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APPLICATION NOTE 4067

Using the MAX1452 for Remote-Sensor Compensation

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Abstract: The MAX1452 high-performance analog signal conditioner allows linear compensation either by using the on-chip flash memory lookup tables or by using the OTC and FSOTC DACs. For applications in which the MAX1452 and a sensor cannot be at the same temperature (e.g. the sensor is remote from the MAX1452), the OTC and FSOTC DACs should be used to compensate the sensor output. This application note details the procedure for performing such a remote-sensor compensation. In this article, it is assumed that the reader is already familiar with the MAX1452 and its basic operation.

Introduction

The MAX1452 is a high-performance, low-cost signal conditioner with on-chip flash memory, an on-chip temperature sensor, and a fully analog signal path. This signal conditioner has been utilized in a variety of industrial and automotive sensor applications, including applications that are limited to performing a compensation with only two temperature points. This limitation could be due to cost, manufacturing, and/or because the sensor and the signal conditioner cannot be maintained at the same temperature.

With the MAX1452 signal conditioner, two compensation methods are possible:

1. The first method performs linear extrapolation (of the FSO and OFF DAC values) between the two compensation temperature points, and loads each element of the OFF and FSO lookup tables with unique temperature coefficients to correct TC error of the input signal. In this method, the OTC and FSOTC DACs are set to fix arbitrary values (the same values used during compensation). During operation, compensation of the input signal is achieved by updating the OFF and FSO DACs with corresponding coefficients as the temperature of the MAX1452 changes.

2. The second method treats the OFF and FSO lookup tables as single DACs. The temperature-dependent bridge-excitation voltage (VB), which is the reference voltage to the OTC and FSOTC DACs, is used as the temperature parameter. Based on the measurements taken during the compensation procedure, unique values for the OFF, FSO, OTC, and FSOTC DACs are calculated. This method must be used for cases in which the MAX1452 and the sensor cannot be at the same temperature. It can also be used for cases in which the MAX1452 and the sensor are at the same temperature.

Both of these compensation methods should yield similar results. If implemented correctly, they will completely eliminate the linear component of the input signal's TC error and reduce the output error to only the nonlinear component of the input signal's TC error.

The first method is described in detail in the MAX1452 User Manual and will not be covered in this application note. The second method, commonly referred to as remote-sensor compensation, is described below.

Procedure for Remote-Sensor Compensation

The procedure below describes how to compensate a pressure transducer that incorporates the MAX1452 and a 100KPaG PRT pressure sensor. The compensation results are shown in **Table 1** and **Figures 1–3**. The transducer was compensated to produce the desired offset voltage [$V_{OUT}(P_{MIN})$] of 0.5V and the desired FSO voltage [$V_{OUT}(P_{MAX}) - V_{OUT}(P_{MIN})$] of 4.0V. Thus, the output voltage at full-scale pressure [$V_{OUT}(P_{MAX})$] should be 4.5V. The procedure requires a minimum of two pressure points (zero and full scale) and two arbitrary temperature points (T1 and T2, where T2 > T1). T1 and T2 should be selected such that the best linear fit through the data points produces the smallest error over the full operating temperature range.

The following outlines the main steps of the procedure:

1. Coefficient Initialization
2. FSO Calibration
3. FSO and FSOTC Compensation
4. OTC Compensation
5. OFF Compensation

Coefficient Initialization

To start the procedure, the PGA gain, IRO index, and DACs must be set to values that will prevent overload of the PGA output throughout the compensation procedure. These values depend on the sensor's characteristics, which can be obtained from the sensor's data sheet.

Selecting the PGA Gain Setting

Calculate the required signal gain by dividing the desired transducer's full-scale output voltage ($VFSO_{DESIRED}$) by the measured sensor's span (VS_{OUT}) for a typical bridge-excitation voltage (VB) of 2.5V. Then, from the PGA table in the MAX1452 data sheet, choose the PGA_{INDEX} that gives the next higher PGA_{GAIN}.

For example, a sensor with 0.0364V output at 2.5V excitation and a $VFSO_{DESIRED}$ of 4.0V requires a signal gain of 110V/V. Based on the PGA table in the data sheet, we would choose PGA[3:0] = 0110, which corresponds to a gain of 117V/V.

Selecting the IRO Index

Calculate the sensor's offset for a typical bridge-excitation voltage of 2.5V. Then, from the IRO table in the MAX1452 data sheet, choose the IRO_{INDEX} that provides the nearest IRO DAC output, but with the opposite sign of the sensor's offset.

Example: for a sensor that has +30mV offset, choose IRO[2:0] = 011 and sign bit = 0, which corresponds to -27mV of offset correction.

