Dimensioning a pressure sensor system with digital signal correction where the sensor signal is amplified using IC AM401

One of the common problems with sensor applications is that the error of the sensing element has to be compensated for. Using potentiometers or trimmable resistors the gain and offset of back-end electronics have to be adapted to the values of the sensing element. If the application includes a processor, errors can be corrected digitally. However, the sensor signal must be conditioned as otherwise A/D converters with a too high bit rate are necessary. The application described in this article demonstrates how the concept of Frame ASICS [1] devised by Analog Microelectronics [2] can be put to simple use to create an entire sensor system with one sensing element and just one analog IC.

General description of the application

The basic assembly of the application is shown in Figure 1. The sensor element prone to error, here a piezoresistive silicon pressure sensing element, is supplied by the analog ***Frame ASIC*** AM401 (current or voltage supply with integrated supply sources is possible). AM401 converts and amplifies the differential output signal of the pressure sensing element into an output voltage referenced to ground which lies within the dynamic input range of the A/D converter (the input voltage is usually somewhere between 0 and 5V). The sensor signal is digitally calibrated and compensated for with the aid of a back-end processor. The A/D converter is powered by the integrated voltage reference on AM401. The entire system can thus be run on a supply voltage of 10 to 35V without the need for an additional voltage regulator; the system is also protected against reverse polarity and short circuiting by the protective circuitry integrated on AM401.

Definitions

Calibration:	correction of absolute values, such as offset and span.
Compensation:	correction of induced disturbance variables, such as temperature coefficients from offset and span.

As demands for precision (e.g. better than 1.5%FS in the industrial –40 to 85°C temperature range) dictate that not only the error of the sensor system but also that of the amplifier circuit be corrected with the help of a back-end processor the amplifier circuit must be dimensioned in such a way that the system lies within a defined operating point for all temperature and pressure ranges. In worst-case sensor and IC specifications the amplification and offset must ideally be dimensioned so that the output voltage always remains within the range of V_{OUT} = 0...5V and makes optimum use of the dynamic range of an A/D converter as mentioned above.

