Low-Power Signal Conditioning for a Pressure Sensor

Application Report

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Application Report

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Abstract

This application report describes the signal conditioning required to interface an analog pressure sensor to a digital processing unit for further processing. Design considerations and specific steps are shown for conditioning the output signal of a pressure sensor to serve as an input to an A/D converter. The resulting application is a low-power and low-cost system suitable for altitude measurements. Methods of correcting inherent system errors and calibration of the circuit are also covered.

Contents

Texas Instruments

Figures

Tables

1   Introduction

This application report details signal conditioning for a pressure sensor circuit that can be used for altitude measurements. The goal is to develop a very small system with an acceptable resolution for low-power and low-cost applications. The resulting circuit described here uses a 3-V supply and a single operational amplifier. It is shown that a smart digital processing system can be designed to correct some of the system errors and create a highly competitive product.

The application is designed for a pressure range of 9.9 psi to 15.75 psi. This relates to the usual range of air pressure from below sea level up to a height of 3000 m above sea level, and fulfills barometric meter requirements.

This report provides information on how a low-cost pressure and height meter might be designed. In addition, it covers some simple basics of altitude measurements and includes a discussion of a pressure–height translation (application example: hiker watch). This document refers to the application report *Signal Acquisition and Conditioning With Low Supply Voltages* (TI literature number SLAA018), available at any TI sales office or from the TI internet site (www.ti.com).

2   General Circuit Basics

Signal conditioning in today's applications typically consists of a circuit to connect an analog sensor to a digital acquisition system. This circuit requires three functions: the first one to linearize the output signal of the sensor, the second to amplify the signal to a degree that it falls within the ADC input range, and the third to limit the signal frequency such that it does not exceed the capabilities of the digital system that follows (see Figure 2–1).

The first task, the linearization of the output, can alternatively be performed digitally. The other two functions, however, are analog requirements.

Before delving into the circuit details, the need for the three functions (linearization, amplification, and limiting) in a pressure sensor application is discussed. The basic circuit concept and its subsequent development then follows.
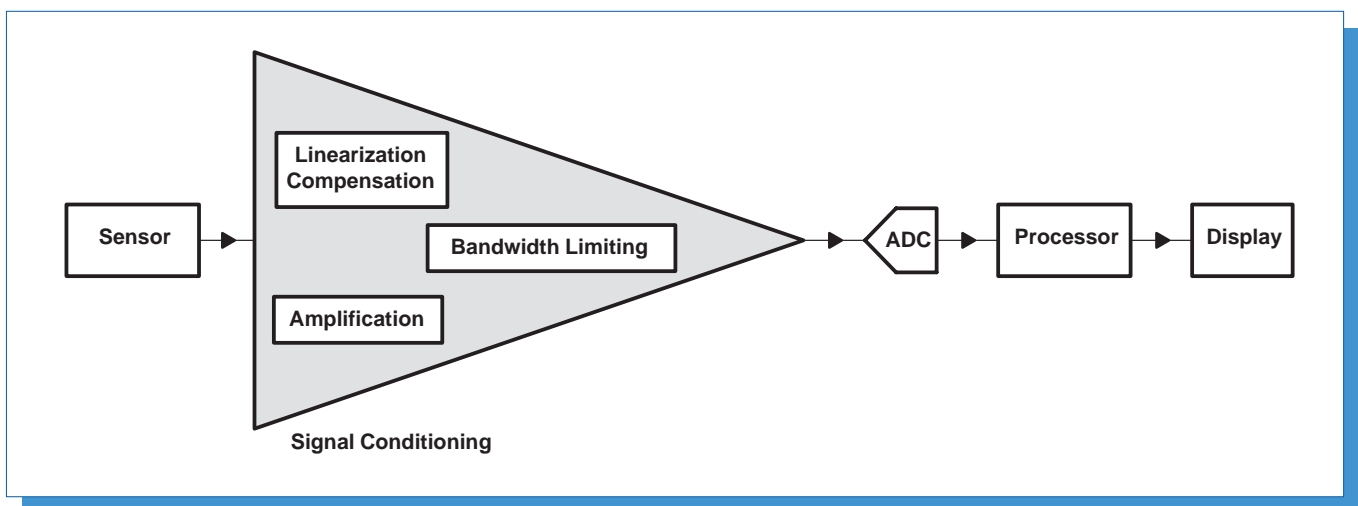

Figure 2–1. Signal Conditioning

2.1 Linearization/Compensation

The output characteristics of a pressure sensor vary somewhat with the product design. The ideal response is a linear relationship of pressure to output — or a straight line. In general, however, actual pressure variation and the sensor's output are related by a curve with a shape that is close to a straight line. Correcting the deviation from the straight line (curve) requires either an amplifier circuit with a response that is a mirror-image of the sensor response curve or a digital algorithm implemented in a microcontroller or DSP. The digital solution currently seems to make the most sense.

The simplest correction in the digital domain would be a multipoint measurement of the pressure sensor output, stored in the DSP memory. Then, the actual pressure can be easily calculated through a linear approximation between the two points, which captures the actual value (see *Linear Approximation* later in this document).

Hysteresis and repeatability errors can degrade the accuracy of most pressure sensors:

- Hysteresis error
    - Sensor output is different for a given pressure when the pressure changes from a higher or lower pressure
- Repeatability errors
    - Gain variations between two measurements

Environmental factors such as temperature, humidity, and time can also adversely affect sensor accuracy. Temperature, in particular, influences the output signal of pressure sensors. Compensation for temperature variations can be accomplished by regulating the sensor supply voltage, by regulating the sensor output signal, or in the digital domain with an additional temperature measurement (see SLAA018 for more information). This document does not include temperature compensation. Instead, the user can determine if it makes more sense to accept the temperature errors or to compensate for them based on application and cost considerations.

2.2 Amplification

All analog-to-digital converters (ADCs) are limited in their input (measurement) voltage range for operation. Often, the ADC reference input voltage can be varied within a small range to adjust the overall input voltage range. In any case, the pressure sensor output signal is usually in the millivolt range and must be amplified to a point where it falls within the input voltage range of the ADC. Most amplifiers currently in use for these applications are operational amplifiers. The amplifier section described here is based on a single operational amplifier.

2.3 Bandwidth Limiting

Every analog-to-digital interface has frequency constraints. As provided by Nyquist, the highest allowable frequency component in an analog signal before sampling with an ADC is less than or equal to one-half the sampling frequency. A low-pass filter function is implemented ahead of almost every ADC to remove the higher frequency components that are present in most analog signals. This ensures that the input signal to the ADC contains no component of significant magnitude whose frequency is above Nyquist limit.

The low-pass filter must be designed carefully. Filter order depends on the required steepness of the slope of the filter, which is dependent on how close the required filter cutoff frequency is to the Nyquist limit imposed by the ADC sampling frequency. The required filter order increases as the filter cutoff frequency approaches the Nyquist limit.

The ADC architecture also influences filter requirements. For example, using a sigma-delta ADC reduces the complexity of the filter because of internal ADC oversampling.

The amplifier section, implemented with an operational amplifier, also realizes the filter function by simply adding an RC network around the amplifier. In this application, a single capacitor provides a first-order low-pass filter function (see *Circuit Description*).

Because altitude measurements do not provide output signals that are faster than a few Hz, a first order filter with a cutoff frequency of 1 Hz and an ADC sampling rate higher than 100 Hz will fulfill the sampling theorem requirements with room to spare. Therefore, signal components above the Nyquist rate (50 Hz in this case) are attenuated at least 34 dB.

2.4 Circuit Description

Two general types of pressure sensors are available. One requires a constant current supply and the other requires a stable voltage supply. The application in this report uses the voltage-type sensor.

The pressure sensor used in this application is basically a resistor bridge with a pressure-variable resistor in each leg (figure 2–2). Hence, the output is a differential voltage referenced to $V_{CC}/2$.

Many different circuits for signal conditioning can be found. These circuits typically use a large number of components, which improves circuit accuracy, but cost more and require more space.