Selecting the Initial OTC DAC Value

Generally, the OTC DAC value can initially be set to zero since the OTC will be compensated for in a later step. However, sensors with large offset TC errors may require an initial coarse OTC adjustment to prevent the output from saturating during the compensation procedure. An initial nonzero OTC value is recommended for sensors with an offset TC error of greater than 10% of the full-scale output. The initial OTC value can be calculated using the following equation:

$$OTC = 65535 \times \frac{[VS_{OUT}(T1) - VS_{OUT}(T2)]}{[VB(T1) - VB(T2)]} \qquad \text{(Eq. 1)}$$

Where VB(T1) = 2.5V and VS_{OUT}(T1), VS_{OUT}(T2), and VB(T2) can be calculated using the sensor parameters given by the sensor's data sheet.

The value of OTC must be written to the OTC DAC, and the OTC sign bit in the configuration register must be set accordingly.

FSO Calibration

Perform the following steps to determine the initial FSO DAC value:

1. Set the FSOTC DAC to an arbitrary value, e.g., 0.
2. Apply P_{MIN} to the sensor. P_{MIN} represents the minimum pressure.
3. Adjust the FSO DAC until the bridge-excitation voltage is approximately 2.5V.
4. Measure the bridge-excitation voltage (VB).
5. Set the PGA_{OUT} voltage to 0.5V by adjusting the OFF DAC.
6. Measure PGA_{OUT}, $V_{OUT}(P_{MIN})$.
7. Apply P_{MAX} to the sensor. P_{MAX} represents the maximum pressure.
8. Measure PGA_{OUT}, $V_{OUT}(P_{MAX})$.
9. Calculate VB_{IDEAL} by applying the following equation:

   $$VB_{IDEAL} = VB \times \frac{(VFSO_{DESIRED})}{[V_{OUT}(P_{MAX}) - V_{OUT}(P_{MIN})]} \qquad \text{(Eq. 2)}$$

   If VB_{IDEAL} is outside the allowable range [1.5V to (V_{DD} - 0.5V)] readjust the PGA_{GAIN} setting. If VB_{IDEAL} is too low, decrease the PGA_{GAIN} by one step and then return to Step 2. If VB_{IDEAL} is too high, increase the PGA_{GAIN} setting by one step and then return to Step 2. Note that the 1.5V < VB < (V_{DD} - 0.5V) range limitation applies over the full operating range. Therefore, sufficient margins must be allowed for VB changes over temperature.

10. Set VB_{IDEAL} by adjusting the FSO DAC.
11. Readjust the OFF DAC until PGA_{OUT} is 0.5V.

FSO and FSOTC Compensation

The FSO and FSOTC coefficients can be determined in four steps. In Step 1, two pairs of FSO and

FSOTC values that yield VB_{IDEAL} at T1 are determined. In Step 2, two pairs of FSO and FSOTC values that yield VB_{IDEAL} at T2 are determined. In Step 3, the FSO and FSOTC values measured at T1 and T2 are applied to appropriate equations to calculate the compensation FSO and FSOTC values that (theoretically) will produce a VB_{IDEAL} value that applies at any temperature. In Step 4, the FSO DAC can be adjusted to fine-tune the full-scale output.

1. Ideal bridge voltage at T1, $VB_{IDEAL}(T1)$

   A. Set the temperature to T1 and allow enough soak time for the bridge voltage to stabilize within 0.1mV/min.

   B. Apply P_{MIN} to the sensor.

   C. Measure the bridge-excitation voltage (VB).

   D. Measure PGA_{OUT}, $V_{OUT}(P_{MIN})$.

   E. Apply P_{MAX} to the sensor.

   F. Measure PGA_{OUT}, $V_{OUT}(P_{MAX})$.

   G. Calculate $VB_{IDEAL}(T1)$ by applying Equation 2.

   H. Set VB_{IDEAL} by adjusting the FSO DAC.

   I. Remeasure $V_{OUT}(P_{MAX})$ and $V_{OUT}(P_{MIN})$ to verify that the appropriate $VFSO_{DESIRED}$ level has been achieved. If not, repeat all steps starting from Step B.

   J. Record the current FSO and FSOTC values as FSO1(T1) and FSOTC1(T1), respectively.

   K. Increase (or decrease) the FSO DAC value by 5000 counts.

   L. Adjust the FSOTC DAC value until $VB = VB_{IDEAL}(T1)$.

   M. Record the current FSO and FSOTC values as FSO2(T1) and FSOTC2(T1).

   N. Apply P_{MIN} to the sensor.

   O. Read and record the output voltage as $V_{OUT}(T1)$. This value will later be needed for the OTC compensation.

   P. Read and record VB as VB(T1). This value should be the same as $VB_{IDEAL}(T1)$ and will be needed for OTC compensation.