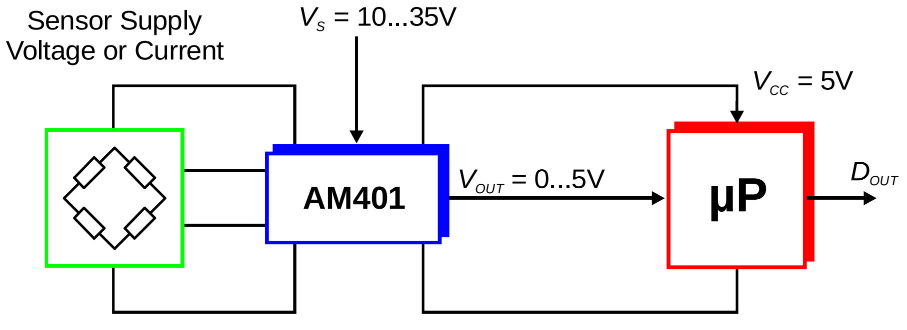

***Figure 1**: schematic circuit diagram of the system*

Circuit for a current driven sensor element

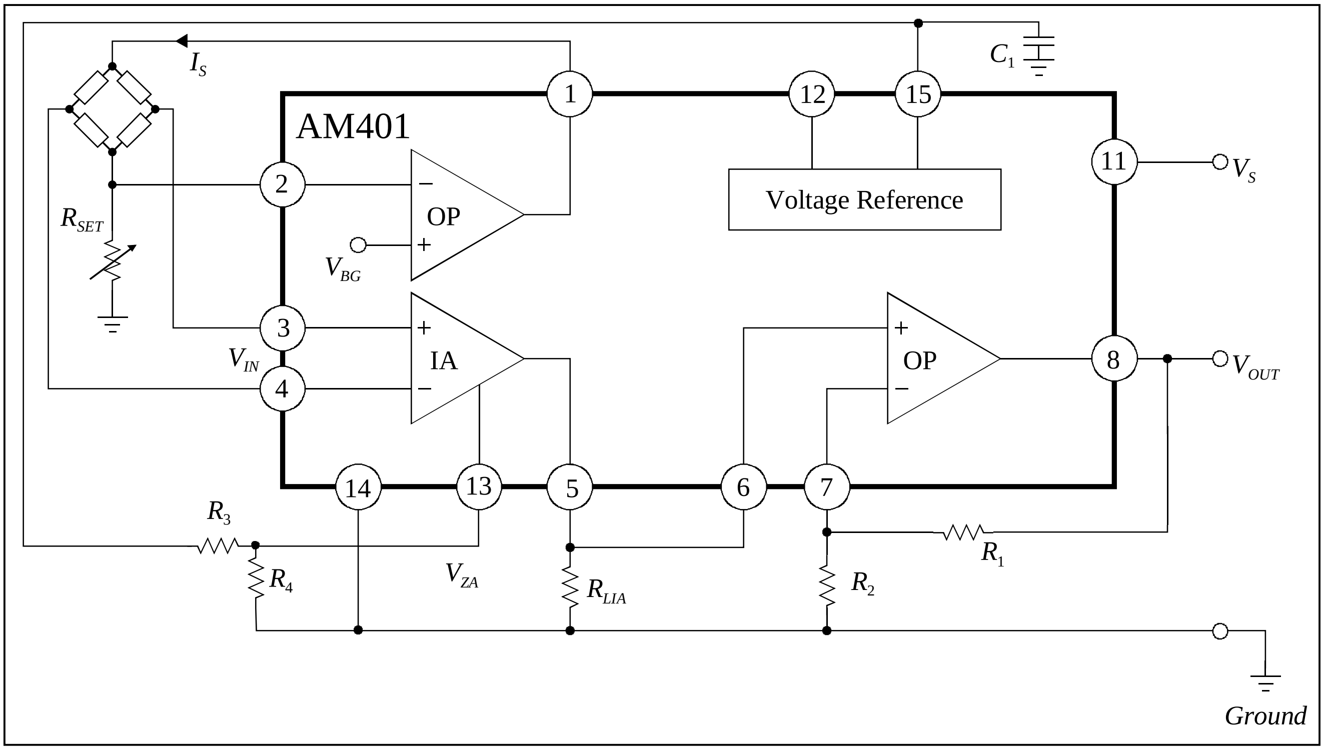

Figure 2: application diagram for a current driven sensor element

The circuitry in Figure 2 is a basic diagram of a sensing element supplied by current (e.g. an SMD transducer in the 0 to 15PSI pressure range by **AMSYS** of Mainz, Germany [3]). Piezoresistive silicon sensing elements in particular lend themselves to a constant current supply. As the output signal of sensing elements such as these is proportional to the supply voltage, with the temperature drifts of span and bridge resistance working in opposite directions (see Table 1) a self-compensatory effect is generated for the span drift. This and the fact that the sensing element is supplied with constant current result in errors being much slighter than those produced with voltage-driven sensors.

The following section outlines the dimensions needed for an application such as the above (see Figure 2). The sensor element is supplied with I_S = 1.5mA via an integrated operational amplifier (OP) and the processor with V_{CC} = 5V via an integrated voltage reference. The reference point of the input instrumentation amplifier (IA) can be set using the integrated voltage reference and an external voltage divider. It is then possible to compensate for the input offset of the sensing element and amplifier and to pre-adjust the temperature drifts of this offset. The output span is set via amplifier resistors R_1 and R_2. Taking the specifications of the sensing element from Table 1 and the specifications of the IC [4] the overall system can now be dimensioned for a predefined output voltage range of 0 to 5V.

