Characterization and compensation circuitry for piezo-resistive pressure sensor to accommodate temperature induced variation

M. Santosh[1], Anjli Bansal[2], Jitendra Mishra[3], K. C. Behra[4], S. C. Bose[5]

CSIR-Central Electronics Engineering Research Institute, Pilani, India
[1]satosh.manabala@gmail.com,[2]anjlibansal92@gmail.com,
[3]jmishra92@gmail.com,[4]kanhucharan@yahoo.com,
[5]bose.ceeri@gmail.com

Abstract. The paper presents a simple circuit for piezo-resistive pressure sensors which compensates the temperature dependency of sensors. The output of piezo-resistive sensors generally, decreases with the increase in temperature when subjected to constant voltage excitation. To control the change with temperature, a varying excitation method is used. The proposed technique utilizes current steering DACs and a digital controller to compensate the variations. The technique is experimentally verified at hardware level where the digital control circuit is implemented on FPGA and tested with ASIC's comprising of interface circuit. For the purpose of compensation, temperature is sensed using the same sensor. The temperature resolved is less than 1ºC for a range of 10ºC to 70ºC with zero pressure correction technique. The test results for implementation show that the sensitivity and offset shift is compensated by a factor of 10 and 44 respectively. The complete fabricated chip, consisting of interface circuit and algorithm occupies $10mm^2$ area.

Keywords: Piezo-resistive, Voltage excitation, Current steering DACs, FPGA, Sensitivity, Offset.

1 Introduction

MEMS (Micro Electro Mechanical Systems) pressure sensors are used to measure ambient/differential pressure electronically, used in many applications like avionics, automobiles, biomedical industries etc. Both avionics (Micro Air Vehicle) and automobile applications measure altitude by a barometric pressure sensor. Different applications demand suitable pressure transduction principal i.e. piezo-resistive, capacitive or piezo-electric sensing mechanism [1]. Piezo-resistive sensor has gained wide acceptance due to ease of fabrication, scalability and linear output. The sensor consists of four piezo-resistors arranged in the wheat-stone bridge configuration. The resistance of resistors varies with the application of pressure and ideally, should remain constant with temperature variation. But in reality, the resistances also change with temperature. The temperature effect on sensor's sensitivity leads to nonlinear differential output. Apart from thermal impact, fabrication errors result into a mismatch of bridge resistors. Such mismatch generates a non-zero output offset even at zero applied pressure. The generated differential output offset also varies with temperature [1]. In order to remove the zero pressure offset error and nonlinearities of sensor, several compensation circuits and algorithms are reported in literature [2-5].

Two side-by-side bridge sensors are used [2-4], one for pressure and the other for temperature measurement. In the previous techniques, offset is compensated with the help of nullifying resistor internal to sensor and the sensitivity drift is compensated by changing voltage bias of pressure sensing bridge. For such techniques, fabrication process related to two bridges and an extra internal resistor becomes complicated.

In order to reduce process complexity and hardware requirement, pressure and temperature are measured simultaneously by a single bridge [6] or an additional temperature sensor embedded on sensor [7]. A single bridge based sensing requires a complex signal conditioning circuit with multiple feed-back loops i.e. comprising of variable gain differential amplifier, tunable current generator, ADC, DAC, PROM and control logic. Addition of an on-chip temperature sensor leverages the signal conditioning circuit complexity [7]. The major limitation with the second approach comprises of collecting huge amount of sensor specific characterized data and multiple high resolution DAC's for controlling variable gain amplifier.

Another technique uses a microprocessor for the temperature compensation of bridge type piezo-resistive pressure sensor. The microprocessor controls the reference voltage applied to the dual slope integrator included in the analogue to digital converter used for signal conditioning [8]. Although, microcontroller based solutions have gained wide acceptance and provided solutions with reasonable power but occupied large footprint on the developed board. Applications such as avionics require a minimum geometry and weight budget conditioning circuit, which are difficult to achieve from microcontroller based solutions (rather a control unit assisted by a look-up table based solution) [9]. Such devices are co-fabricated with sensor and mixed-signal circuits to achieve required weight and power budget at the expense of higher fabrication cost especially designed for batch fabricated MEMS sensors under controlled conditions.