2. Ideal bridge voltage at T2, $VB_{IDEAL}(T2)$

   A. Set the temperature to T2 and allow enough soak time for the bridge voltage to stabilize within 0.1mV/min.

   B. Apply P_{MIN} to the sensor.

C. Read and record the output voltage as $V_{OUT}(T2)$. This value will later be needed for OTC compensation.

D. Read and record VB as VB(T2).

E. Determine the $VB_{IDEAL}(T2)$ value using the same steps as above.

F. Determine the FSO1(T2) and FSOTC1(T2) values using the same steps as above.

G. Determine the FSO2(T1) and FSOTC2(T2) values using the same steps as above.

H. Apply P_{MIN} to the sensor.

3. Calculate the FSO and FSOTC Coefficients

A. FSO and FSOTC curve/function at T1:

$$m(T1) = \frac{[FTC1(T1) - FTC2(T1)]}{[FSO1(T1) - FSO2(T1)]} \qquad \text{(Eq. 3)}$$

$$z(T1) = FTC1(T1) - m(T1) \times FSO1(T1)$$

B. FSO and FSOTC curve/function at T2:

$$m(T2) = \frac{[FTC1(T2) - FTC2(T2)]}{[FSO1(T2) - FSO2(T2)]}$$

$$z(T2) = FTC1(T2) - m(T2) \times FSO1(T2)$$

C. Final FSO coefficient:

$$FSO = \frac{[z(T2) - z(T1)]}{[m(T1) - M(T2)]} \qquad \text{(Eq. 4)}$$

D. Final FSOTC coefficient:

$$FSOTC = z(T1) + m(T1) \times FSO \qquad \text{(Eq. 5)}$$

4. Load the calculated FSO and FSOTC values in the FSO and FSOTC DACs and, if necessary, adjust the FSO DAC until the bridge-excitation voltage is equal to $VB_{IDEAL}(T2)$.

This completes the FSO and FSOTC compensation. At this point, the FSO output of the transducer must be equal to the level of $VFSO_{DESIRED}$.

OTC Compensation

All necessary information to calculate the final OTC value has already been gathered. Use the following equation:

$$NewOTC = CurrentOTC - 65535 \times \frac{[V_{OUT}(T1) - V_{OUT}(T2)]}{[VB(T1) - VB(T2)]} \qquad \text{(Eq. 6)}$$

Where:
NewOTC is the final OTC coefficient;
CurrentOTC is the value currently in the OTC DAC;
V_{OUT}(T1) and VB(T1) are the last measurements while at T1;
V_{OUT}(T2) and VB(T2) are the first measurements after the T2 soak.

Write the NewOTC value in the OTC DAC and set the OTC DAC sign bit in the Configuration Register accordingly.

OFF Compensation

At this point the sensor should still be at temperature T2 and pressure P_{MIN}. The final offset adjustment can be made at T2 or T1 by adjusting the OFF DAC, and, if necessary, the OFF DAC sign bit, until V_{OUT} equals the desired offset voltage (0.5V in this example).

Sensor compensation is now complete!

Verifying Sensor Compensation

Compensation should be verified by subjecting the transducer to various temperature and pressure points and checking PGA_{OUT}.

Example

The data presented below is a demonstration of the effectiveness of the procedure detailed above. A 100KPaG gauge sensor (part number: NPH-8-100GH) was used and its output compensated at P_{MIN} = 0, P_{MAX} = 100KPaG, T1 = -40°C, and T2 = +125°C. The target output voltage was $PGA_{OUT}(P_{MIN})$ = 0.5V and $PGA_{OUT}(P_{MAX})$ = 4.5V. At the completion of the compensation process, the compensated transducer was characterized at T = -40°C, 0°C, +25°C, +75°C, and +125°C. The two-temperature compensation has completely eliminated the linear part of the sensor's error. Total error from the compensated transducer is comparable to that of the nonlinear component of the uncompensated sensor's error.

Table 1 lists the measured outputs and calculated errors for both the uncompensated sensor and compensated transducer. The uncompensated sensor's error is presented in two formats: Total Error (TE) and Nonlinear Error (NE). TE refers to the combined linear and nonlinear components of the TC error (referenced to the span at 25°C). NE is the Total Error minus the linear component of the error calculated as deviation from a straight line passing through the two end points of the data set (end-point straight-line fit). The data in Table 1 is graphically presented in Figures 1–3. Figure 1 shows the Total Error from the uncompensated sensor; Figure 2 shows the nonlinear component of the uncompensated sensor error; and Figure 3 shows the Total Error from the compensated transducer. The data shows that our two-point compensation procedure has completely eliminated the linear component of the sensor, and the TE from the compensated transducer is comparable to that of the nonlinear component of the uncompensated sensor.