This report, however, demonstrates the applicability of a single operational amplifier solution.
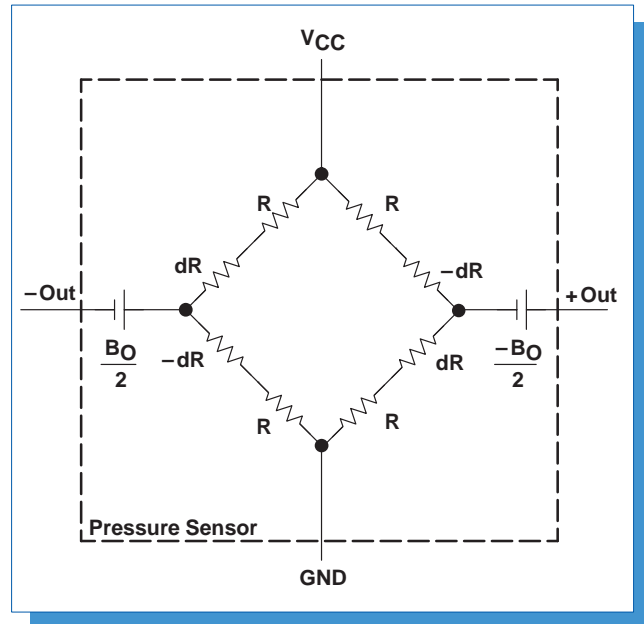

Figure 2–2. Pressure Sensor Model

3 Atmospheric Pressure

Because of gravity, the air that surrounds us has a particular weight. And the force that this weight exerts on objects is called air pressure. The weight of a vertical column of air one inch square that extends from sea level upward to the end of the atmosphere is approximately 14.7 pounds. Thus, air pressure at sea level is approximately 14.7 pounds force per square inch of area, or 14.7 psi.

Air pressure diminishes as the altitude of the measurement point increases because the length of the column of air above the measuring instrument is shorter and, therefore, weighs less. Atmospheric pressure decreases by approximately 0.036 psi for each 1000 feet of elevation. In addition, local weather phenomenon can increase or decrease the air pressure at a particular altitude a small amount from the norm.

Elementary kinetic gas theory and Newton's law of universal gravitation being well understood as they relate to air pressure, it is possible to calculate the approximate air pressure at a certain point above sea level.

3.1 Units of Measure

The standard unit of pressure in the English or foot-pounds-second (FPS) system is pounds per square inch, or psi. Once force has been accurately measured, pressure can be determined by dividing the force by the area it is exerted over (*P=F/A*). At sea level, the gases and liquids that make up the atmosphere exert a pressure of approximately 14.696 psi.

In some situations, it may be necessary to know if an indicated pressure includes or excludes atmospheric pressure. Pounds per square inch *absolute* is referenced to a starting point of no pressure (0 psi). Thus, a pressure measuring instrument designed to indicate PSIA will read 14.696 pounds per square inch when the sensing element is exposed to atmospheric pressure at sea level.

The more common pressure measurement is pounds per square inch *gage.* Psi gage measurements are referenced to a starting point of atmospheric pressure and therefore indicate 0 PSI at sea level. Pressure measurements are assumed to be in pounds per square inch gage unless otherwise noted (with an A for absolute, for example), and are usually abbreviated as simply psi.

3.2 Approximation of Atmospheric Pressure

Air pressure can be approximated with the equation:

- Pressure calculation:

$$p(h) := k1 \cdot 2^{k2 \cdot h} \tag{1}$$

h = height over sea level

constants:

$$k2 := -1.813 \cdot 10^{-4} \cdot m^{-1}; \; k1 := 101600 \cdot Pa \tag{2}$$

$$or \; k1 := 14.7 \, psi \tag{3}$$

- Pressure at sea level:

$$p(0 \, m) = 14.7 \, psi \tag{4}$$

Because of the different international unit system, the most important translation is probably between psi and Pascal:

- Unit transfer psi into Pascals:

$$p\_pa \, (p\_psi) := p\_psi \cdot 6.894757293168362 \cdot 10^3 \tag{5}$$

- Unit transfer Pascals into psi:

$$p\_psi \, (p\_Pa) := \frac{p\_Pa}{6.894757293168362 \cdot 10^3} \tag{6}$$

3.2.1 Setting the Input Range for a Pressure Sensor

To define a useful operating range for the pressure sensor, it is probably a good idea to set the minimum altitude to a value that is slightly lower than the normal sea level elevation. It is reasonable to set the maximum altitude to 3000 m to allow measurement in high mountains.

- Maximum altitude above sea level
  - max_height = 3000 m
- Maximum pressure:
  - p_max = p(sea level) + 1 psi
    $max\_pressure = 14.7 \, psi + 1 \, psi = 15.7 \, psi$
- Minimum pressure
  - p_min = p(max_height)
    $min\_pressure = 10.1 \, psi$

The application must also be able to cope with pressure variations at various locations. Allowing for a maximum pressure variation of ±0.2 psi, the lowest pressure becomes:

- Minimum pressure
  - p_min = p(max_height)−0.2 psi
    $min\_pressure = 9.9 \, psi$

The graph in figure 3–1 illustrates the working range of pressure the application must handle properly.

It can also be seen in figure 3–1 that altitude is an exponential function of the atmospheric pressure. If one were to calculate the height of the sensor above sea level with this application, the evaluation of the result would requires a logarithmic calculation or a look-up table to approximate the curve. Paragraph 5.3 *Simplification for µP/DSPs to Calculate Actual Altitude*, later in this document, covers the approximation in more detail.
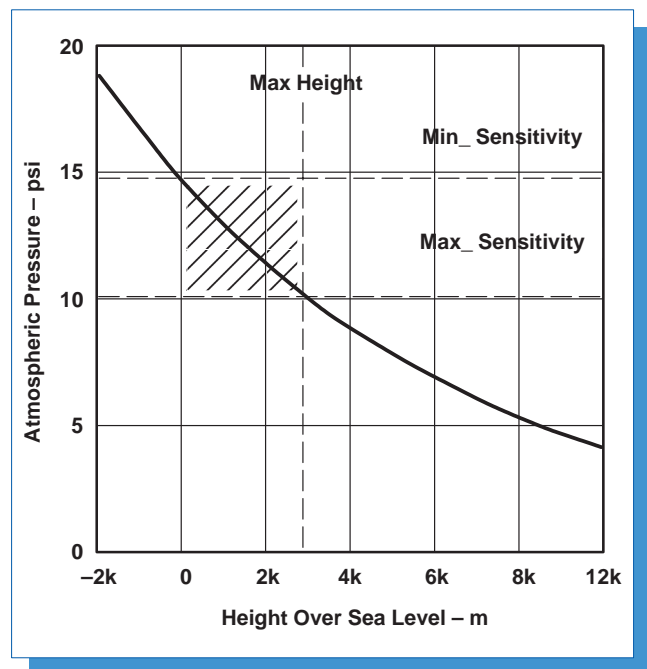

Figure 3–1. Atmospheric Pressure vs Altitude

3.3 Pressure–Altitude Translation

The following measurement results are used to analyze the accuracy of a transformation from atmospheric pressure into a height level under various weather conditions.

Measurement Results

Altitude of sensor:
    15 m above sea level

Location:
    Germany (JO33VN)

Pressure variation over the year:
    14.36 psi – 15.01 psi

Translation of the Pressure Variation Into the Altitude Calculation Formula

Lowest pressure:
    altitude (14.36 psi) = 206 m

Highest pressure:
    altitude (15.01 psi) = –147 m

Altitude calculation error:
    Δh = 353 m

This shows, that at one location on the earth, the pressure can vary about 1.4% over a long period of time, correlating to an altitude miscalculation of approximately 350 m.

Accordingly, having a simple pressure sensor in a portable device to measure the atmospheric pressure and to calculate the altitude from that would be so imprecise as to be useless. However, if the pressure could be measured according to a reference pressure measurement taken at the same time, the pressure variation would cancel itself and the result would be quite accurate.

This could be implemented in a portable device using a differential mode. If the user (for example: mountain climber) starts a day trip, they can set the instrument to a reference value (either the actual altitude or to zero). Then, assuming that the atmospheric pressure will vary only a small amount during a single day with stable weather conditions (for example: weather report forecasts clear conditions for the entire day), the user is now able to measure the actual altitude difference to the point where the instrument was to the reference.

A more detailed discussion on how the pressure–height translation can be implemented in a digital processor is in paragraph 5.3 *Simplification for μPs/DSPs to Calculate Actual Altitude*.

