Signal conditioning circuitry for the RXU and XSU series sensors

INTRODUCTION

Ideally, a piezoresistive pressure sensor's output should be independent of temperature. Unfortunately, for all piezoresistive silicon pressure sensors, as the ambient temperature is increased, the sensitivity actually decreases. This is because the piezoresistive effect is decreasing with higher temperature. Therefore, the sensitivity of the diaphragm to pressure actually decreases with increases in temperature (see Fig. 1).

To compensate for these changes in sensitivity, the sensor's bridge voltage must change to keep the output independent of temperature. Historically, this has not been an easy problem to solve in production as thermistors and other compensation schemes require tweaking or adjustment to meet reasonable tolerances over industrial temperature ranges.

This application note describes a low cost approach for temperature compensating Sensortechnics' RXU series sensors which is easy to implement in production. The discussed solution can also be used for other uncompensated pressure sensors such as Sensortechnics' XSU series.

THE PROBLEM

The sensor's actual span is equal to the product of the sensitivity (S), the transducer bridge voltage (V_B) and the pressure change from a reference pressure ($P-P_O$):

$$\text{Span} = S \cdot V_B \cdot (P - P_O) \qquad (1)$$

However, because the sensitivity actually decreases with an increase in temperature, the bridge voltage must increase or change in the opposite direction in order for the output voltage span to remain independent of temperature.

THE OLD SOLUTION - THERMISTORS

One of the older and more common methods of providing span compensation for pressure sensors involves the use of thermistors as shown in Fig. 2.

The basic idea behind the various thermistor compensation schemes is that the resistance of the thermistor decreases with increasing temperature. Therefore, with a constant voltage source, the voltage across the bridge will increase with increasing temperature. This then compensates the sensor for decreases in sensitivity and keeps the overall sensor output independent of temperature.

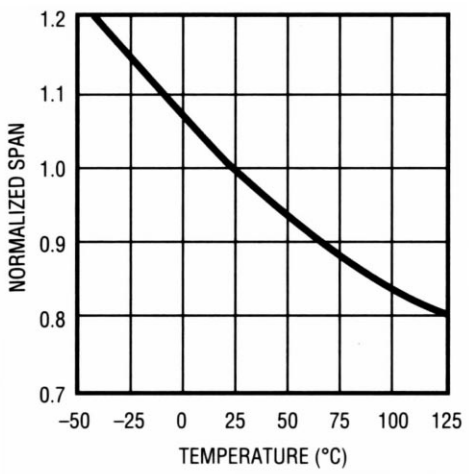

Figure 1: Typ. sensitivity vs. temperature response for piezoresistive silicon pressure sensors

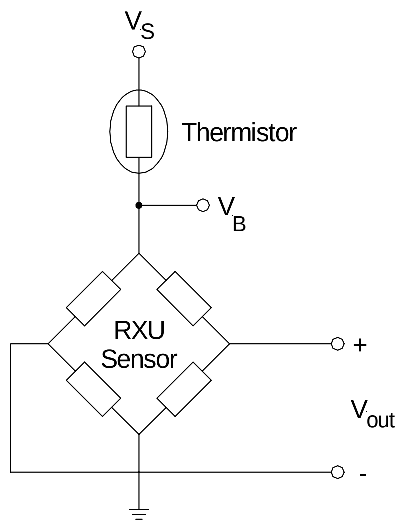

Figure 2: Simple thermistor compensation scheme

Unfortunately, thermistors do not provide a simple and easy-to-use solution for most applications. Some of the problems with thermistors are as follows. First, low cost thermistors are non-linear, making the desired thermal response difficult to obtain. Second, many times a significant amount of voltage must be dropped across the thermistor compensation network in order to get the proper thermal characteristics. This leaves less voltage across the sensor which necessitates more gain in the output amplifiers. Last and perhaps most important, low cost thermistors typically have ten percent tolerances and, as a result, there is a trade-off between thermistor error, cost, and ease of production manufacturing. The following section discusses a method of temperature compensating First Sensors RXU sensors using low cost, close tolerance current source such as the LM334 to eliminate these problems.

THE NEW SOLUTION

General Discussion

By using an LM334, one can compensate a silicon pressure sensor easily and inexpensively. The LM334 is a three-pin programmable current source featuring an output current that rises linearly with temperature at +0.33 %/°C (see the LM334 data sheet from National Semiconductor Corp.). Taking the typical temperature coefficients from the RXU data sheet, one can see that putting the LM334 directly in series with the RXU pressure sensor would result in overcompensating for the sensor's changes in sensitivity over temperature. This is due to the fact that the bridge sensitivity changes at -2150 ppm/°C while the LM334 and changing resistance of the sensor would combine to cause the voltage across the sensor to change at +2250 ppm/°C.
The circuit shown in Fig. 3 allows one to adjust resistor R_2 to reduce the overall TC of the compensation circuitry to provide span compensation of +2150 ppm/°C, which compensates for the drop in bridge sensitivity.