In all the techniques described in literature, both offset and gain related digital compensation values are pre-stored in memory for temperature compensation, leading to complicated characterization process. Gain and offset values control is achieved by inserting variable gain amplifier and tunable current source in conjunction with an external temperature sensor. Proposed work eliminates the requirement of external temperature sensor. Instead, the modified bridge senses the pressure as well as temperature simultaneously. The output offset is compensated with the help of DAC thus, eliminating the need of tunable current regulator [2]. Also, an extra digital circuit for offset compensation [2, 6] is eliminated as the same digital circuit meant for sensitivity compensation also used for offset compensation as well. Thus, the proposed technique is less hardware extensive with a simpler compensation algorithm as compared to previously reported work. The technique implementation is carried out using an in-house piezo-resistive pressure sensor (designed and fabricated in-house) working up to 30 Bar (with sensitivity 1.2 mV/bar for full bridge bias voltage of 3.3V) for a temperature range of 10°C to 70°C. The sensitivity and offset drift with respect to room temperature is -11.7 % and -21% respectively (for amplified output of sensor).

2 Sensor Characterization

The fabricated sensor implemented by four resistors in bridge configuration, vary in opposite direction with the application of pressure [1]. Fig. 1 shows the SEM image of fabricated sensor.

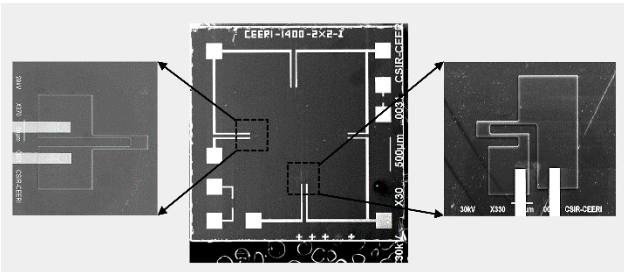

Fig. 1. SEM Image of fabricated Pressure Sensor showing the Implemented Resistors

In order to bias the sensor, superior current biasing scheme [7] is implemented in the proposed work. In contrast to reported work [7], the fabricated sensor does not have two independent on-chip temperature sensors. In the current implementation, the bridge resistors sense both temperature and applied pressure.

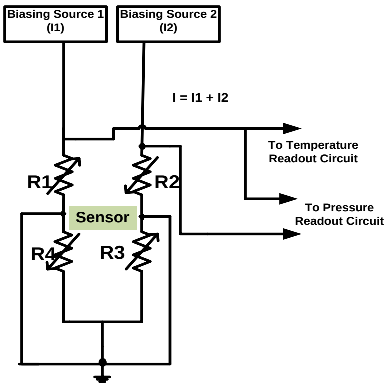

Fig. 2. Sensor in wheat-stone bridge configuration

Fig.2 shows the electrical equivalent of sensor connection. Resistors R1 and R2, do not match perfectly with each other due to fabrication error. The mismatches in resistors are compensated in current implementation by un-equal bias current sources i.e. I1 and I2 are different. The sensor resistors R1 and R2 are much more sensitive to temperature than pressure when characterized individually. Thus, the voltage drop across R1 is used to measure the temperature and differential output across R1 and R2 is used to measure the output variation with pressure.

Fig.3 represents the differential output of sensor with variation of pressure. Biasing current to the resistors is kept fixed where I1 is 0.2 mA and I2 is 0.224 mA. The temperature is 40^0 C which is assumed to be the reference temperature for the purpose of compensation. Fig.4 shows the shift in the average sensitivity and offset relative to reference temperature under same bias condition.

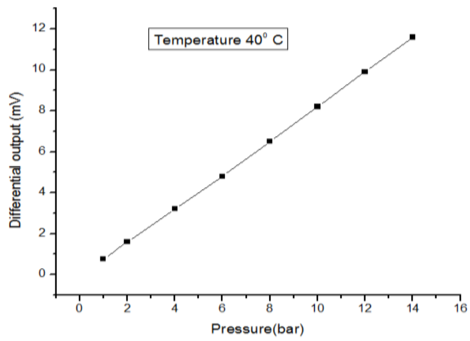

Fig. 3. Output response of sensor with pressure at reference temperature (with unequal bias current)

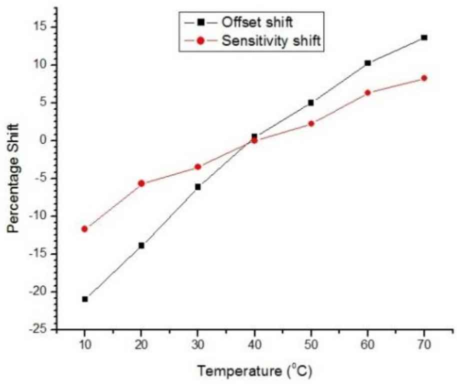

Fig. 4. Percentage shift in the offset and sensitivity with temperature

3 Proposed Architecture

In the proposed technique, full bridge MEMS sensor is configured as half bridge by connecting the two output terminals and the bias point to ground as shown in Fig. 5. The other two terminals, meant for externally tunable resistor (zero pressure output offset compensation resistor), are connected with tunable current sources used to bias the half bridge.