All parameters are for a 1.5mA current supply at room temperature (22.5°C), unless otherwise noted

Parameter	Symbol	Min.	Typ.	Max.	Unit
Supply current	I_S		1.5	3.0	mA
Span (FS range)	V_{FS}	115	145	175	mV
Offset	V_{OS}	– 50	0	50	mV
Span temperature coefficient	TCS		– 22 ± 5		% FS/100°C
Bridge resistance temperature coefficient	TCR		28 ± 5		%/100°C
Offset temperature coefficient	TCO		± 7		% FS/100°C
Bridge resistance	R_B	2.7	3.3	4.0	kΩ
Proof pressure		3×			Nominal pressure
Burst pressure		5×			Nominal pressure
Working temperature range	T_{AMB}	– 40		85	°C
Storage temperature range	T_{STO}	– 55		125	°C

Table 1: specifications of the AMS5310 sensor

Equations for AM401

The general transfer function of AM401 [4] for output voltage V_{OUT} (circuit as in Figure 2) is

$$V_{OUT} = (G_{IA}\, V_{IN} + V_{ZA})\, G_{OP} \qquad (1)$$

With regard to the amplification of the instrumentation amplifier, $G_{IA} = 5$. Gain G_{OP} can be set via two external resistors R_1 and R_2, where

$$G_{OP} = 1 + R_1 / R_2 \qquad (2)$$

The offset of the sensing element and amplifier circuit can be compensated for via pin *ZA* which is used to vary the internal reference voltage of the instrumentation amplifier. With an arrangement such as the one depicted in Figure 2 the voltage at *ZA* is calculated as

$$V_{ZA} = V_{REF} \frac{R_4}{R_3 + R_4} \qquad (3)$$

The current powering the sensing element can be set via an external resistor R_{SET}. The current variable is defined as

$$I_S = \frac{V_{BG}}{R_{SET}} \qquad (4)$$

For $V_{BG} = 1.27$V (see [4]) and a required current of $I_S = 1.5$mA R_{SET} must be set to ca. 847Ω.

Dimensioning the circuit

As both the absolute and temperature errors of the IC are small compared to the error of the sensing element the following worst-case dimensioning scenarios for the circuit refer to the tolerances of the sensing element. The values given for the sensing element in Table 1 always apply to room temperature. The following calculations thus differentiate between two temperature ranges ($T < 22.5°C$ and $T > 22.5°C$). At a required working temperature range of $T_{AMB} = –40$ to 85°C a ΔT of 62.5°C is produced in both directions. Calculation of fluctuations in the offset and span temperature is based on this value. The largest possible fluctuations for offset and span are computed as these define the maximum range of adjustment necessary for the electronics.

Calculating offset drifts

According to Table 1 the offset of the sensing element can fluctuate by ± 50mV with a supply current of 1.5 mA. For the drift of the offset versus temperature

$$TCO = \pm\ 7\%FS/100°C \tag{5}$$

As the absolute value of the offset is defined at room temperature the maximum possible change in offset is identical in both directions. The result is a maximum swing of the offset[1] versus temperature ($\Delta T = 62.5°C$) of

$$V_{OS\_Drift} = V_{FS}\ TCO_{MAX}\ \Delta T = 145mV \cdot 62.5°C\ /\ 100°C \cdot 0.07 \approx 6.34mV,$$

i.e. in the worst instance the offset amounts to $V_{OSmax} = V_{OS} + V_{OS\_Drift} = \pm\ 56.34mV$.

Temperature drifts of the span signal

According to Table 1 the sensing element's output signal at nominal pressure can fluctuate between 115 and 175mV with a supply current of 1.5 mA. For a temperature range of –40 to 85°C the temperature drift of the span

$$TCS = (–22 \pm 5)\ \%FS/100°C \tag{6}$$

must also be taken into account when setting the amplification. As the temperature drift of the bridge resistance

$$TCR = (28 \pm 5)\ \%/100°C \tag{7}$$

works in opposite directions and the temperature effects are multiplicative, together with Equations 6 and 7 the following equation is produced for the output signal of a pressure sensor versus temperature:

$$V_{OUT\_FS} = V_{FS} \cdot (1 + TCS \cdot (T – T_0)) \cdot (1 + TCR \cdot (T – T_0)) \tag{8}$$

with $T_0 = 22.5°C$.