This method of span compensation also allows the bridge voltage to be selected and not determined by the voltage across the compensation network. The main advantage of this is that one can select the bridge voltage to be as high as 1 V below the supply voltage. This higher voltage across the bridge minimises gain needed in later amplifier networks.

Span errors of less than 1 % can be obtained between 0 °C and 75 °C by using this circuit. One should note, however, that beyond this temperature range thermistors or more complex compensation schemes will be needed to again achieve errors on the order of 1 %.

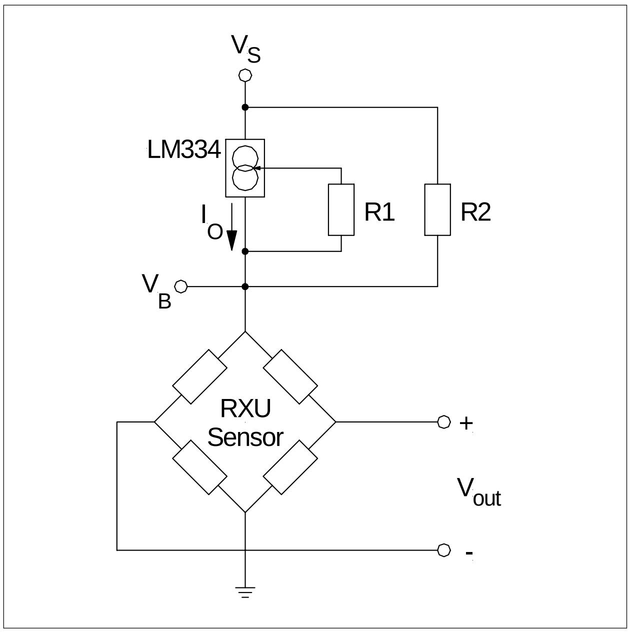

Figure 3: LM334 compensation network

Calculations

In order to obtain the desired span compensation, the best resistor values of R_1 and R_2 must be calculated. By solving the nodal equation for the bridge voltage, the bridge voltage equation becomes:

$$V_B = \alpha\left(V_S + I_O \cdot R_2\right) \qquad (2)$$

Now taking the derivative with respect to temperature and normalising it with respect to the bridge voltage at 25 °C, we obtain:

$$\frac{\dot{V}_B}{V_B} = \frac{\dot{I}_O}{I_O}\left(1-\alpha\frac{V_S}{V_B}\right) + \frac{\dot{R}_B}{R_B}\left(1-\alpha\right) \qquad (3)$$

Where

$\frac{\dot{V}_B}{V_B}$ = Temperature coefficient of the bridge voltage [ppm/°C]

$\frac{\dot{I}_O}{I_O}$ = Temperature coefficient of the LM334 current source [ppm/°C]

V_S = Supply voltage [V]

V_B = Desired initial bridge voltage at 25 °C [V]

$\frac{\dot{R}_B}{R_B}$ = Temperature coefficient of the bridge resistance [ppm/°C]

R_B = Initial bridge resistance at 25 °C [Ω]

$\alpha = \frac{R_B}{R_2 + R_B}$

Solving equation (3) for resistor R_2 gives

$$R_2 = \frac{R_B\left[\frac{\dot{I}_O}{I_O}\left(\frac{V_S}{V_B}-1\right)+\frac{\dot{V}_B}{V_B}\right]}{\frac{\dot{R}_B}{R_B}+\frac{\dot{I}_O}{I_O}-\frac{\dot{V}_B}{V_B}} \qquad (4)$$

Once R_2 is known, R_1 can be derived from the equation

$$R_1 = 67.7\ \text{mV}\,\frac{\left(R_2\,\alpha\right)}{V_B - \alpha\,V_S} \qquad (5)$$

and $$I_O = \frac{\left(R_2\,\alpha\right)}{V_B - \alpha\,V_S}$$ (see LM334 datasheet)

EXAMPLE

Assume that V_S is 5 V with an initial bridge voltage V_B = 4 V. From the RXU data sheet we have

R_B = 4100 Ω

$\frac{\dot{I}_O}{I_O}$ = 3300 ppm/°C

V_S = 5 V

V_B = 4 V

$\frac{\dot{V}_B}{V_B}$ = 2150 ppm/°C

$\frac{\dot{R}_B}{R_B}$ = 750 ppm/°C

Substituting the above values into equations (4) and (5) we find that

$$R_2 = 6.42\ \text{k}\Omega$$
$$R_1 = 82.56\ \Omega$$

The closest standard value 1% resistors are R_2 = 6.49 kΩ and R_1 = 82.5 Ω.

Calculated resistor values for other supply voltages are shown in table 1.

V_S	V_B (@ 25°C)	R_1	R_2
9 V	5 V	81.3 Ω	10.34 kΩ
12 V	7.5 V	51.1 Ω	8.91 kΩ

Table 1: Calculated resistor values vs. V_S

Typical Circuit Performance

Using the values calculated above for R_1 and R_2, several devices were measured over temperature with the results of these devices shown in Fig. 4. Typical errors were found to be in the range of ±1%.

