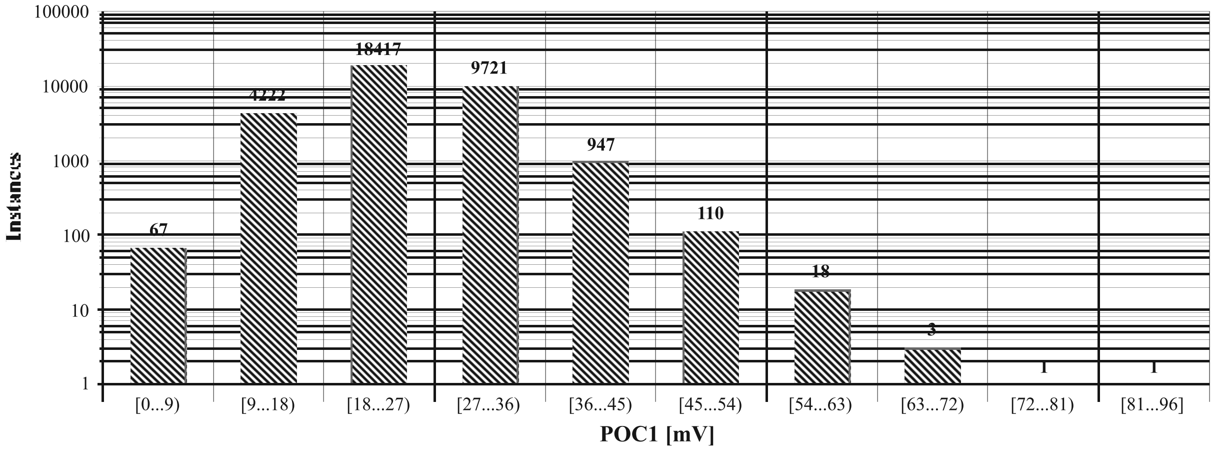

Fig. 9: Corrected raw pressure sensor response at calibration point 1.

sensor. Maximal nonlinearity of uncalibrated pressure sensors was limited to 2%

Sensor is discarded from further calibration and resulting histograms of raw pressure readout are evaluated again. Resulting histograms after discarding are depicted in Figure 9 and Figure 10.

The resulting limits for raw pressure response stay between 0 and 96mV as can be seen in the Figure 13, and for the pressure sensitivity in interval /21…41mV/V/bar/.

3.4 Failure analysis of calibrated sensors

Failure analysis was performed upon a set of calibrated sensors. A detailed insight of failure analysis results is summarized in Table 3. Calibration yield, which would be calculated disregarding failure analysis, would yield 93.7%, since there are 2289 failed sensor out of 36711 calibrated. However, the calibration database stores everything including failed attempts related to system causes, which are not caused by failed sensors. Most of system failures are attributed to improper sensor connection (operator

Table 3: Failure analysis of calibrated sensors.

Cause of failure	Origin of failure	Nr. of sensors
Inadequate response of pressure sensor	Sensor	220
Inadequate response of temperature sensor	Conditioner	81
Calibration coefficients clamped	Calibration	373
Communication failure	System	1108
Inadequate temp. stabilization	System	34
Excess nonlinearity	Sensor	384
Tolerance error during coefficient calculation	Calibration	36
Calibration of sensor output stage failure	System	20
Output stage clamped to maximum level	Conditioner	33
Total		2289

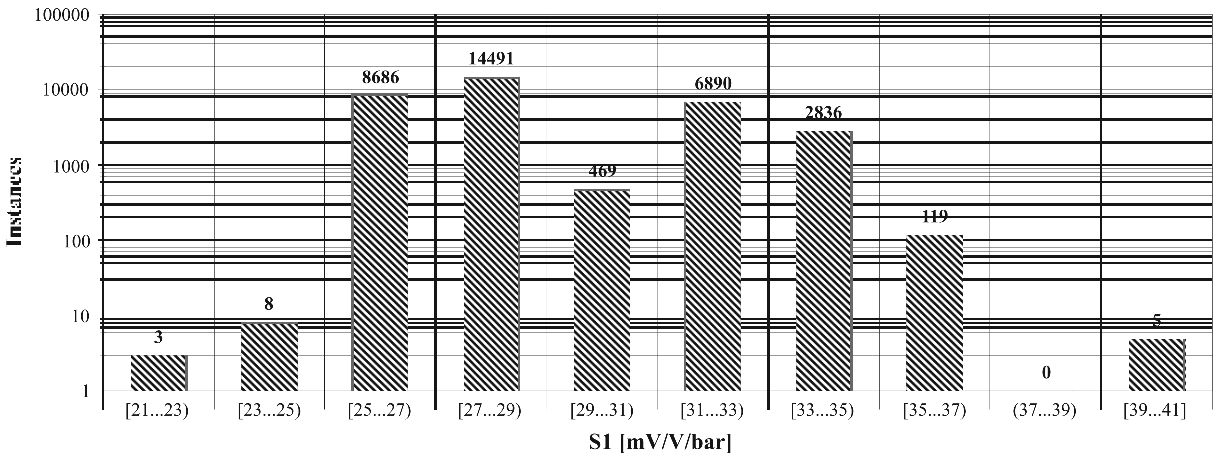

Fig. 10: Corrected pressure sensor sensitivity at calibration point 1.

error). Therefore the system related causes must be removed from analysis to obtain actual yield of calibration. After this, the calibration yield improves to 96.8%, since there are only 1127 failed sensors of 35549.

4 Conclusion

Adaptive calibration and quality control of smart pressure sensors were presented. Presented digital temperature compensation reduces typical sensor temperature error after calibration to 0.05%FS, based on calibration of 34422 MAP sensors. During initial calibration stage, early detection of faulty sensors has proven essential for the calibration yield improvement. Yield improvement is achieved by thorough analysis of sensor properties such as offset, sensitivity, nonlinearity and temperature coefficients of sensitivity and offset. Further refinement of calibration failure causes gives a detailed insight into sensor related failure causes, system related failure causes and signal conditioner failure causes. Described quality control mechanisms enable automatic sensor classification. Proposed calibration system shortens the total time for calibration of smart sensors, by implementing the input testing of sensor parameters as well as final testing of the calibrated sensors. Final testing was achieved by inserting additional test points into the calibration scenario. In current calibration system configuration, the calibration time was 42 seconds per sensor. In system maximal extension, enabling simultaneous calibration of 2048 sensors, calibration time would be reduced to 3 seconds per sensor.

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