4   Pressure Sensor Signal Conditioning Circuit

4.1   Signal Conditioning with a Single Operational Amplifier

4.1.1   Requirements for the Circuit
- Low-power/low-voltage application (3-V battery powered)
- Limited tolerance in a given temperature range (0°C to 50°C working range)

- Low system cost (simple pressure sensor, single operational amplifier, small geometry)

4.1.2   A Simple Application Circuit
The circuit in figure Figure 4–1 shows a very simple solution to amplify the output voltage of a pressure sensor to levels suitable for A/D conversion and subsequent digital processing.
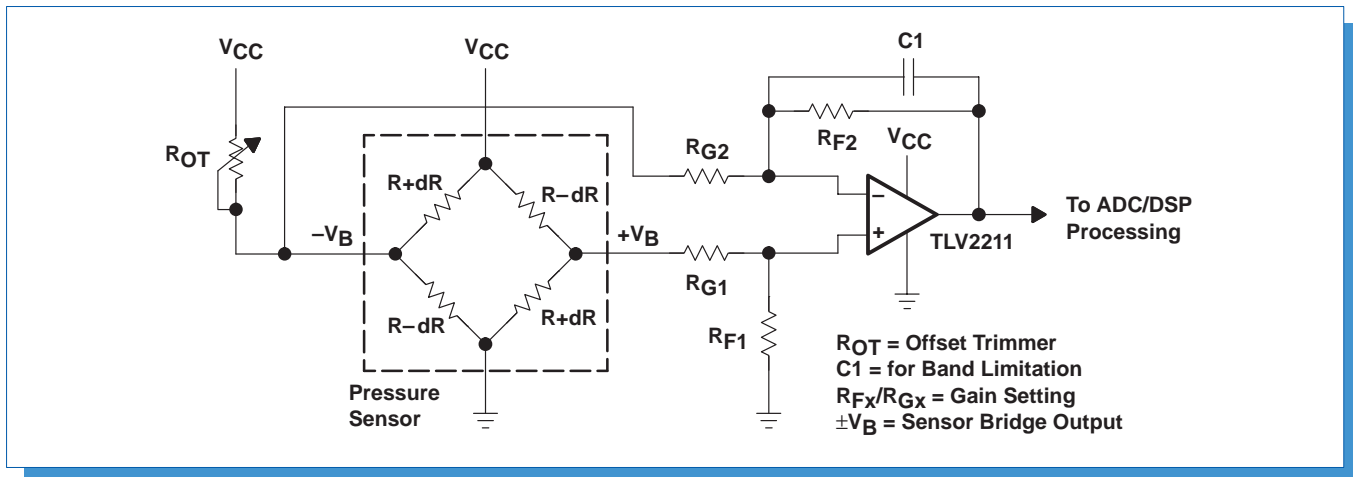

Figure 4–1. Pressure Sensor Signal Conditioning Circuit to Interface to an ADC

4.1.3   Component Error Listings
Various manufacturing tolerances and environmental factors can cause the performance of certain components to drift from their design specifications. For the highest accuracy, the system must compensate for these errors.

Tables 4–1 and 4–2 list the expected errors and their sources for the operational amplifier and the pressure sensor.

Table 4–1. Errors Contributed by the Operational Amplifier (TLV2211)

Parameter	Specification and Variation	Comment
Offset voltage	Typical: 0.47 mV Maximum: 3 mV	The input offset voltage will cause an output offset voltage equal to the amplitude of the input offset multiplied by the amplification ratio (R_F/R_G) of the op amp.
Bias current	Typical: 1 pA, Max: 150 pA	$I_B = \frac{1}{2}(I_{B+} + I_{B-})$
Offset current	Typical: 0.5 pA Maximum: 150 pA	$I_O = \|I_{B+} - I_{B-}\|$ Typically, I_{B+} is approx 1.25 pA and I_{B-} is approx 0.75 pA, so I_O works out to approx 0.5 pA.
Input resistance of operational amplifier	depends on R_F and R_G values	Lower resistance values for R_F and R_G will decrease the offset effect from the bias currents but will also influence the bridge voltage (low impedance network), higher values for R_F and R_G have the opposite effect.
Load current to charge the ADC input		Depending on the input capacitance of the ADC, a current supplied by the op amp is required. This current will decrease the op amp gain and therefore change the results. As the sampling rate is reduced (increasing the time to charge the capacitor), the accuracy will improve.

Table 4–2. Errors Contributed by the Pressure Sensor Bridge (Sensym SX15A)

Parameter	Specification and Variation	Comment
Sensitivity mismatch	1.5 mV/V/psi $\pm$ 0.5 mV/V/psi [$\pm$ 33%]	psi – pounds per square inch — unit of measurement for atmospheric pressure
Temperature	–2150 ppm/°C$\pm$250 ppm/°C [$\pm$ 0.24% per °C]	ppm – parts per million
Offset at zero psi	–4 mV/V – 3 mV/V /+ 4 mV/V	Must be removed by calibration of the resistors parallel to the bridge or by giving an additional digital offset to the ADC
Bridge resistor impedance variation	4.1 kΩ $\pm$ 0.5 kΩ	A variation of this parameter will influence the ratio for the parallel bridge resistors and produce an additional offset.
Noise	$\approx$ 3 μV at 0.1 Hz and 2 μV at 10 Hz	A low pass filter with a corner frequency around 10 Hz should be added to stabilize the output.

4.1.4 Compensating for Component Tolerances

A good circuit design for this application requires compensation for all component tolerance errors. Otherwise, the output line of the circuit can vary significantly — up to never intersecting the ADC working window at all, as shown in figure 4–2 (lower worst-case line). The data depicted in the graph is generated by a system gain of 114. This gain would drive an ideal pressure sensor output (no component tolerance errors) within the operating window.

One possible way to avoid having the lines fall out of the working window at any likely error level is to lower the amplifier gain and to offset the output until both worst case lines hit the window for the working range (see figure 4–3).

The disadvantage will be a very low gain, and consequently, a lower resolution. One might consider compensating the lower gain with a highly precise ADC. Although this seems possible, one would need to investigate and evaluate the noise characteristics of the pressure sensor carefully. Furthermore, the coupling of environmental noise into the circuit board would make good results difficult to achieve.
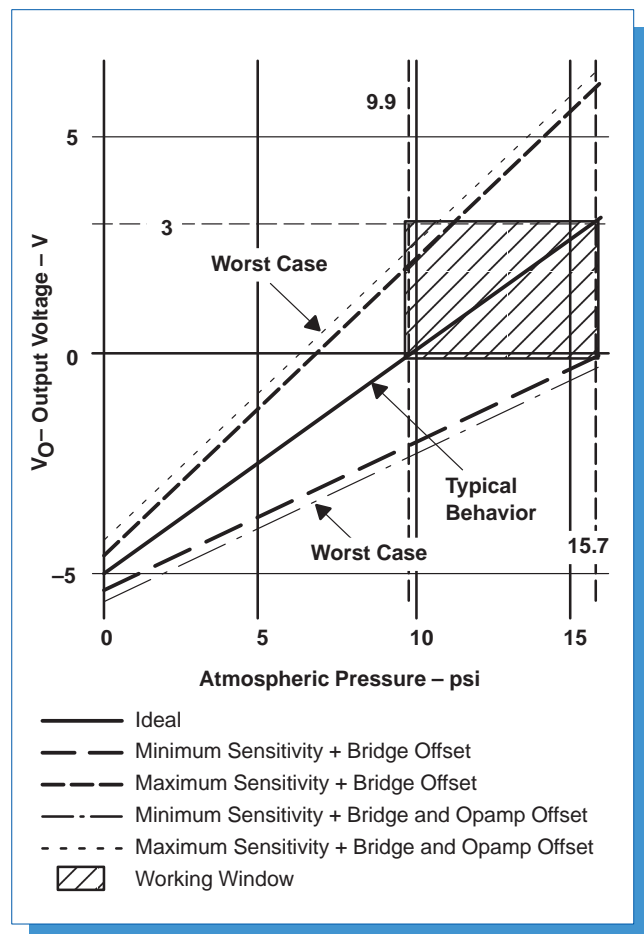

Figure 4–2. Offset Error of the Pressure Sensor and the Operational Amplifier

No Trimming Solution

[Figure: Graph titled "No Trimming Solution". X-axis: Atmospheric Pressure – psi, ranging 8 to 16. Y-axis: V_O – Output Voltage – V, ranging –1 to 4. Vertical markers at 9.9 and 15.7. Labels "Worst Case" (upper and lower), "Typical Behavior".]