If these fixed resistor values are used in volume manufacturing, the worst case span error of a single device that can be expected over a 50 °C temperature range is +2.9 % to -3.6 %. This is computed using the maximum and minimum limits from the RXU dies design given for R_B/R_B, R_B and TC span. This is a worst case calculation and it would be extremely improbable that all errors would accumulate in the worst case direction.

If higher accuracy is desired, resistor R_2 can be replaced with a 5.99 kΩ 1 % metal-film resistor in series with a 2 kΩ metal-film potentiometer. Each system can then be individually adjusted to be within acceptable limits. When using a pot and adjusting the value of R_2 in each circuit, the initial voltage across the bridge (V_B) will also change slightly from the initial value. This will then change the sensor's initial (25°C) span slightly. These changes in span are, however, relatively small and should be easily accommodated by adjusting the gain in the output amplifiers.

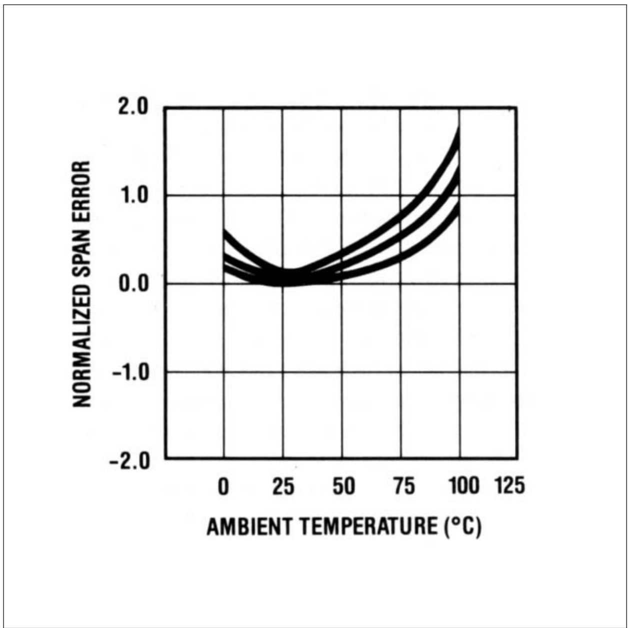

Figure 4: Typ. results using the LM334 span compensation network

BATTERY OPERATION

For battery operation, the circuit shown in Fig. 5 is recommended. By using a second LM334, the current I_2 will not change with the battery voltage. An LM336-5.0 is used to isolate the resistor R_2 from the battery voltage. Equations (4) and (5) can be used to find R_1 and R_2 with V_S replaced by V_Z (5 V in this example).

To find R_3 we need to find the current through R_2 which is given by:

$$I_2 = \frac{(V_Z - V_B)}{R_2}$$

Then R_3 should be selected to give I_2 plus an additional I_Z for the zener diode. Therefore

$$R_3 = \frac{67.7\ \text{mV}}{I_2 + I_Z}$$

Notice I_2 will change with temperature but the voltage V_Z will not.

Typical values for operation using a 9 V battery and 3 V across the bridge would be:

I_Z = 1 mA
R_1 = 82.5 Ω 1 %
R_2 = 6.49 kΩ 1 %
R_3 = 59 Ω 1 %

This circuit will operate until the battery voltage drops below V_S=6.0 V.

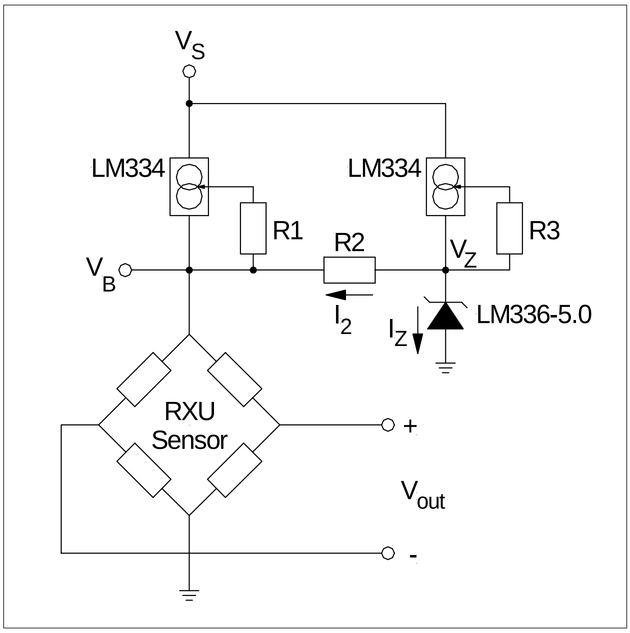

Figure 5: LM334 portable span compensation

CONCLUSION

By using the LM334 current source and two metal-film resistors, span compensation of piezoresistive silicon pressure sensors can be accomplished easily and accurately. The span compensation error will typically be less than 1 % from 0 °C to 75 °C. This technique is conductive to volume manufacturing as it does not involve non-linear elements such as thermistors. Additionally, the method is suitable for portable and battery applications since the voltage across the bridge can be made independent of the supply (battery) voltage.