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Application Report
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Connecting PGA900 Instrumentation Amplifier to Resistive Bridge Sensor

Miro Oljaca, Peter Semig, Collin Wells *Enhanced Industrial and Precision Analog*

ABSTRACT

Understanding the input and output limitations of an instrumentation amplifier (IA) is important in interfacing a resistive bridge sensor to the PGA900. Adjusting the common mode voltage of the input signal appropriately allows you to maximize the gain. Maximizing the gain yields the largest output signal span for the 24-bit analog-to-digital converter (ADC). The largest signal span maximizes the code utilization and effective noise-free resolution. This application report discusses the limitations of the signal sensor, IA, and PGA900. This report shows that by adding two resistors to the bridge, it is possible to increase the resolution compared to directly connecting the bridge to the PGA900.

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2 Ideal Resistive Bridge Sensor

Resistive bridge sensors are widely used in the industry for measuring different physical properties like pressure and temperature. A real sensor differs from an ideal one by introducing limitations that the designer must take into account when designing a measurement system. Figure 1 depicts a pressure sensor element from Metallux AG. The center of the sensor element has four resistors. When pressure is applied, two resistors are stretched and other two are compressed as shown in Figure 1.

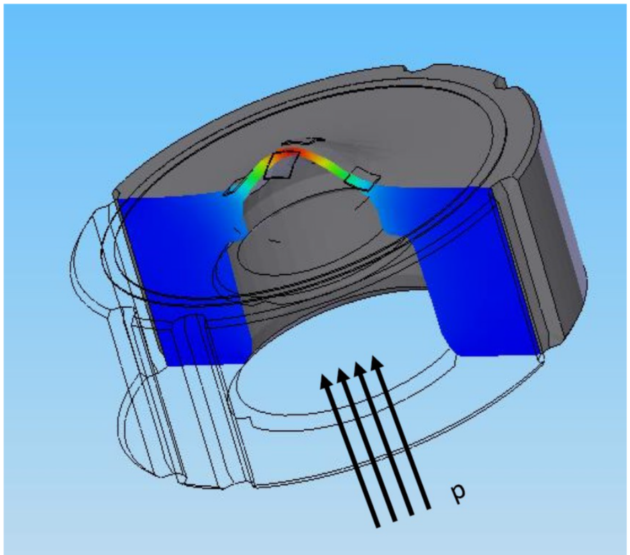

Figure 1. Pressure Sensor Operating Principle

These four resistive sensor elements are connected as a Wheatstone bridge as shown in Figure 2. When no external pressure is applied, four bridge resistors for the ideal sensor have the same initial value R and output voltage between nodes B and D, V_{BD}, is zero.

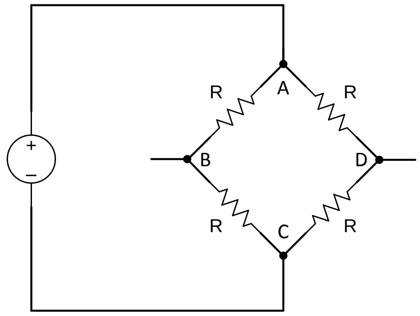

Figure 2. Resistive Bridge Sensor Without Pressure Applied

When the resistive bridge from Figure 1 and Figure 2 is exposed to the physical signal, in this case pressure, the four resistors change value. The resistance of the stretched resistors increases, while the resistance of the compressed resistors decreases. Referring to Figure 2, resistors with the same behavior are placed on opposite sides of the bridge. Compressed resistors are placed between nodes A and B, R_{AB}, and nodes C and D, R_{CD}. Stretched resistors are placed between nodes C and B, R_{CB}, and nodes D and A, R_{DA}.

Change in resistance is proportional to the applied excitation or pressure. For the full range of physical excitation, the bridge resistors have a maximum change in value, R_{SPAN}, that produces the maximum differential output voltage. Figure 3 shows that R_{SPAN} is added or subtracted from the ideal resistance, R, depending on whether the resistor is stretched or compressed, respectively.