Legend:
- ——— Typical Output
- – – – Minimum Sensitivity + Bridge Offset
- — — Maximum Sensitivity + Bridge Offset
- —·— Minimum Sensitivity + Bridge and Opamp Offset
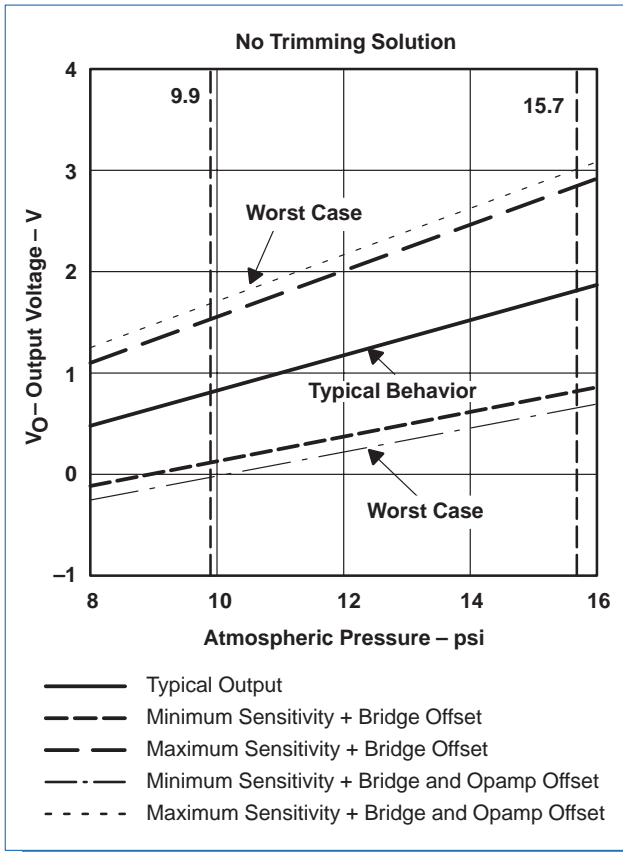- - - - - Maximum Sensitivity + Bridge and Opamp Offset

Figure 4–3. Correcting Component Tolerance Errors with a Fixed Offset and a Decreased Gain to Fit the Window

The ideal solution is to compensate for all errors. This would require a gain adjustment and offset calibration for every circuit. At least three potentiometers are required — one to compensate the offset and the other two for the gain correction. However, the focus of this application is a low-cost solution and uses only one operational amplifier. The extra components and calibration labor required for a fully compensated system would negate any savings.

A balanced compromise could be an offset calibration during the factory process but no gain correction. The amplifier gain is set for the highest possible sensitivity. A gain about 87 (see calculations in 4.4, *Circuit Parameter Derivation*) will be used. As shown in figure 4–4, the output sits between 0 V and 2.3 V for most sensors.

Offset Trim at Lowest Pressure

[Figure: Graph titled "Offset Trim at Lowest Pressure". X-axis: Atmospheric Pressure – psi, ranging 9 to 16. Y-axis: V_O – Output Voltage – V, ranging –1 to 4. Vertical markers at 9.9 and 15.7. Annotation: "The gain can be set higher when a calibration offsets the amplifier output to zero volt at the lowest expected pressure."]

Legend:
- ——— Typical Output
- – – – Minimum Sensitivity
- - - - - Maximum Sensitivity

Figure 4–4. Offset Calibration, No Gain Adjustment

Sensitivity $\times$ gain $\times$ V_{CC} $\times$ pressure_range =

$$1.5 \, \frac{mV}{V \times psi} \times 87 \times 3V \times (15.7 - 9.9) \, psi \; = \; 2.3 \, V \qquad (7)$$

For sensor specs with the lowest sensitivity, the output at the highest pressure does not exceed 1.5 V, which is within the lower half of the ADC sampling range. Fortunately, this is a loss of only one bit, which is acceptable with high resolution ADCs (example: the sensitivity error lowers the resolution from 84 dB to 78 dB on a 14-bit ADC).

4.2 Error Compensation Circuits

There are several possible basic circuit designs that will remove the offset errors. The following paragraphs offer some details.

If only one operational amplifier is used in the amplifier stage, the differential sensor output must be zero V when the lowest expected pressure is applied. This ensures that the amplifier output feeds the ADC within the working window. The two resistors R_{T1} and R_{T2} (parallel to the differential sensor outputs, see figure 4–5 a) can move the output signal on each side to $V_{CC}/2$ for the lowest pressure point. This will lower the sensitivity of the sensor, but only a relatively small amount (1.66%). This is because the resistor values for this application are in the 100 kΩ range, while the sensor resistance is approximately 4.5 kΩ. The disadvantage of this solution is the requirement of two trim potentiometers.

By using only R_{T1} and trimming the output on only one side to the same voltage level as the other side, the sensitivity will be reduced by approximately 2%. However, one step of calibration will be saved and the second potentiometer is eliminated (see figure 4–5 b). This sensitivity reduction can again be canceled by a slightly higher amplifier gain.

The second problem comes with the variation of sensitivity of the pressure sensor. This can be compensated with variable amplifier gain. However, this solution requires 2 potentiometers to trim the gain (see Figure 4–5 c), which drives up the cost and defeats the low-cost goal.
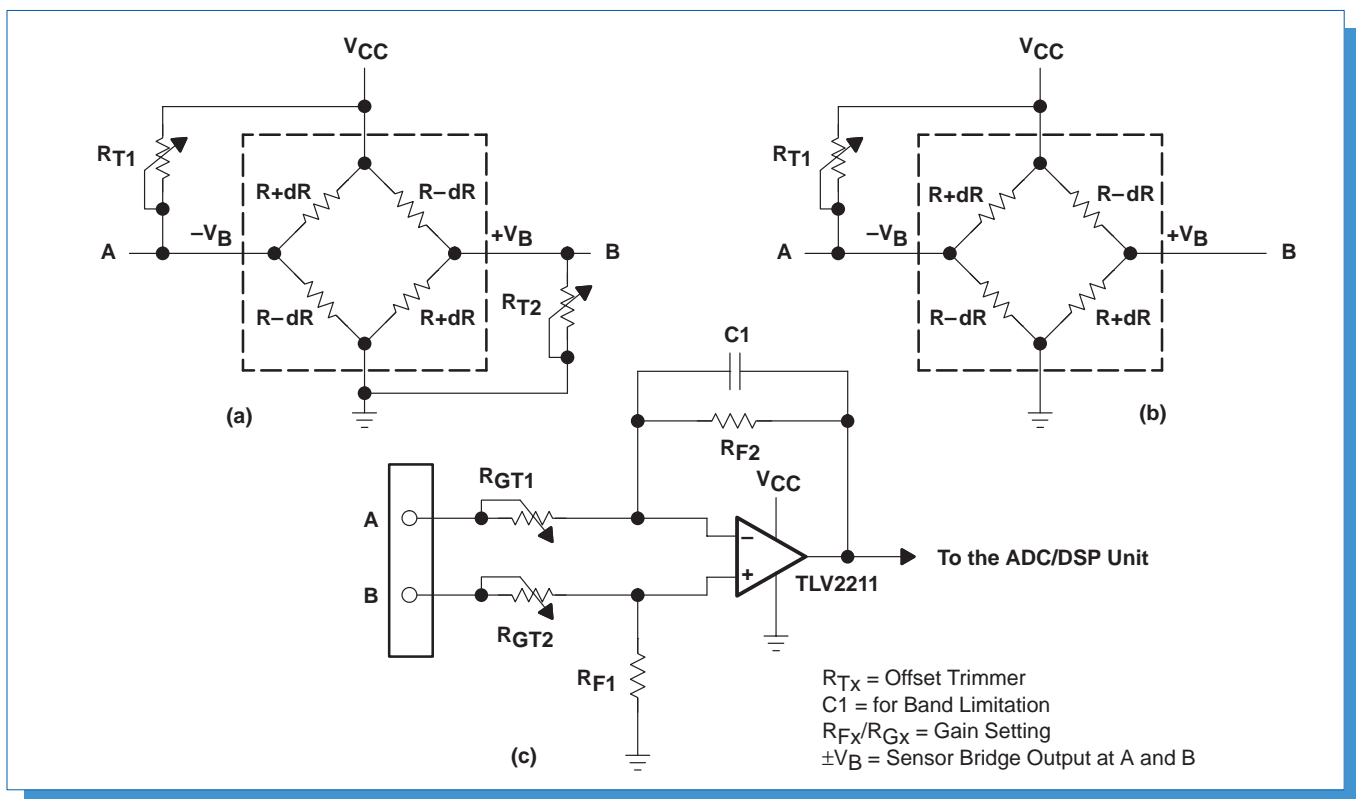

Figure 4–5. Error Compensation Circuits: a) Symmetrical Offset Trim, b) Asymmetrical Offset Trim, and c) Amplifier Gain Adjustment

4.2.1 Gain Adjustment With An Unsymmetrical Operational Amplifier Circuit

One possible solution to compensate for the gain variation of different pressure sensors is to use a potentiometer in one operational amplifier path (figure 4–6). A different zero offset calibration procedure will be required and there will be an unwanted common mode gain of the amplifier. The next paragraphs discuss the major points of implementing this kind of calibration feature and its major disadvantages.