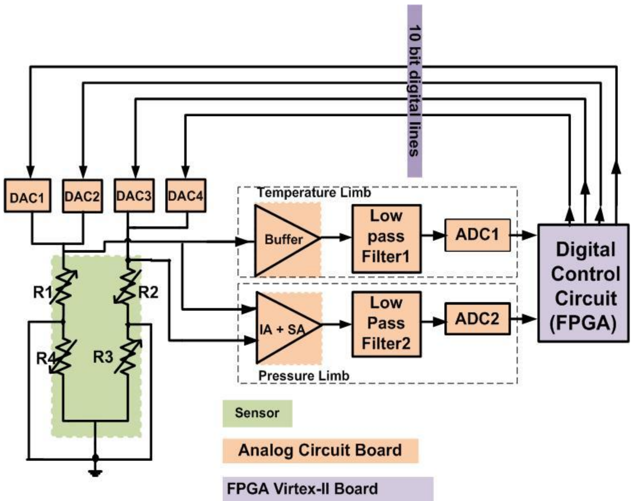

Fig. 5. Architecture for temperature calibration in pressure sensor

10-Bit current steering DACs are used as current sources in order to bias the bridge. DAC1, DAC3 are coarse and DAC2, DAC4 are fine resolution current sources for compensation of the sensor related errors. Two readout circuitries are used to measure temperature and pressure respectively.

Temperature readout circuit consists of a buffer along with filter and ADC. Pressure readout circuit consists of an instrumentation amplifier along with second inverting gain amplifier providing sufficient gain at output, low-pass filter and ADC. A 10-bit SAR ADC is used for data conversion [10].

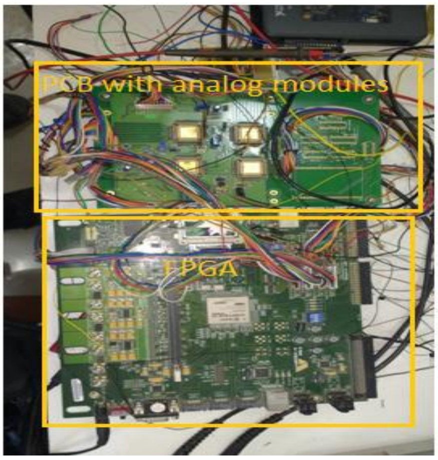

Fig. 6. Complete setup for compensation of sensor output

The converted digital data is fed to digital control circuit implemented using Vertex-II pro FPGA board. The sensor compensation control algorithm is implemented on

FPGA board (connected through expansion header pins J1-J4) using VHDL language. The readout circuit (shown in Fig. 5) consists of all analog modules assembled on a single PCB board. The system clock is 1 KHz which is generated from an arbitrary wave form generator. Fig. 6 shows the complete implementation of analog modules PCB connected with FPGA board through various input output pins (expansion header pins J1-J4) available on FPGA.

4 ASIC Implementation

The targeted application requires considerable reduction in weight and volume of implemented architecture shown in Fig. 5. The volume reduction is achieved by integrating all the analog sub-modules and control algorithm on a single chip using AMS 0.35µm CMOS technology. The analog sub-modules are DAC, ADC, IA (Instrumentation Amplifier), Buffer, Inverting gain amplifier and digital control circuit (DCC) implementing the algorithm.

A traditional 10-bit segmented current steering DAC is designed with a tunable reference current source from 10nA to 1 mA [11]. Two different reference currents act as coarse and fine DAC. The implemented ADC samples the input directly on the DAC and comparison is achieved by cascaded inverters [10]. A buffer is required to drive the high capacitive input (approximately 10pF) of ADC. The sensor output is amplified by an IA based on three op-amps based approach [12]. The mismatch of on-chip resistors is minimized by a common-centroid layout approach, which has direct impact on CMRR of IA. A second inverting amplifier is also cascaded with IA to control the cumulative gain of amplifying stages, offset and thermal noise generated from sensor. Both IA and second amplifier is designed using high gain folded-cascode buffered output amplifier.

