Two-step calibration of sensor signal conditioners

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Introduction

Mixed-signal integrated circuits (ICs) for sensor signal conditioning are widely used today in sensor applications such as pressure, temperature and position monitoring. In these signal conditioners, the conditioning of the output signal from the sense element is performed with mixed-signal circuits, which are a combination of analog and digital circuits. Moreover, the actual conditioning of the sense-element signals is implemented in the digital domain. The conditioned signal is the output of the sensor signal conditioner. The sensor output is transmitted to a control or monitoring system either in analog or digital form. If an analog form of transmission is used, the processed digital signal must be converted back to analog form.

This article examines the calibration of sensor signal-conditioning algorithms implemented in signal conditioners that transmit data in analog form. Note that sensor calibration includes the sense-element non-idealities as well as signal-conditioner non-idealities, such as offset and gain errors. The calibration scheme will take care of analog signal-chain errors of the analog circuit that are in front and back of the digital circuits.

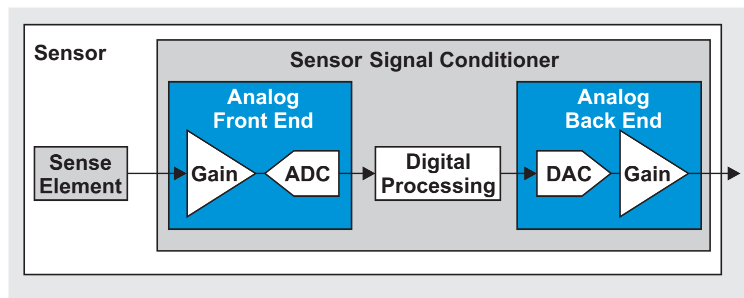
Sensor signal conditioners

The electrical output of a sense element is usually small in value and has non-idealities, such as offset, sensitivity errors, and nonlinearities. These non-idealities cause errors in measurements. Sensor signal conditioners are used to minimize these non-idealities. An example of these types of conditioners is the PGA400-Q1 from Texas Instruments.

Mixed-signal conditioners

Figure 1 shows a block diagram of a mixed-signal conditioner with analog output. Mixed-signal conditioners implement front-end analog circuitry to connect with a sense element. Because the output of a sense element is usually very small, the front end consists of a gain stage followed by an analog-to-digital converter (ADC). The ADC is used to digitize the output of the sense element, which means that flexible techniques of digital signal processing can be used to condition the sense element signal. The gain stage may consist of single-ended differential amplifiers or instrumentation amplifiers, which depends on the sense-element pinout.

Figure 1. Block diagram of a mixed-signal conditioner



After the data from the front end is conditioned by the digital circuitry, it is sent to the back end for transmission to a control or monitoring system. The transmission of the conditioned signal can occur in either analog or digital form. In order to transmit the conditioned digital signal in analog form, a digital-to-analog converter (DAC) with a buffer or gain stage converts the digital value into analog form. Again, the PGA400-Q1 is an example of this type of signal conditioner.

Errors in analog signal chain

The sense-element output is usually a signal with a very low span; in other words, the range of its output signal is small. Because of this, the conditioning of the sense-element output starts with a gain stage. As a result, the sense-element output is subject to different sources of amplifier errors such as input offset, gain and nonlinearity errors. These errors are in addition to the offset and nonlinearity errors inherent to the sense element itself.

The signal conditioners discussed in this article also have analog outputs that are typically generated with a DAC followed by a gain stage. This means that the conditioned signal is also subject to amplifier errors such as input offset, gain and nonlinearity errors in the analog output stages. These errors in the sensor conditioner occur as a result of mismatches between devices and components inside the IC. The errors can become exacerbated by how large a gain is applied to the sense element output signal, or to the conditioned output signal prior to being transmitted to the control or monitoring system.

Note that signals from sense elements have non-idealities. Therefore, the sense-element output is corrected for these non-idealities during sensor manufacturing, often with the help of a signal conditioner. It is during this calibration process that the errors in the analog signal chain are taken into consideration.

Figure 2 illustrates an example of an uncalibrated sensor signal conditioner and the desired output of a calibrated sensor conditioner with respect to the sense-element input signal. Note that the uncalibrated output includes non-idealities of both the sense element and analog circuits in the signal conditioners signal flow.

Two-step calibration process

The two-step calibration process consists of:

1. *Calibration of the back-end analog circuit errors*
   This calibration accounts for errors introduced to the signal after being conditioned by the digital circuits and converted back to analog form.
2. *Calibration of the front-end analog circuit errors*
   This calibration accounts for input offset, gain and non-linearity errors introduced in the signal from the sense element prior to being digitized.

Figure 3 shows the sections within the sensor conditioner that are related to the two-step calibration process.

The order of the calibration process matters because the calibration of the back-end analog circuits provides the "desired" output values needed for the calibration of the sense element and the front-end analog circuits.