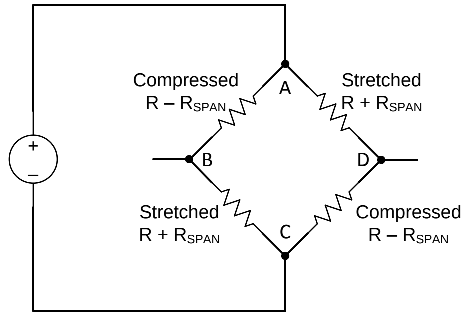

Figure 3. Resistive Bridge Sensor With Pressure Applied

For future analysis, the four bridge resistors R1, R2, R3, and R4 are defined in through Equation 1.

$$R_1 = R_{AB} = R - R_{SPAN}$$
$$R_2 = R_{BC} = R + R_{SPAN}$$
$$R_3 = R_{DA} = R + R_{SPAN}$$
$$R_4 = R_{CD} = R - R_{SPAN} \quad (1)$$

Using Equation 1, Figure 3 can be redrawn as shown in Figure 4.

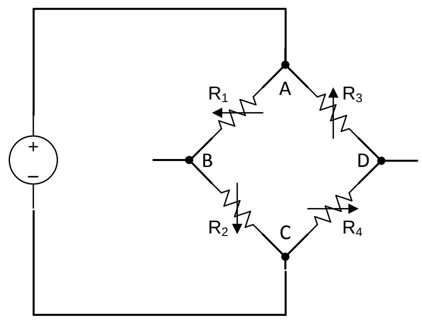

Figure 4. Resistive Bridge Sensor

3 Real Resistive Bridge Sensor

Despite good sensor manufacturing processes, imperfections can lead to differences in initial resistor values. The initial values of the four bridge resistors are not equal, which results in different initial output voltages for each sensor. For a real sensor, two parameters define the output voltages at nodes B and D. First, Equation 2 defines the common-mode voltage (V_{CM}).

$$V_{CM} = \frac{V_{BC} + V_{DC}}{2} \tag{2}$$

Secondly, Equation 3 defines the offset voltage (V_{OFFSET}) with no external applied pressure.

$$V_{OFFSET} = V_{BD} \tag{3}$$

As previously mentioned, these two parameters are a consequence of the initial values of the bridge resistor. Equation 4 and Figure 5 show this relationship.

$$\begin{aligned} R_1 &= R + \Delta R_1 \\ R_2 &= R + \Delta R_2 \\ R_3 &= R + \Delta R_3 \\ R_4 &= R + \Delta R_4 \end{aligned} \tag{4}$$

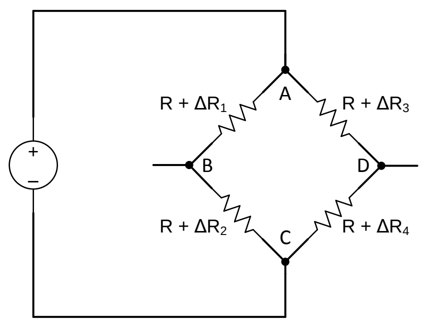

Figure 5. Real Resistive Bridge Sensor Without Pressure Applied

An example of a real sensor is initial values for 10-kΩ sensor are shown in Equation 5.

$$\begin{aligned} R_1 &= 9.4\ k\Omega \\ R_2 &= 10.6\ k\Omega \\ R_3 &= 9.6\ k\Omega \\ R_4 &= 10.4\ k\Omega \end{aligned} \tag{5}$$

Using the values from Equation 5, calculate the initial change in the resistance for every resistor by applying Equation 4.

$$\begin{aligned} \Delta R_1 &= -0.6\ k\Omega \\ \Delta R_2 &= +0.6\ k\Omega \\ \Delta R_3 &= -0.4\ k\Omega \\ \Delta R_4 &= +0.4\ k\Omega \end{aligned} \tag{6}$$

The initial change in resistance for each resistor in the bridge contributes to the common-mode and offset error. You can rewrite Equation 6 using Equation 2 and Equation 3 as shown in Equation 7. R_{CM} and R_{OFFSET} represent the common-mode and offset error contribution.

$$\begin{aligned} \Delta R_1 &= -R_{CM} - R_{OFFSET} \\ \Delta R_2 &= +R_{CM} + R_{OFFSET} \\ \Delta R_3 &= -R_{CM} + R_{OFFSET} \\ \Delta R_4 &= +R_{CM} - R_{OFFSET} \end{aligned} \tag{7}$$