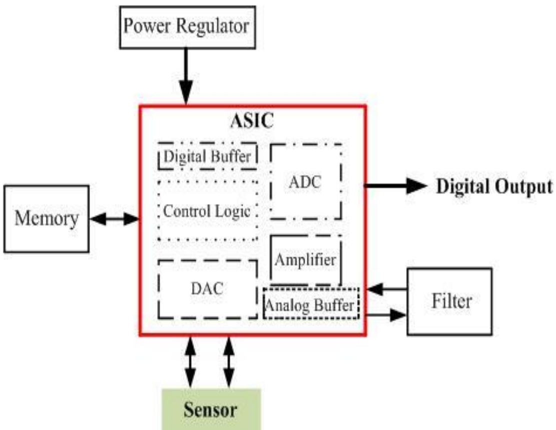

Fig. 7. Block level implementation of ASIC designed for sensor

The analog block is separated by a double guard ring from digital block. The resistor variations with process and temperature are controlled by sizing the dimension and adapting suitable resistor design strategy [13]. A grounded signal shield isolates the substrate injection noise getting merged with analog signal. Table.1 shows the detailed testing results of fabricated chip. The active-RC analog filters are implemented off-chip on fabricated PCB (basically area constraint) [12].Fig.7 shows the block level implementation using the designed ASIC and other components. An external memory is interfaced with ASIC (the fabrication technology node does not support on chip memory) to store the compensation co-efficient.

The die photo of chip designed with all the on chip analog modules i.e. four DACs, two ADCs, IA, amplifier and also, digital compensation circuit is shown in fig.8. The size of die is 10 mm^2.

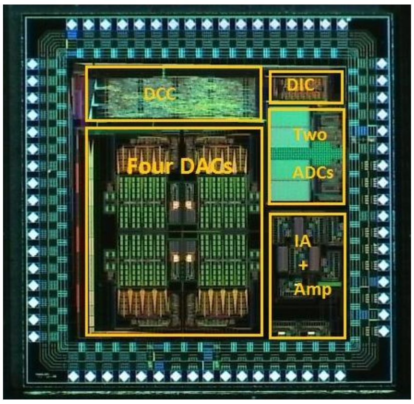

Fig. 8. Die photo of fabricated chip (ASIC) with analog and digital module

Table 1. Measurement Data Result

Sub-blocks	Operating Conditions	Measurement Results	Make & Type
DAC	Supply voltage: 3.3V	Resolution: 10 Bit. **DNL: -0.7/0.3 **INL : -1.4/1.9 Output Range: 10nA – 1mA. SNR: 57 dB for 10Hz input @ 16 KHz sampling rate. Conversion speed: 100 KSPS. ENOB : 8.1	Make: in-house designed & fabricated at Euro practice. Technology: 0.35 um, 3.3V, triple metal, double poly. Type: Current Steering.
Sensor	Bias voltage: 3.3V	Sensitivity: 1.2mV/Bar. Burst pressure: 40 Bar. Maximum applied pressure: 15 Bar.	Make: In-house designed & fabricated. Type: piezo-resistive.

IA	Supply voltage: 3.3V	ICMR: 0.3V to 2.5V. Gain: 1-45V/V. CMRR:60dB @ 1KHz Output offset: 6 mV. OCMR: 150mV to 2.5V Output Transient Noise: 700µV at full gain.	In-house designed & fabricated at Euro practice. Technology: 0.35 um, 3.3V, triple metal, double poly. Type: three op-Amps based architecture.
Filter	Supply voltage: 3.3V	ICMR: 0.3V-2.5V 3-dB cutoff frequency < 20 Hz Pass band gain : 1V/V Order : 2nd	Make: same as IA Type: sallen-key architecture
ADC	Supply voltage: 3.3V. Reference voltage : 2.5V	Resolution: 10 Bit. **DNL: 0.3/-0.6 **INL : 1.2/-3.0 Input Range: 0-2.5V. SNR: 56 dB for 10Hz input @ 16 KHz sampling rate. Conversion speed: 200 KSPS. ENOB : 7.9	Make: same as IA Type: Successive approximation architecture.

**DNL & INL are respectively calculated in the ADC input voltage operating range of 0 - 2.5V.

5 Test Analysis

The output of sensor (in mV) varies with temperature i.e. offset and sensitivity both varies.

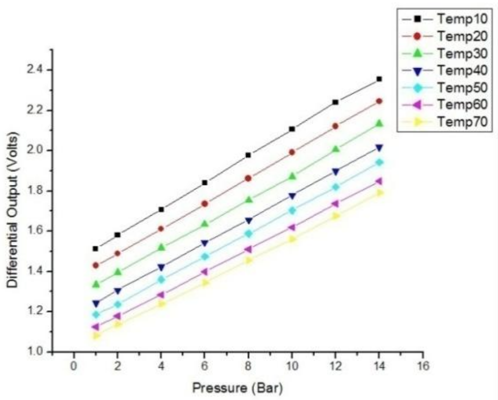

Fig. 9. Readout Circuit output

In order to satisfy the input range of ADC and to detect the pressure variation efficiently (i.e. to increase sensitivity), raw output is further amplified with a system gain of

80V/V. The amplified output of sensor at different temperatures is shown in fig.9 (un-compensated data). Temperature is varied by 10^0C in range of 10^0C to 70^0C. Fig. 10 presents the output of sensor at same temperatures after compensation with pressure variation.