Back-end circuit calibration

The calibration goals for the back-end and front-end analog circuits are nearly the same—to reduce errors introduced by the analog signal chain non-idealities and thereby improve accuracy of the sensor output. However, the data points used to calibrate the back-end circuits come from within the sensor conditioner, not the sense element.

To truly calibrate the back-end circuits, the DAC and the rest of the output analog circuitry has to be isolated from the digital signal-conditioning circuits. The external calibration system then writes to the DAC directly and measures the output of the back-end analog circuits (output pin of the signal conditioner). Standard curve-fitting algorithms are used to curve-fit the data. This curve is used to determine the DAC value required in the calibration of the sense-element output. Note that the number of data points needed for this calibration depends on the non-idealities present in the back-end analog circuits. Since the data points are controlled by the user and not the sense element, the calibration is usually done with only a few data points. Additionally, if the back-end analog circuit behavior changes with temperature, this process must be repeated at different temperatures.

Once the transfer function of the back-end analog circuit and the desired DAC codes are determined, these DAC codes are then incorporated in the calculations for the calibration of the front end.

Figure 2. Ideal output of a calibrated sensor versus the signal from the sense element

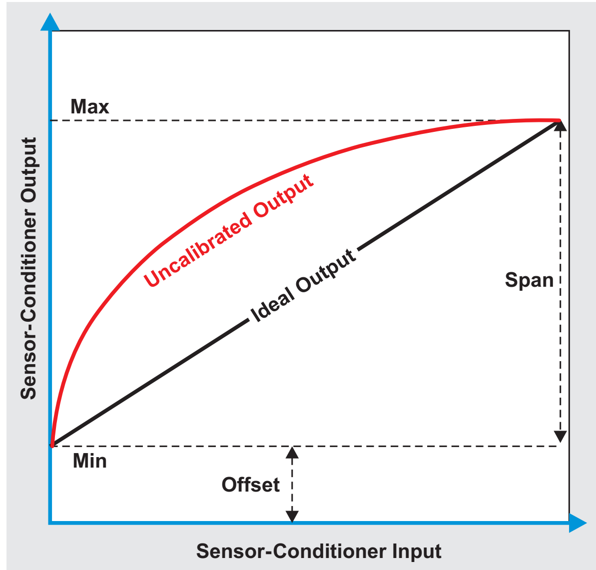
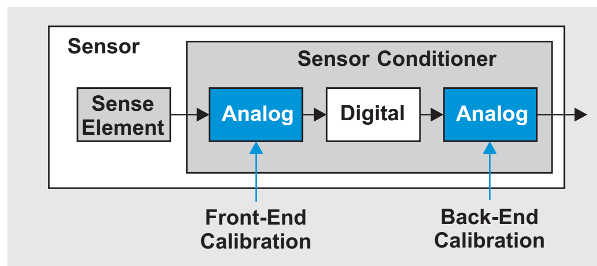


Figure 3: Sensor calibration requires both front-end and back-end curve fitting



Front-end calibration

Front-end calibration depends largely on the output signal linearity of the sense element. Moreover, since the calibration of the sensor is performed by the manufacturer, time and cost are also driving factors. As mentioned earlier, different methods, depending on the desired accuracy of the sensor, can be implemented.

In general, the sensor conditioner uses mathematical algorithms to calibrate the sensor output when the sense element is excited by the specific stimulus related to the application (pressure and temperature, for example). The number of measurements depends on the capability of the sensor conditioner to process the data, as well as the time required to calibrate the sensor. For example, the front-end of a pressure sensor could be calibrated by measuring the output of the ADC at three input signal points. Standard curve-fitting techniques can be used to determine the desired transfer function from ADC output to DAC input. This is accomplished using the ADC data and

DAC code calculated during calibration of the back-end circuits. However, the same three pressure points could be taken at three different temperatures. This would turn into nine total measurements—three pressure values at three temperatures. The resulting mathematical expression for the output of the sensor conditioner is then a second order equation:

$$\text{Output} = \left(h_0 + h_1 T + h_2 T^2\right) + \left(g_0 + g_1 T + g_2 T^2\right)P + \left(n_0 + n_1 T + n_2 T^2\right)P^2 \quad (1)$$

where h_0, h_1, h_2, g_0, g_1, g_2, n_0, n_1 and n_2 are the coefficients used to match the output of the sense element to the desired output of the sensor conditioner. Because the back-end circuit results are used to calculate these coefficients, back-end calibration must be preformed first.

As can be inferred, three different pressure measurements across three different temperatures (3P:3T) would be more time-consuming and complex than just three pressure measurements all at one temperature (3P:1T). However, the sensor's output could be more accurate for the former compared to that of the latter. Depending on the application and capabilities of the sensor conditioner, a combination of these could be used, such as two pressure measurements at two temperatures (2P:2T) or four pressure measurements at four temperatures (4P:4T).

Conclusion

A two-step calibration process can be used in mixed-signal sensor conditioners with analog outputs. The process improves the accuracy of the sensor in general by mitigating errors in the analog signal chain.

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