The curve of results for Equation 8 is given as a graph showing the typical drifts and extreme values of the application illustrated in Figure 1. The top graph in Figure 3 depicts the resulting curves when $V_{FS} = 115mV$, with the bottom graph describing events when $V_{FS} = 175mV$. The middle curve in each graph shows the course of the span drift when average TCS and TCR drifts are substituted. The two other

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[1] The influence the swing in voltage across the bridge has on the offset, this swing caused by a change in bridge resistance versus temperature, is disregarded in this calculation.

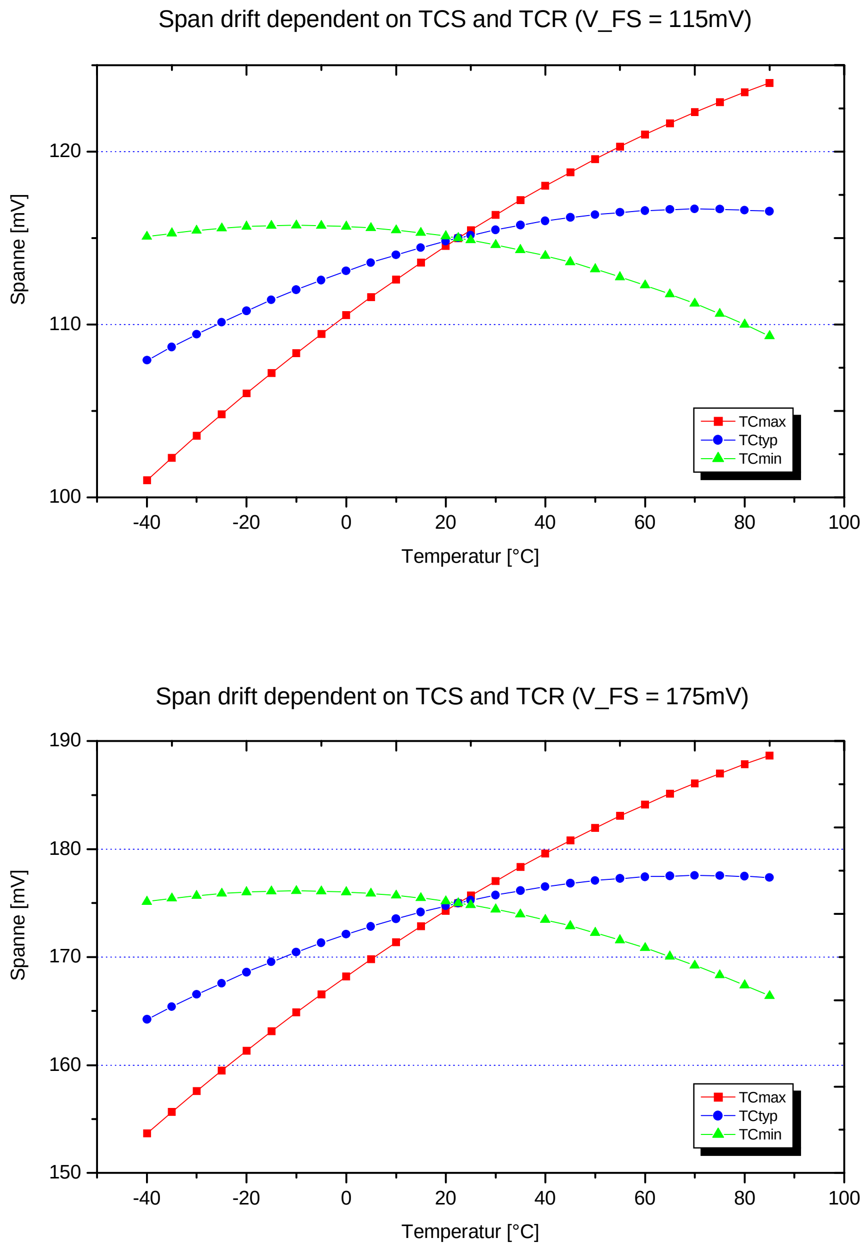

***Figure 3*:** curve of span vs. temperature when the sensing element is powered by current

curves give the maximum and minimum span drift. To calculate the maximum span drift the maximum *TCR* and minimum *TCS* must be substituted (red curve with squares in Figure 3).

Calculating the minimum possible span (V_{FS} = 115mV)

Substituting in Equation 8, the following is obtained for $T < 22.5°C$:

$$\begin{aligned} V_{OUT\_FS} &= 115\text{mV} \cdot (1 - 0.0017 \cdot (-40 - 22.5°\text{C})) \cdot (1 + 0.0033 \cdot (-40 - 22.5°\text{C})) \\ &= 115\text{mV} \cdot (1 + 0.10625) \cdot (1 - 0.20625) \\ &= 115\text{mV} \cdot 1.10625 \cdot 0.79375 \approx 100.98\text{mV} \end{aligned}$$

For $T > 25°\text{C}$ the equation is as follows:

$$\begin{aligned} V_{OUT\_FS} &= 115\text{mV} \cdot (1 - 0.0017 \cdot (85 - 22.5°\text{C})) \cdot (1 + 0.0033 \cdot (85 - 22.5°\text{C})) \\ &= 115\text{mV} \cdot (1 - 0.10625) \cdot (1 + 0.20625) \\ &= 115\text{mV} \cdot 0.89375 \cdot 1.20625 \approx 123.98\text{mV} \end{aligned}$$

A minimum span value of 100.98mV is thus achieved.

Calculating the maximum possible span ($V_{FS} = 175\text{mV}$)