Table 1. Uncompensated Sensor and Compensated Transducer Data

Temp (°C)	Uncompensated Sensor (P_{MIN} = 0; P_{MAX} = 100KPaG; VB = 5V)						Compensated Transducer (P_{MIN} = 0; P_{MAX} = 100KPaG; V_{DD} = 5V)			
	Offset (mV)	FSO (mV)	Total Error (% FSO, Referenced at +25°C)		Nonlinear Error (% FSO, End-Point Fit)		Offset (V)	FSO (V)	Total Error (% FSO, End-Point Fit)	
			Offset	FSO	Offset	FSO			Offset	FSO
-40	-4.2	97.7	-5.3	9.9	0.0	0.0	0.496	4.006	-0.1	0.2
0	-1.0	89.3	-1.5	3.8	1.5	-1.8	0.553	3.933	1.3	-1.7
+25	0.3	84.8	0.0	0.0	1.6	-2.0	0.565	3.930	1.6	-1.8
+75	2.5	76.6	2.6	-7.1	1.3	-1.5	0.552	3.957	1.3	-1.1
+125	3.8	69.2	4.1	-14.3	0.0	0.0	0.500	4.001	0.0	0.0

In this example, extreme temperature points were used for compensation, and an end-point straight-line fit was applied to the measured data to more clearly demonstrate the effectiveness of the two-temperature point compensation. Extreme temperature points are not the optimum points for sensor compensation as the error will be one-sided (and mathematically, twice the magnitude). In application, the optimum compensation temperature points must be chosen empirically so that the transducer's error is distributed evenly around the 0% error line. Typically, temperature points at 25% and 75% (mid-points) of the full range will give optimum error distribution. If we had chosen optimum compensation temperature points for this exercise, then the error distribution would have been approximately ±½ of the one-sided errors given in Table 1 (centered around the 0% error line).

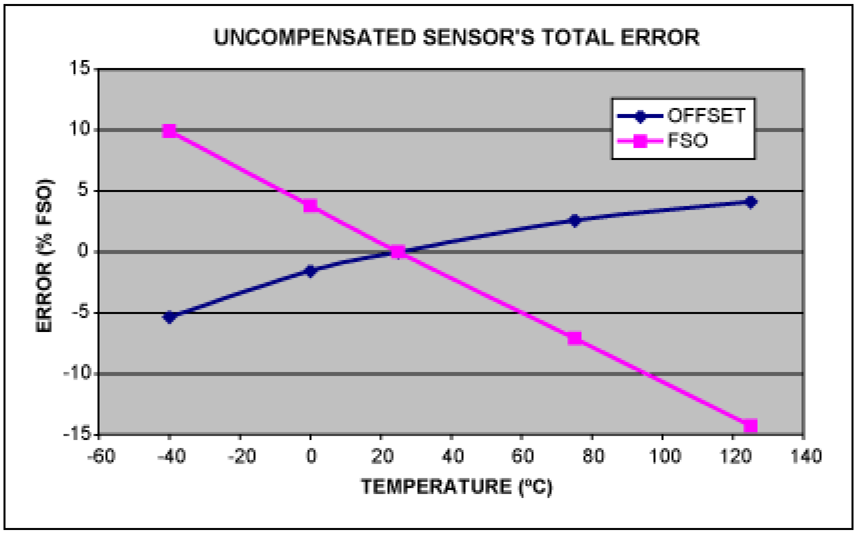

Figure 1. Uncompensated sensor's total error—combined 1st-order and 2nd-order error.