Idea

Fixed resistor R_{G2} is replaced with a series combination of a fixed resistor of one-half the original value and a potentiometer of approximately the same value.

$$R_{G2\_new} = R_{G2\_old}/2 + potentiometer(R_{G2\_old}/2) \tag{8}$$

Consequently, the gain in this path can be adjusted between the old value (G = 87 for pot. = max) up to double the gain of this path (G = 2×87). As the following equations show, this cancels the sensitivity error of the sensor variations.

$$1.2\left(\frac{\frac{mV}{V}}{psi}\right) \tag{9}$$

Defining the gain of both tracks:

$$G1 = \frac{RF1}{RG1} \quad G2 = \frac{RF2}{RG2} \tag{10}$$

The output voltage of the operational amplifier is calculated by:

$$Vpos = Vneg = VBrpos \times \frac{G1 - 1}{G1} \tag{11}$$

$$Vout = G2 \times Vneg - G2 \times VBrneg + Vneg \tag{12}$$

$$= VBrpos \times G1 \times \left(\frac{G2 + 1}{G1 + 1}\right) - G2 \times VBrneg$$

This result shows that the operational amplifier output is dependent on the differential input and the input voltage levels. Therefore, the amplifier will have the disadvantage of a common mode gain that is larger than zero. It also points out the need for recalculating the value of R_{OT} to get an operational amplifier output in the working range.

The gain of the new circuit can be estimated with:

$$Gx \times \frac{Vout}{Vin} = \frac{VBrpos \cdot G1 \cdot \left(\frac{G2 + 1}{G1 + 1}\right) - G2 \cdot VBrneg}{VBrpos - VBrneg} \tag{13}$$

For G1 and G2 much bigger than 1, the overall gain is:

$$Gx \approx \frac{VBrpos \cdot G2 - G2 \cdot VBrneg}{VBrpos - VBrneg} = G2 \tag{14}$$

In summary, this circuit would perfectly compensate the sensor sensitivity error, but has the annoying common mode gain, which is especially problematical with power supply variations.
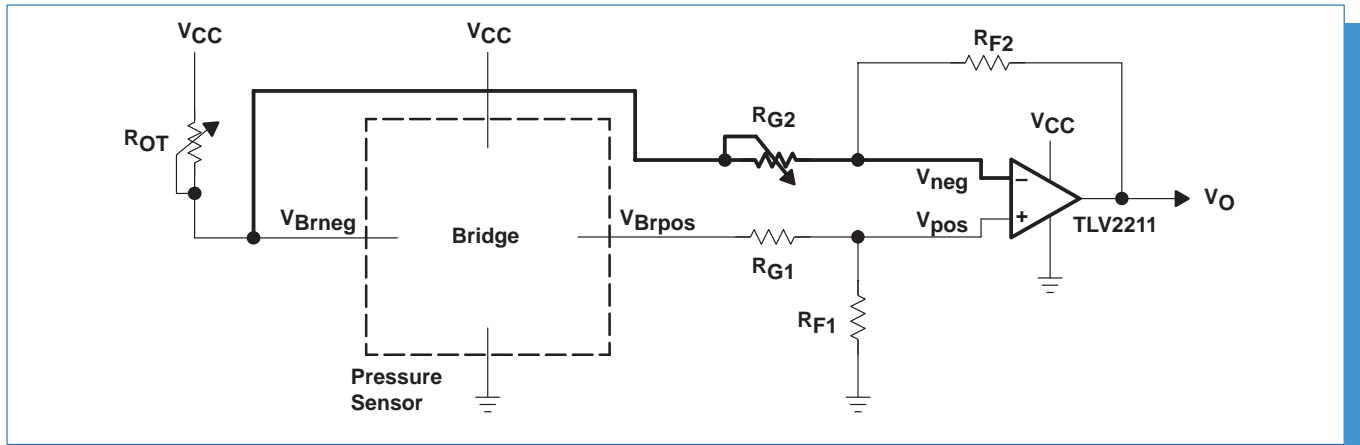

Figure 4–6. Unsymmetrical Gain Calibration

4.3 Designing a Complete Automated System

4.3.1 Circuit Suggestion

This section details a system that requires no manual offset trimming with potentiometers. Instead, a digital-to-analog converter (DAC1) handles this task. Another DAC (DAC2) is provided to allow gain adjustments.

The design of the new system begins with the following expectations:

The design begins with DAC2 because the offset correction (DAC1) will depend on the bridge supply voltage provided by DAC2. The function of DAC2 is to cancel the sensitivity error. Since DACs typically are not able to drive a load up to the DAC supply voltage, the operating range of DAC2 will be between its maximum output voltage and one-half of this voltage (typical sensors vary from 1 mV/V psi to 2 mV/V psi in their sensitivity). A 0.4-V offset for the DAC would give an operating range of 2.6 V down to 1.3 V.

Some DACs can drive an output much higher than 2.6 V in a 3 V system. However, the design proceeds with the selected DAC because a reference input voltage variation or some other small trick would be needed for the higher output voltage.

DAC1 must have an output voltage higher than the positive bridge voltage to drive a current through R_T, which offsets the system to zero volt differential output at the lowest pressure of 9.9 psi. Therefore, it makes sense to set its operating range to the maximum output voltage of 2.6 V for the DAC to have the most available voltage drop over R_T.

The choice of the value for resistor R_T is such that the voltage drop of 2.6 V minus the output voltage of the negative bridge output side cancels the highest possible system offset.

The amplifier gain is set so that a bridge pressure sensor with the lowest possible sensitivity of 1 mV/V psi still drives the operational amplifier output up to the ADC reference voltage when the bridge is operating from the 2.6 V supply.

Having outlined the advantages of a fully automated system, it must now be shown to be feasible to implement the system in a small amount of space. Good choices for the required DACs in terms of accuracy and capability of outputting the required currents, as well as small physical size, include the TLC5614 and TLC5616. Both DACs have a serial interface (SPI) that supports TI DSPs and a broad range of microcontrollers.
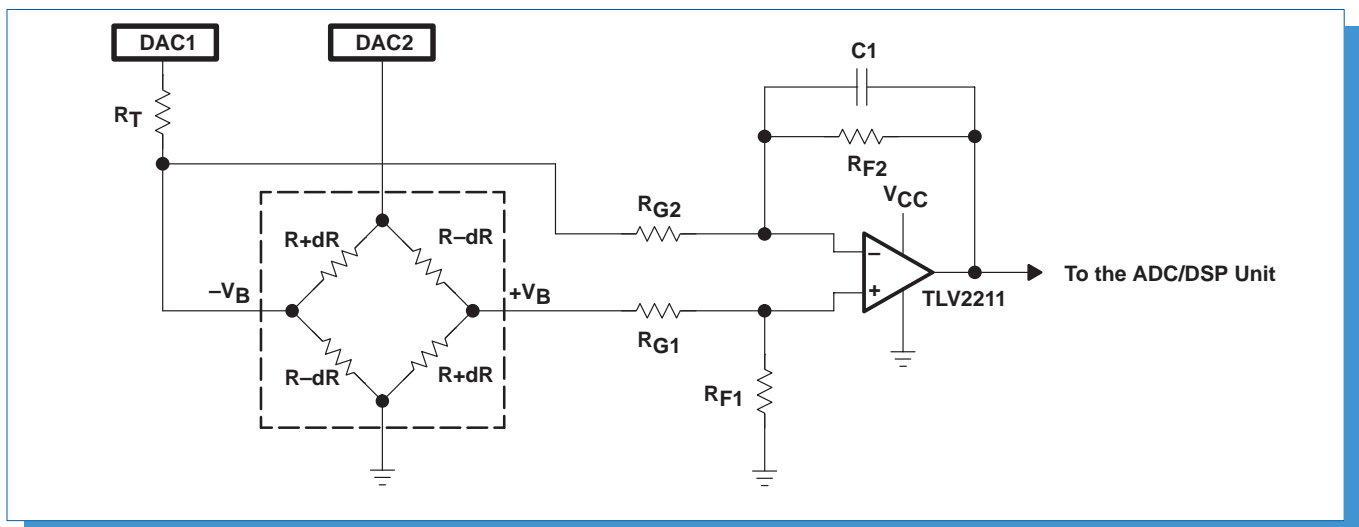
Figure 4–7. Fully Automated Error Compensation System

TLC5616

This is a single-channel, 12-bit resolution converter that is able to drive a 2 kΩ load up to a level of $V_{DD} - 0.4$ V. Tests have shown that this converter will drive the bridge sensor supply very close to the DAC supply voltage of 3 V.