Three coefficients that are interesting in where describing a real sensor in a final application are the initial common-mode voltage, initial offset voltage, and output span voltage. All three output voltages, V_{CM}, V_{OFFSET}, and V_{SPAN} are a function of the bridge excitation voltage, or voltage apply between inputs A and C, V_{AC}. For future analysis, it is more convenient to define the output voltage coefficients as shown in Equation 8.

$$k_{CM} = 0.5 \times \frac{1 + R_{CM}}{R}$$

$$k_{OFFSET} = \frac{R_{OFFSET}}{R}$$

$$k_{SPAN} = \frac{R_{SPAN}}{R} \quad (8)$$

To understand differential signal values, use following example. The restive bridge has a nominal value of 10 kΩ. Common mode resistance is 500 Ω, offset resistance is 100 Ω, and span resistance is 10 Ω. Based on these values, you can now calculate corresponding voltage coefficients.

$$k_{CM} = 525 \text{ mV/V}$$

$$k_{OFFSET} = 10 \text{ mV/V}$$

$$k_{SPAN} = 1 \text{ mV/V} \quad (9)$$

Select a bridge excitation voltage of 1.25 V. Now it is easy to calculate corresponding components of the differential voltage signal.

$$V_{CM} = k_{CM} \times V_{EXT} = 656.25 \text{ mV}$$

$$V_{OFFSET} = k_{OFFSET} \times V_{EXT} = 12.5 \text{ mV}$$

$$V_{SPAN} = k_{SPAN} \times V_{EXT} = 1.25 \text{ mV} \quad (10)$$

4 Definition of the Differential Signal

Differential signaling is a method for electrically transmitting information using two complementary signals. The technique sends the same electrical signal as a differential pair of signals, each in its own conductor. The signals on the two conductors are of opposite polarity so their waveforms are mirror images. The receiving circuit responds to the electrical difference between the two signals rather than the difference between a single wire and ground.

A resistive bridge sensor as shown in Figure 2 provides a differential signal between nodes B and D. If you include the previously defined common-mode, offset, and span voltages, you can replace the resistive bridge sensor with an equivalent circuit as shown in Figure 6.

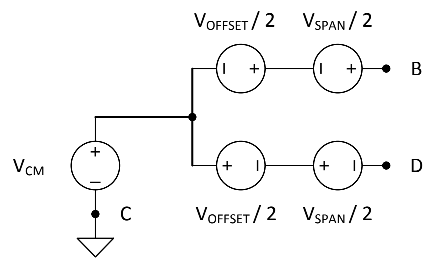

Figure 6. Resistive Bridge Output Voltages

The voltages at nodes B and D are given in Equation 11 and Equation 12, respectively.

$$V_B = V_{CM} + ½\ V_{OFFSET} + ½\ V_{SPAN} \quad (11)$$

$$V_D = V_{CM} – ½\ V_{OFFSET} – ½\ V_{SPAN} \quad (12)$$

Now you have all the values needed to calculate output voltages at the pins B and D in the example. Use Equation 11, Equation 12, and Equation 10. Voltages from initial values to the full span are:

$$V_B = 662.5\ ...\ 663.13\ mV$$

$$V_D = 649.38\ ...\ 650\ mV \quad (13)$$

5 Interfacing Resistive Bridge Sensor to PGA900

An instrumentation amplifier (IA) is typically used to interface with a resistor bridge sensor because of the amplifier's high input impedance. Figure 7 shows the input gain stage of the IA as implemented in the PGA900.