Substituting in Equation 8, the following is obtained for $T < 22.5°\text{C}$:

$$\begin{aligned} V_{OUT\_FS} &= 175\text{mV} \cdot (1 - 0.0017 \cdot (-40 - 22.5°\text{C})) \cdot (1 + 0.0033 \cdot (-40 - 22.5°\text{C})) \\ &= 175\text{mV} \cdot (1 + 0.10625) \cdot (1 - 0.20625) \\ &= 175\text{mV} \cdot 1.10625 \cdot 0.79375 \approx 153.67\text{mV} \end{aligned}$$

For $T > 25°\text{C}$ the equation is as follows:

$$\begin{aligned} V_{OUT\_FS} &= 175\text{mV} \cdot (1 - 0.0017 \cdot (85 - 22.5°\text{C})) \cdot (1 + 0.0033 \cdot (85 - 22.5°\text{C})) \\ &= 175\text{mV} \cdot (1 - 0.10625) \cdot (1 + 0.20625) \\ &= 175\text{mV} \cdot 0.89375 \cdot 1.20625 \approx 188.67\text{mV} \end{aligned}$$

A maximum span value of 188.67mV is thus achieved.

Dimensioning the amplifier circuit

As the instrumentation amplifier in AM401 is unable to process negative input voltages it may be necessary to increase the IA reference voltage; this is possible via pin *ZA*. The smallest offset value is –56.34mV as given in the example. As the instrumentation amplifier has a fixed gain of $G_{IA} = 5$ a value of ca. 281.7mV is generated at its output; this must be compensated for using pin *ZA*. According to Figure 1 voltage V_{ZA} can be set via R_3 and R_4. In accordance with Equation 3 the following is calculated for the resistor values with $V_{REF} = 5\text{V}$:

$$\frac{R_3}{R_4} = \frac{V_{REF} - V_{ZA}}{V_{ZA}} \approx 16.75$$

The voltage at the IA output V_{IAOUT} can be computed using

$$V_{IAOUT} = G_{IA}\, V_{IN} + V_{ZA} \tag{9}$$

When substituted, under ideal conditions (with the IC contributing zero errors) a voltage somewhere between 0 to 563.4mV is produced at the instrumentation amplifier output with the values calculated for the offset ($V_{OS} = \pm 56.34\text{mV}$).