SOP Small Outline
Pin spacing: 1.27 mm
Package dimensions: 5.00 mm × 6.20 mm
Power consumption: 600 μW (in a 3-V system)

TLC5614

The TLC5614 is a four-channel converter with basically the same circuit in each channel as in the single-channel TLC5616. It should have the same accuracy and be able to drive the same load.

Fortunately, this converter is available in two different packages. The TSSOP version is as small as one TLC5616 device. Therefore, this converter might be preferred because all required DACs are in a single package. Furthermore, the other two channels of the TLC5614 could be used to provide a reference voltage for the ADC and to handle other customized tasks.

SOIC Small Outline Integrated Circuit
Pin spacing: 1.27 mm
Package dimension: 9.9 mm $\times$ 5.72 mm

TSSOP Thin Shrink Small–Outline Package
Pin spacing: 0.65 mm;
Package dimension: (5.10 $\times$ 6.60) mm
Power consumption: 3.93 mW (in a 3-V system);

4.3.2 Fully Automatic Calibration

A design to cancel offset and gain error without trimming any resistors is possible. The details of this design and how the software could handle the complete calibration procedure appear below.

The following steps could be performed for calibration:

1. Apply a pressure of 9.9 psi to the system.
   a. Set the bridge supply voltage (DAC2) to its minimum of 1.3 V.
   b. Increase the output voltage of the DAC1 until the ADC reads a value greater than zero (the offset voltage is removed, the bridge sensor differential output is zero).
   c. Store the digital value of DAC1 and DAC2 in a table.
   d. Increase the DAC2 output voltage one bit and increase the DAC1 output until the ADC reads again something greater than zero; store the value in the table.
   e. Cycle through step 1 d until DAC2 reaches its maximum.
2. Apply a pressure of 15.7 psi to the system.
   a. Turn down the DAC2 voltage to 1.3 V (lowest output) and write the digital value out of the table to DAC1 to remove the offset for 1.3 V.
   b. If the ADC input reads below its maximum, write the next table value to DAC1 and DAC2 until the supply voltage of the bridge is high enough to drive the amplifier output to the reference voltage of the ADC (this is the maximum output for the highest pressure).

   c. Store the last two words sent to DAC1 and DAC2 in memory; These are the numbers that the digital processing unit must send to the DACs after a reset to reinstate the calibration.

4.4 Circuit Parameter Derivation

This paragraph outlines component parameters in the circuit and provides the calculations for the value of each component. The calculations start from the typical parameters given by the components and end with a worst case check of all tolerances according to the device variations:

- Supply voltage:

$$V_d = 3V \tag{15}$$

- Typical sensor sensitivity:

$$S_{typ} = 1.5 \frac{mV}{V \times psi} \tag{16}$$

- Minimum sensitivity:

$$S_{min} = 1 \frac{mV}{V \times psi} \tag{17}$$

- Maximum sensitivity:

$$S_{max} = 2 \frac{mV}{V \times psi} \tag{18}$$

- Lowest atmospheric pressure expected:

$$P_{min} = 9.9 \, psi \tag{19}$$

- Typical atmospheric pressure (sea level):

$$P_{typ} = 14.7 \, psi \tag{20}$$

- Highest atmospheric pressure expected:

$$P_{max} = 15.7 \, psi \tag{21}$$

- Op amp voltage amplification (RF/RG):

$$G = \frac{V_{OUT\_max}}{S_{max} \times P_{diff} \times V_{CC}} \tag{22}$$

$$G = \frac{1}{2 \frac{mV}{V \cdot psi} \times (15.7 - 9.9) \, psi} \tag{23}$$

$$G = 87 \tag{24}$$

The required gain of the amplifier stage is related to the sensor output voltage span within the pressure operation range. Using the whole possible range of the operational amplifier output (rail-to-rail), the gain depends on the sensitivity of the bridge and the pressure window. The gain is calculated for the maximum sensitivity to cover every bridge deviation.

- Typical output offset of the bridge:

$$off_{typ} = -4 \times 10^{-3} \times V_{CC} \tag{25}$$

$$-7 \cdot 10^{-3} \cdot V_{CC} \le off \le 0$$

- Op amp offset:

$-3\ mV \leq op\ amp\_offset \leq 3\ mV$

- Impedance of the bridge input and output and its variation:

$$R_{B\_typ} = 4.1\ k\Omega \qquad (26)$$

$$R_{B\_min} = 3.6\ k\Omega \qquad (27)$$

$$R_{B\_max} = 4.6\ k\Omega \qquad (28)$$

- The pressure variable resistance (ΔR) for every segment of the bridge (R±ΔR) is calculated with:

$$dR(s) = s \times p \times R_B \qquad (29)$$

- The bridge output voltage $V_{\pm Out}$ is described with the bridge supply voltage V_{CC}, the bridge resistance R_B, sensitive resistance ΔR and the parallel resistor RP_x:

$$V_{+Out} = \frac{V_{CC} \times RP_x \parallel (R_B + dR)}{(R_B - dR) + RP_x \parallel (R_B + dR)} \qquad (30)$$

$$V_{-Out} = \frac{V_{CC} \times RP_x \parallel (R_B - dR)}{(R_B + dR) + RP_x \parallel (R_B - dR)} \qquad (31)$$

- Calculation of the low pass filter capacitance C1 for the op amp feedback path:

First order filter:

$$A(p) = \frac{a0}{1 + a1 \times p} \qquad (32)$$

$$C1 = \frac{1}{2 \times \pi \times f_g \times RF2} \qquad (33)$$

with the cutoff frequency f_g = 1Hz:

$$C1 = \frac{1}{2 \cdot \pi \cdot 50\ M\Omega} \approx 3\ nF \qquad (34)$$

4.5 Worst Case Calculation

Probably the most widely used types of error analysis are worst case analysis and sum of the squares analysis. The major task in performing an error analysis is to identify and quantify the error sources.

Worst case analysis assumes that all errors will compound, one on top of the other. Therefore, the maximum error is found by adding up the errors in all circuit elements to arrive at the total system error.

In a sum of the squares analysis, the assumption is that some errors will tend to cancel each other. By summing the square of all the errors and taking the square root, the result reflects this cancellation effect. A sum of the squares analysis gives a realistic depiction of the how well the typical system will perform and is found using the following formula:

- Total System Error:

$$TSE = \sqrt{\sum_{n=1}^{k} Error_n^2} \qquad (35)$$

where the subscript n indicates an individual error component and k is the total number of error components.

Analyzing the formula shows that a circuit with only one very significant error source will consequently retain this error magnitude as the TSE. Because of the very large variation of the pressure sensor parameter, this does not calculate the TSE of our system since the total system error will be as large as the sensor error.

A worst case analysis must be done, however, to find the required gain parameter of the amplifier and to calculate all component values. Two analyses, one for the highest possible bridge sensitivity and the other for the smallest possible bridge sensitivity are performed below.

Case 1 — Highest Bridge Sensitivity

Concerning the highest possible bridge sensitivity, the worst case is described as the lowest possible bridge input/output resistance and the zero-pressure offset voltage is at the minimum (0 V) (figure 4–8). In that case, the required offset trimming resistor R_{OT} will have the smallest value. Using the fully automated solution, the DAC1 would have to drive its maximum defined output voltage.

Calculation of RG2 and RF2:

Simulations have shown that the best solution is a very high input resistance into the amplifier for this path. A good fit has been found with the choice of:

RF2 = 50 MΩ
Therefore RG2 = RF2/Gain
             =50 MΩ/Gain

NOTE: Calculation of RG1, RF1, and R_{OT} is covered in Case 2.

$$R_B = R_{Bmin} (1 + \frac{V_O \cdot V_{CC}}{4}) = 3.6 \text{ k}\Omega + 0 = 3.6 \text{ k}\Omega$$

$$R_B = 3.6 \text{ k}\Omega$$

$$V_O = \text{Bridge Offset Voltage} = 0 \quad \frac{mV}{V}$$

$$\dagger dR\_max = s \cdot R_S = 2 \frac{mV}{V \cdot psi} \cdot 3.6 \text{ k}\Omega = 7.2 \frac{\Omega}{psi}$$