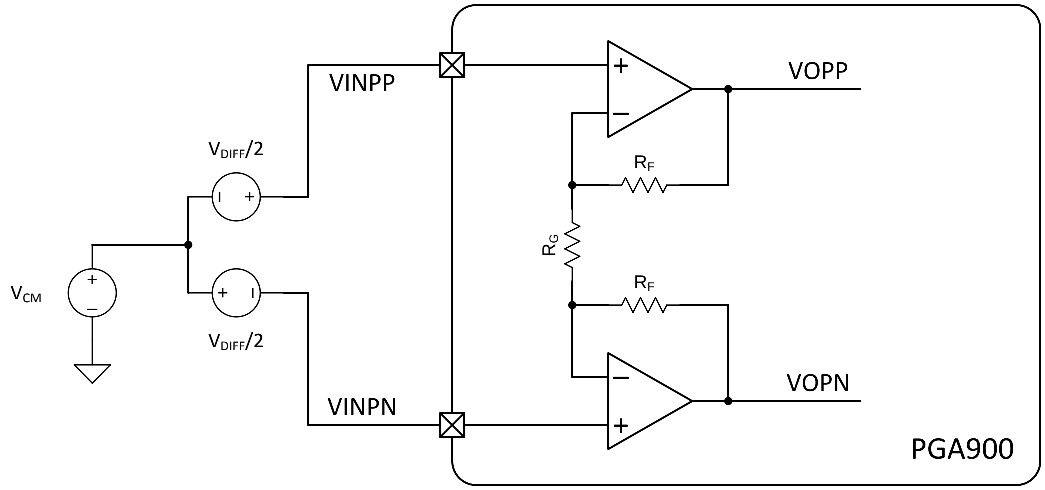

Figure 7. PGA900 Instrumentation Amplifier Input Stage

In Figure 7, offset and span signals are replaced with more commonly used input differential signal.

$$V_{DIFF} = V_{OFFSET} + V_{SPAN} \tag{14}$$

The IA output voltages, V_{OPP} and V_{OPN}, are defined in Equation 15 and Equation 16, respectively.

$$V_{OPP} = V_{CM} + \frac{V_{DIFF}}{2} \times \left(1 + 2\frac{R_F}{R_G}\right) \tag{15}$$

$$V_{OPN} = V_{CM} - \frac{V_{DIFF}}{2} \times \left(1 + 2\frac{R_F}{R_G}\right) \tag{16}$$

The PGA900 has digitally programmable gain that ranges from 5 V/V up to 400 V/V. This gain can be set up using P_GAIN bits.

$$PGAIN = 1 + 2\,\frac{R_F}{R_G} \tag{17}$$

Replacing Equation 17 into Equation 15 and Equation 16, you have the final description of the output voltages.

$$V_{OPP} = V_{CM} + \frac{V_{DIFF}}{2} \times PGAIN \tag{18}$$

$$V_{OPN} = V_{CM} - \frac{V_{DIFF}}{2} \times PGAIN \tag{19}$$

6 Input and Output Voltage Limitations of PGA900's IA

The IA input stage of the PGA900 has a differential output. This output is fed directly into a 24-bit ΔΣ ADC. The applied sensor signal to the PGA900 has two main constraints. The absolute value of the input signal to V_{INPP} and V_{INPN} must be in the range from 0.3 V to 1.8 V. If one or both signals violate one of these limits, the quality of the output signal is compromised.

$$V_{INPP}, V_{INPN} \in (0.3\text{ V} \ldots 1.8\text{ V}) \quad (20)$$

The second limitation is related to the range of the IA output signals. Both output IA signals, V_{OPP} and V_{OPN}, must be in the range from 0.1 to 2.0 V. If the input signal or IA gain is not properly set and the output signal of one or both signals violate one of these limits, the integrity of the signal is not linear.

$$V_{OPP}, V_{OPN} \in (0.1\text{ V} \ldots 2.0\text{ V}) \quad (21)$$

Using Equation 20 and Equation 21 and the transfer function graph for the, IA, you can plot boundaries for the input and output signals ensure optimal operation.

7 Selecting Bridge Excitation Voltage

Before you analyzed voltages, that sensor provides to the input of IA and voltages on the output. You saw that the input common-mode voltage is equal to the output common-mode voltage. Also, you saw that the input differential voltage is much smaller than output. Based on these two parameters you can see that ideally, you would like the common-mode voltage to be as close as possible to the middle point of the IA output voltage range.

$$V_{CM\_IN} = V_{CM\_OUT} \tag{22}$$

$$V_{CM\_IDEAL} = \frac{0.1\text{ V} + 2.0\text{ V}}{2} = 1.05\text{ V} \tag{23}$$

The PGA900 has an internal buffer with selectable voltage for the bridge supply. The bridge voltage can be selected between 1.25, 2.0, and 2.5 V. These voltages are created from an internal 2.5-V precision reference. The bridge supply voltage is selected using the VBRDG_CTRL register.