The maximum span signal can amount to 188.67mV as calculated. Thus with the internal gain of $G_{IA} = 5$ from the instrumentation amplifier a signal of 943.35mV is produced at its output. If we add the amplified maximum offset value the maximum gain to be set can be calculated using Equation 1 as follows (maximum output voltage range is 0...5V):

$$G_{OP\,\mathrm{max}} = \frac{V_{OUT}}{V_{OUTIA\,\mathrm{max}}} \approx \frac{5\text{V}}{1.507\text{V}} \approx 3.32$$

with

$$V_{IAOUT\mathrm{max}} = G_{IA}\, V_{IN\mathrm{max}} + V_{ZA} = 5 \cdot (56.34\text{mV} + 188.67\text{mV}) + 281.7\text{mV} \approx 1.507$$

For resistors R_1 and R_2 a value of

$$\frac{R_1}{R_2} \approx 2.32$$

is produced at this amplification with Equation 2.

Taking the values computed above we can now calculate the maximum and minimum output voltage range V_{OUT}.

<u>Scenario 1 (output swing at its lowest)</u>: maximum negative offset sensor voltage, minimum span

$V_{OS} = -56.34\text{mV}$, $V_{FS} = 100.98\text{mV}$

$$V_{OUT\_MIN} = (G_{IA}\, V_{INMIN} + V_{ZA})\, G_{OP} = 0\text{V}$$

$$V_{OUT\_MAX} = (G_{IA}\, V_{INMAX} + V_{ZA})\, G_{OP} = 1.676\text{V}$$

<u>Scenario 2 (output swing at its highest)</u>: maximum positive offset sensor voltage, maximum span

$V_{OS} = +56.34\text{mV}$, $V_{FS} = 188.67\text{mV}$

$$V_{OUT\_MIN} = (G_{IA}\, V_{INMIN} + V_{ZA})\, G_{OP} = 1.871\text{V}$$

$$V_{OUT\_MAX} = (G_{IA}\, V_{INMAX} + V_{ZA})\, G_{OP} = 5.002\text{V}$$

This means that in the worst-case scenario the swing of voltage V_{OUT} at the AM401 output can fluctuate between 1.676V and 3.131V. However, taking the dimensions given here we definitely remain within the dynamic range of the back-end A/D converter, providing us with a defined operating point which permits the piezoresistive sensing element to be measured and then undergo digital correction.

Conclusion

The above calculations demonstrate how to dimension a sensor system consisting of a simple piezoresistive pressure sensing element and a special conditioning IC or Frame ASIC. The sensor signal is amplified and dimensioned so that it can be directly switched to an A/D converter. Both the sensor and A/D converter are powered and protected against reverse polarity and short circuiting by Frame ASIC AM401. The actual correction of the system takes place in a back-end processor. It is sensible to take the temperature measurements necessary for compensation directly from the sensing element. The swing in voltage across the bridge is usually linear and can be used as a temperature sensor. The same calculations can be applied to sensors powered by voltage (e.g. ceramic pressure sensing elements).

Literature

[1] The concept of Frame ASICs:
http://www.Frame-ASIC.com/

[2] Website for Analog Microelectronics GmbH:
http://www.analogmicroelectronics.com/

[3] The AMSYS Website
http://www.amsys-sensors.com/

[4] Data sheet for AM401:
http://www.analogmicro.de/products/sheets/english/am401.pdf