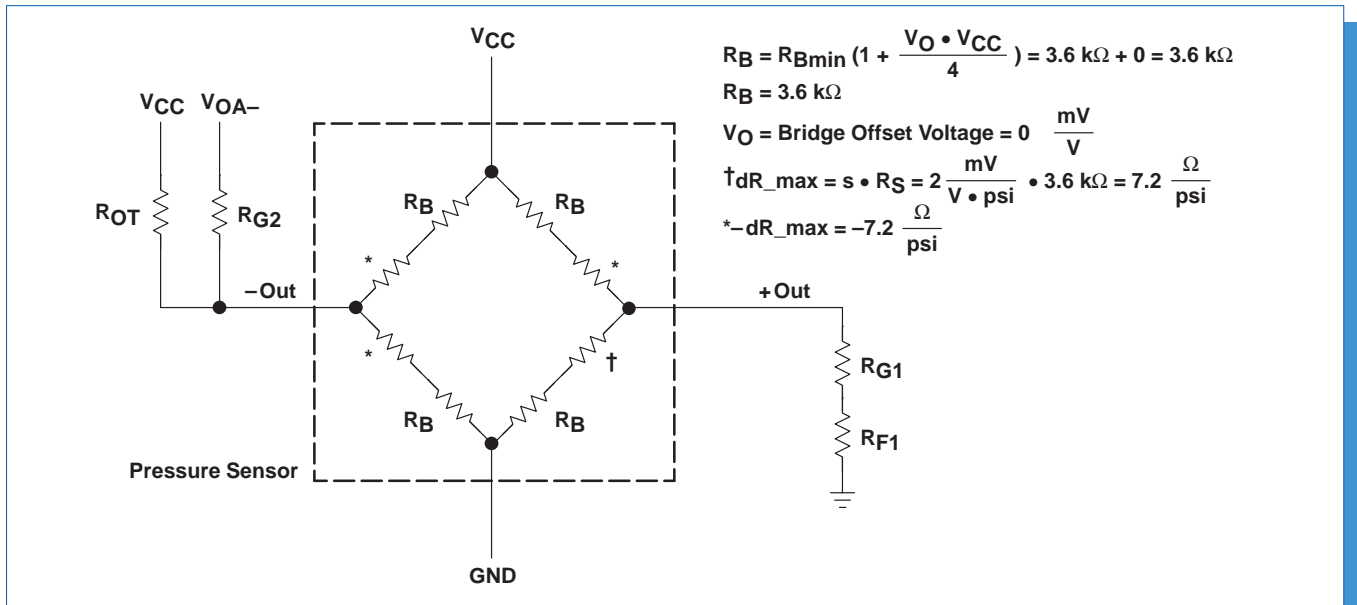$$*-dR\_max = -7.2 \frac{\Omega}{psi}$$

Figure 4–8. Worst-Case Model for Maximum Sensitivity

Case 2 — Lowest Bridge Sensitivity

The lowest possible bridge sensitivity in a worst case is described as having the maximum zero-pressure offset voltage (7 mV/V) and the highest possible bridge input/output resistance (figure 4–9).

In that case, the required offset trimming resistor R_{OT} will have its largest value. Using the fully automated solution, DAC1 would have to feed the offset resistor with its lowest output voltage.
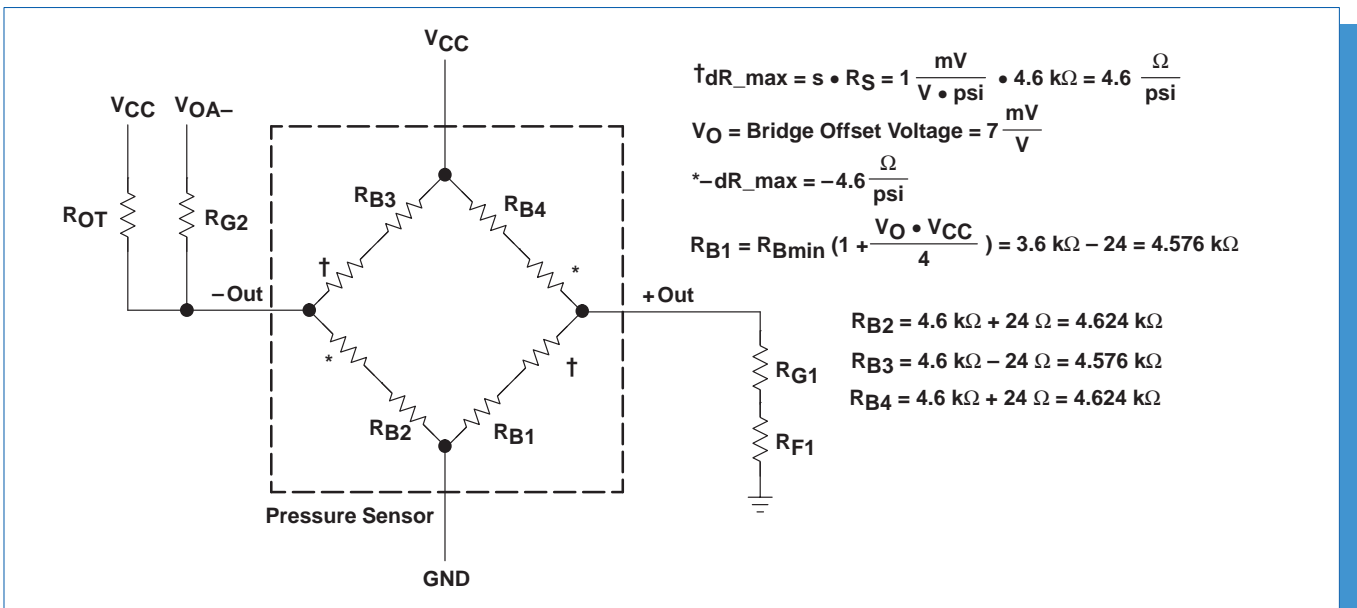

$$\dagger dR\_max = s \cdot R_S = 1 \frac{mV}{V \cdot psi} \cdot 4.6 \text{ k}\Omega = 4.6 \frac{\Omega}{psi}$$

$$V_O = \text{Bridge Offset Voltage} = 7 \frac{mV}{V}$$

$$*-dR\_max = -4.6 \frac{\Omega}{psi}$$

$$R_{B1} = R_{Bmin} (1 + \frac{V_O \cdot V_{CC}}{4}) = 3.6 \text{ k}\Omega - 24 = 4.576 \text{ k}\Omega$$

$$R_{B2} = 4.6 \text{ k}\Omega + 24 \ \Omega = 4.624 \text{ k}\Omega$$

$$R_{B3} = 4.6 \text{ k}\Omega - 24 \ \Omega = 4.576 \text{ k}\Omega$$

$$R_{B4} = 4.6 \text{ k}\Omega + 24 \ \Omega = 4.624 \text{ k}\Omega$$

Figure 4–9. Worst-Case Model for Minimum Sensitivity

Calculation of RG1 and RF1:

Reducing the resistance of RG1+RF1 lowers the bridge output on the *+Out* side. It seems reasonable to choose a value of *RF1+RG1* such that the output reaches $V_{CC}/2$ for Case 2. Thus, the variable resistor R_{OT} has only to cancel the offset from *Vcc/2* minus the negative bridge output.

The following equations determine the *RF1+RG1* value required to get $V_{CC}/2$ at output *+Out*:

- With RP1 = RF1 + RG1:

$$\frac{V_{\pm OUT}}{RP1 \, \| \, (dR\_min + R_B)} = \quad (36)$$

$$\frac{V_{CC}}{R_B - dR\_min + RP1 \, \| \, (dR\_min + R_B)} \quad (37)$$

$$RP1 =$$

$$\frac{\frac{V_{CC}}{2} \times (R_B^2 - dR\_max^2)}{V_{CC} \times dR\_min + V_{CC} \times R_B - 2 \times \frac{V_{CC}}{2} \times R_B} \quad (38)$$

- Parallel resistance:

$$RP1 = 232k\Omega \quad (39)$$

- RF1:

$$RF1 = \frac{G-1}{G} \times RP1 = \frac{86}{87} \times 232k = 229k\Omega \quad (40)$$

- RG1

$$RG1 = \frac{1}{G} \times RP1 = \frac{1}{87} \times 232k = 2.67k\Omega \quad (41)$$

Calculating R_{OT}

The next required parameter is R_{OT}. It is safe to assume that the resistance of *RG2* is insignificant compared to the output impedance of the operational amplifier and resistance R_{OT}. Therefore, *RG2* is neglected.