In some applications, it is important to minimize power dissipation in the sensor element. For that reason, smaller excitation voltage applied to the sensor is desired. Unfortunately, smaller excitation voltages reduces input signal common mode voltage and limits the IA gain. To overcome this problem, it is desirable to add top and bottom resistors to the sensor bridge. These resistors reduce sensor excitation voltage, and at the same time position, the input signal common mode voltage as close as possible to the ideal value.

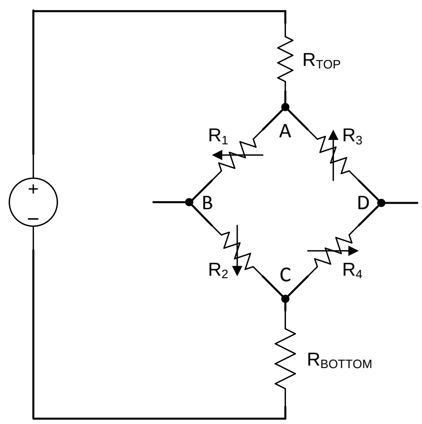

Figure 8. Resistive Bridge Sensor With Added Top and Bottom Resistors

The resistive bridge sensor from Figure 4 is redrawn by adding top and bottom resistors and shown in Figure 8.

Using resistive bridge values and added top and bottom resistors, you can now define the bridge voltage between nodes A and C as:

$$V_{AC} = \frac{R}{R + R_{TOP} + R_{BOTTOM}} \times V_{EXT} \tag{24}$$

For the new common mode voltage calculation, use Equation 25 and Equation 26.

$$V_{CM} = \frac{R_{BOTTOM}}{R + R_{TOP} + R_{BOTTOM}} \times V_{EXT} + k_{CM} \times \frac{R}{R + R_{TOP} + R_{BOTTOM}} \times V_{EXT} \tag{25}$$

$$V_{CM} = \frac{R_{BOTTOM} + k_{CM} \times R}{R + R_{TOP} + R_{BOTTOM}} \times V_{EXT} \tag{26}$$

8 Design Example

For this example, limit the maximum voltage at the sensor to 1.6 V and use a 10-kΩ resistive bridge sensor.

First, calculate resolution when connecting the sensor directly to the PGA900 without any additional top or bottom resistor. Select 1.25 V as a bridge excitation voltage. The next available option is 2.0 V, which violates the initial design criteria. From Equation 10, you can see that the common mode voltage is 656.25 mV. The full span input differential signal is 13.75 mV. For this input voltage, you can apply gain of 80 V/V. With this gain, output voltages V_{OPP} and V_{OPN} are 1.206 V and 0.106 V respectively. The PGA900 P_Gain transfer function given these conditions is shown in Figure 9.

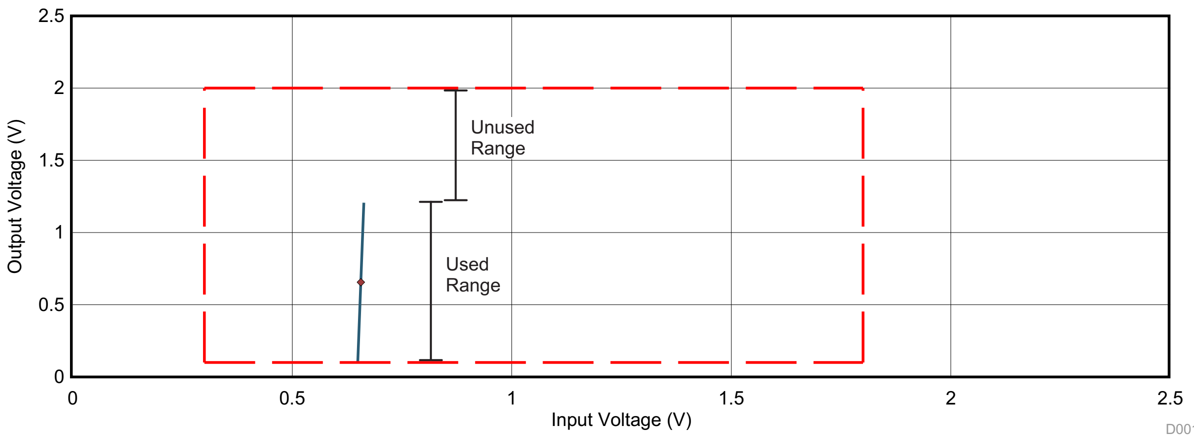

Figure 9. P_Gain Transfer Function for Only Resistive Bridge

Signal from P_Gain is passed to the 24-bit ADC with full scale range (FSR) of 5 V. After gaining the input span voltage of 1.25 mV by 80 V/V, the output span voltage is 100 mV. The resolution of the ADC is 298 nV and span voltage can be presented with 335544 different codes. If you neglect noise, this gives you an effective measurement signal resolution of 18.36 bit.