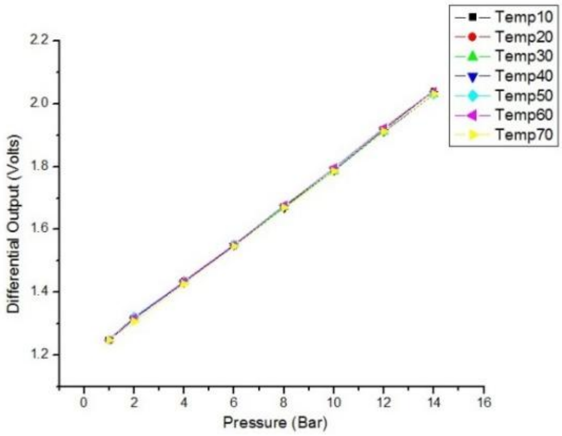

Fig. 10. Output of sensor after compensation

The percentage sensitivity and offset variation is calculated with respect to reference temperature for amplified sensor output. Sensitivity shift is reduced by a factor of 10 and offset shift is reduced by a factor of 44. The respective plots are shown in fig.11 and 12 for uncompensated and compensated data.

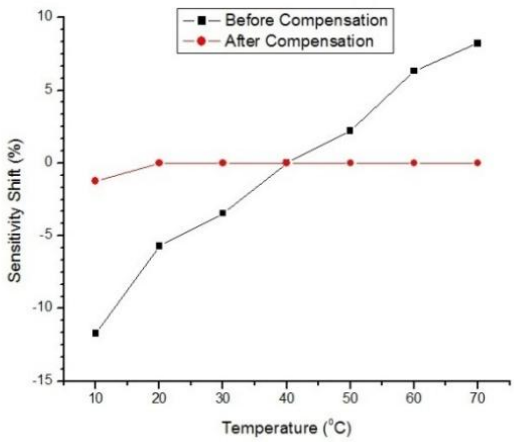

Fig. 11. Percentage variation in sensitivity with temperature

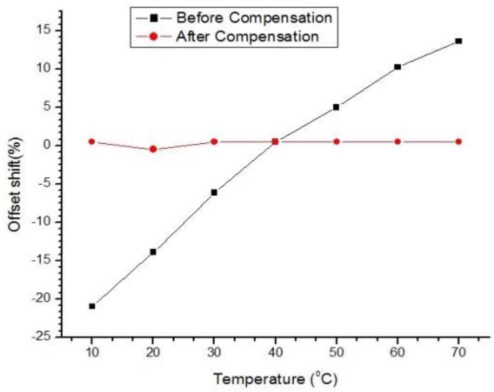

Fig. 12. Percentage variation in offset with temperature

6 Comparison

Table 2. Comparison of Performance

Parameters	Present work	[5]	[14]	[3]
Technology	0.35µm CMOS	3 µm CMOS	_	2µm CMOS
Supply	3.3 V	± 5 V	_	5 V
Temperature Sensor	Not required	PTAT Element	Not used	Required
Ref. Temperature1	40ºC	25ºC	26ºC	25ºC
Offset after compensation	±0.48%	±3.5% (increases after sensitivity compensation)	1.6% (relative error after compensation with reduction factor of 10)	2 - 4 %
Sensitivity after compensation	-1.248% (Worst Case)	±0.5%		
Temperature Compensation range	10ºC to 70ºC	-30ºC to +100ºC	-40ºC to 70ºC	-40ºC to 120ºC
Chip area (mm2)	10	_	_	34

Table 2 represents the comparison of present work with the previous works [3, 5, 14].

7 Conclusion

Current steering DAC's are used to compensate sensor offset and non-linearity (sensitivity variation). The temperature compensation algorithm compensates thermal drift through the DAC without an additional temperature sensor. The implemented algorithm does not require a detailed characterization of sensor. The characterization in the present technique is much simpler than methods reported in literature where a larger lookup table needs to be stored. In this technique, the same values stored for temperature are used to compensate the temperature effect. A total error of 40 % is reduced. The hardware requirement and multiple feed-back loops are redundant in the proposed approach. The Compensation is achieved for a temperature range of 10^0 C to 70^0 C (suitable for MAV application).

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