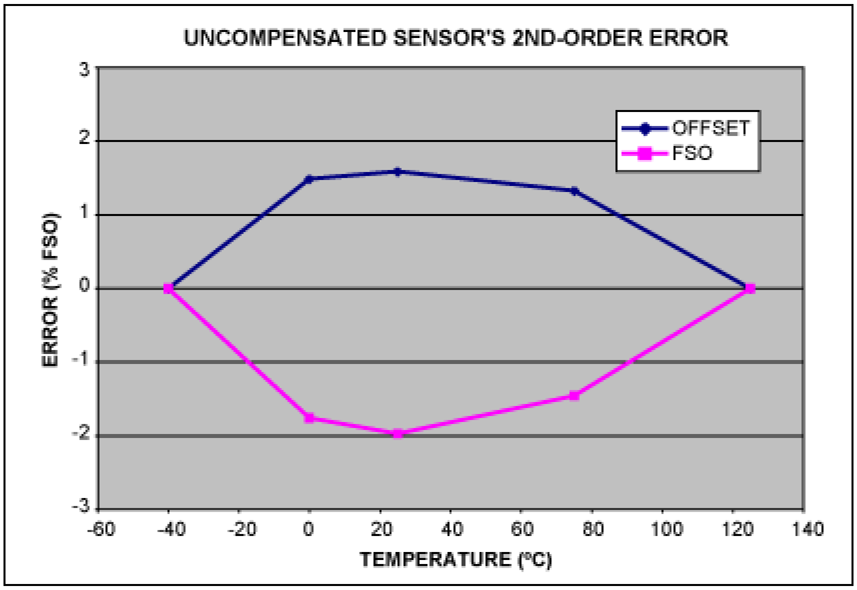

Figure 2. Uncompensated sensor's 2nd-order error. This is the deviation from the end-point straight-line through the data in Figure 1.

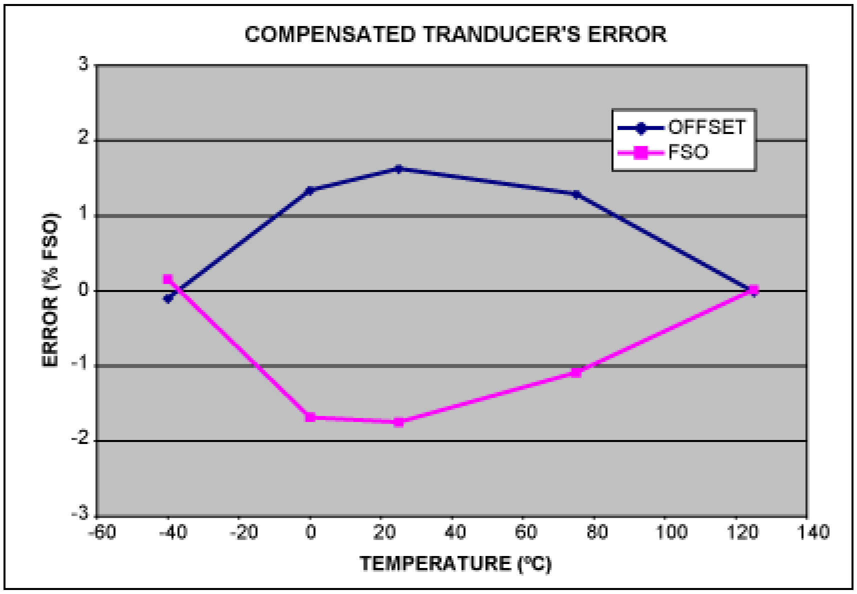

Figure 3. Compensated transducer's error. This is the total error after compensation coefficients have been applied. A two-point temperature compensation can only correct for the linear part of the error.

Concluding Observations

1. This application note is intended as an example to demonstrate a remote-sensor compensation procedure and describe a manual approach for achieving that compensation. Other approaches more suitable for automated compensation are described in the MAX1452 User Manual, included in the EV kit software tool, which can be downloaded from Maxim's website.

2. To take full advantage of the MAX1452's capabilities, it is necessary to perform two runs of compensation. The first run is to determine the OTC and FSOTC coefficients to effectively correct

the linear component of the TC error, as described in this document. The second run is a multitemperature-point compensation to fill the OFF and FSO lookup tables with correction coefficients that cancel out the remaining nonlinear TC error. The multitemperature compensation procedure is described in the MAX1452 User Manual.

3. In a manufacturing environment, it is possible to load the OTC and FSOTC DACs with nominal values and perform only one multitemperature compensation to take full advantage of the MAX1452's capabilities. This is possible because the TC characteristics (such as sensitivity, offset, etc.) of similar sensors are very similar. The nominal OTC and FSOTC (as well as the PGA_{GAIN} and IRO) values can be determined by performing a two-point compensation on representative samples.
4. In this application note, the MAX1452 was used as the product of choice. However, the procedure will equally apply to the MAX1455, as there are only small differences between these two products.

References

Maxim Home Page
MAX1452 Data Sheet
MAX1452 User Manual
MAX1452 EV Kit Software
NPH-8-100GH Data Sheet (included at the end of the MAX1452 user manual).

Related Parts		
MAX1452	Low-Cost Precision Sensor Signal Conditioner	Free Samples
MAX1455	Low-Cost Automotive Sensor Signal Conditioner	Free Samples

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