$$1\ \text{LSB} = \frac{5\ \text{V}}{2^{24}} = 298\ \text{nV} \tag{27}$$

$$\text{codes} = \frac{P_{Gain} \times V_{SPAN}}{1\,\text{LSB}} = 335544 \tag{28}$$

$$\text{Effective measurement resolution} = \frac{\ln(335544)}{\ln(2)} = 18.36\ \text{bit} \tag{29}$$

The second step is to add bottom and top resistors. This permits you to use higher excitation voltage and have a maximum available voltage of 1.6 V on the bridge. Now, select PGA900 bridge output voltage of 2.0 V and add 1.33 kΩ at the bottom and 1.18 kΩ on the top of the resistor bridge. In this configuration, the common mode voltage is 1.052 V, which is very close to ideal one calculated using Equation 23. Full span input differential signal is 17.59 mV. For this input voltage, apply a gain of 100 V/V. With this gain output, voltages V_{OPP} and V_{OPN} are 1.931 V and 0.173 V, respectively. The new PGA900 P_Gain transfer function for these conditions is shown in Figure 10.

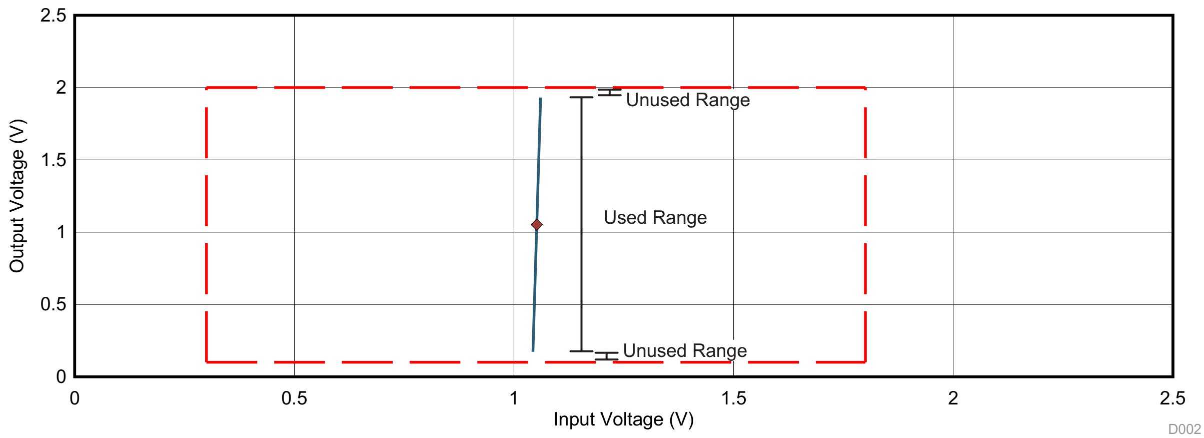

Figure 10. P_Gain Transfer Function for Resistive Bridge With Added Bottom and Top Resistor

After gaining input span voltage of 1.59 mV by 100 V/V output span, voltage is 159 mV. As you saw before with ADC resolution of 298 nV, span voltage can be presented with 536442 different codes compare to previous one of 335544. If you neglect noise, this gives you an effective measurement signal resolution of 19.3 bit, which is an increase compared to the previous one of 18.36 bit.

9 Conclusion

Understanding input and output limitations of the IA is important in interfacing resistive bridge sensor. If the common mode voltage of the input signal is positioned close to ideal, it is possible to use a higher gain. This produces a higher output signal span voltage for the 24-bit ADC. As the resolution of the ADC is fixed, higher gain permits to measure input signal with a higher number of codes or ENOB is higher. In this application report looked at the limitation of the signal sensor, IA, and PGA900. The application report showed that it is possible to add two resistors in the signal path to increase resolution as compared to directly connecting the bridge to the IA.

10 References

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8. Metallux AG, *Pressure Sensors*

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.