The value of R_{OT} must cover Case 1 and Case 2. As it can be seen for Case 2, the value has to be as large as *RF1 + RG1*. Taking Case 1 into account, the output *+Out* will not stay at $V_{CC}/2$ for 9.9 psi. Instead, potentiometer R_{OT} must compensate for the offsets on both sides.

$$V_{+Out} = \frac{V_{CC} \times \frac{RP1 \times (dR\_max + R_B)}{RP1 + dR\_max + R_B}}{R_B - dR\_max + \frac{RP1 \times (dR\_max + R_B)}{RP1 + dR\_max + R_B}} \quad (42)$$

$$V_{-Out} = \frac{V_{CC} \times (R_B - dR\_max)}{R_B - dR\_max + \frac{R_{OT} \times (dR\_max + R_B)}{R_{OT} + dR\_max + R_B}} \quad (43)$$

$$R_{OT} =$$

$$\frac{V_{-Out} \times (dR\_max^2 - R_B^2) + V_{CC} \times (R_B^2 - dR\_max^2)}{2 \times V_{-Out} \times R_B + V_{CC} \times (dR\_max - R_B)} \quad (44)$$

Substituting formula 43 into V_{-Out} of formula 42, the lowest R_{OT} calculates to:

$$R_{OT} = 45 \, k\Omega \quad (45)$$

So finally, the variable resistance of R_{OT} has to cover the range of _45 kΩ – 232 kΩ._

Fully Automated System Solution

The resistance R_{OT} is selected so that the maximum output voltage of DAC1 (2.6 V) still feeds the negative bridge output with enough current to offset the bridge at 9.9 psi. With a DAC1 and DAC2 maximum output voltage of of 2.6 V, the value of R_{OT} becomes:

$$R_{OT} = 44 \, k\Omega \quad (46)$$

4.6 DC Behavior of the Amplifier Stage

The DC performance of the amplifier circuit was tested and the results are shown in figures 4–10 and 4–11. The accuracy of the entire application depends on the sensor behavior. Compared to the typical variations between two pressure sensors, the gain error of the amplifier circuit is negligible.
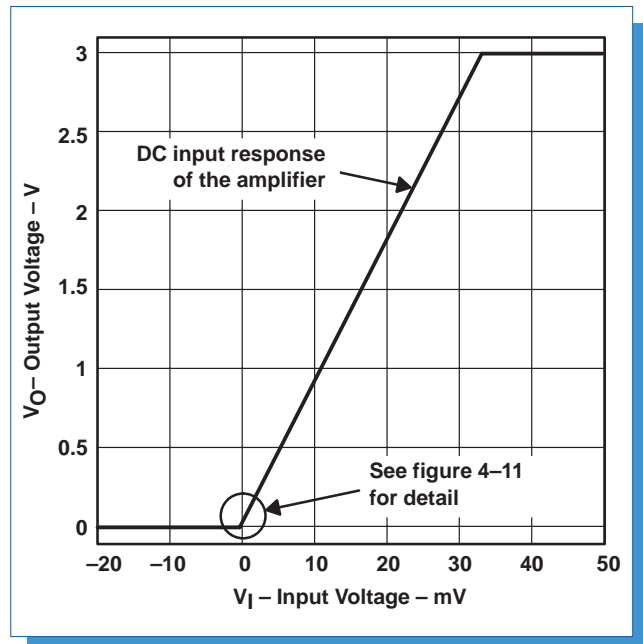

Figure 4–10. Unterminated Amplifier Output

Figure 4–11 zooms in to show more detail at zero input voltage. The operational amplifier offset voltage is measured to be 0.3 mV, which is a typical value for the TLV2211.
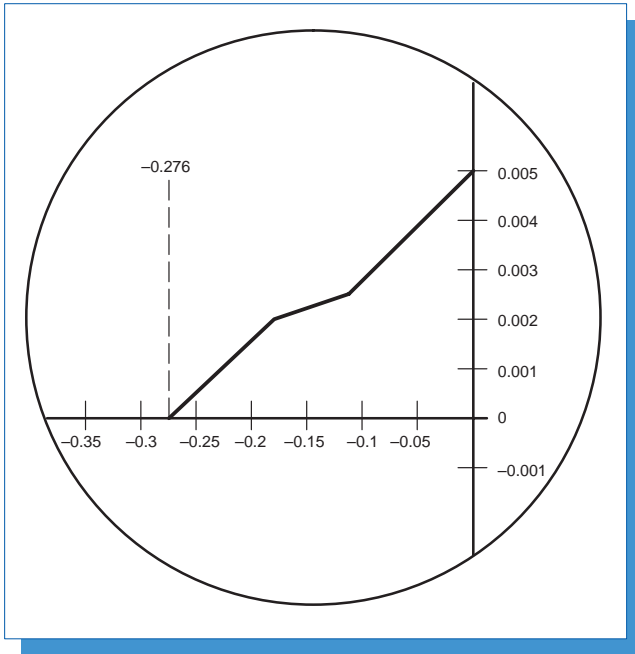

Figure 4–11. Amplifier Output for Very Small Inputs

Some investigations were done to measure the accuracy of the amplifier at output levels close to the supply voltage. Expecting an A/D converter connected to the amplifier output, a switched current has to be driven into the sample and hold capacitor of the ADC. Since the sensor application frequency bandwidth is limited to 1 Hz, the current into the ADC input terminal could be buffered by an RC network with a large capacitance connected between the amplifier output and ground. The amplifier stage would then have to drive a maximum current about 25 μA for an output level close to V_{CC}. This current can be modeled with a 100-kΩ terminator on the operational amplifier output.

Figure 4–12 shows the amplifier error voltage when the amplifier output is terminated into a 100-kΩ load. The error at low output levels is smaller than one LSB of a 12-Bit ADC. However, the accuracy decreases as the output voltage approaches the supply voltage and results in measurement errors in ADCs with 10 or more bits of resolution. A user might compensate for this error with a digital correction or limit the user output voltage range to 2.9 V in a 3 volt system. Generally, the error will decrease with a longer sampling time (long switch time or capacitor charge time for the sample and hold stage). According to the direct relationship between the load resistance and the gain error, an ADC with a relatively small S&H capacitance is recommended.
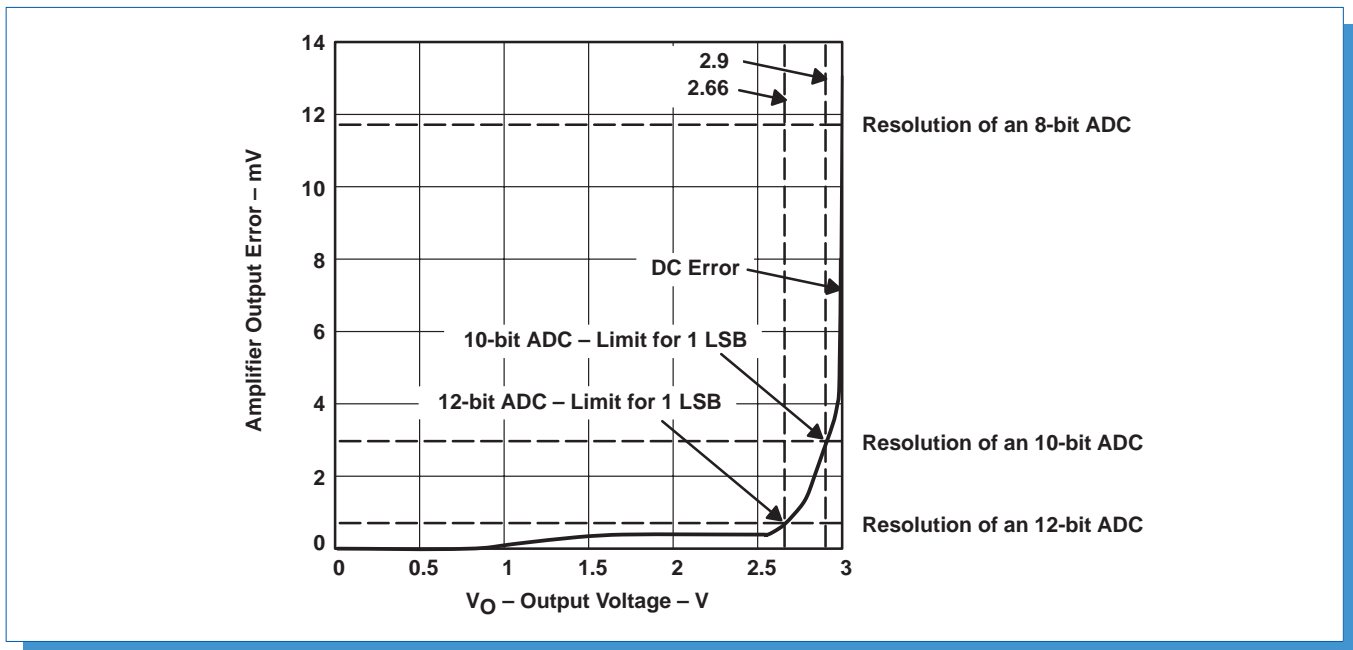

Figure 4–12. Gain Error of the Amplifier Stage When Driving a 100-kΩ Load (25 μA)

5   Designing an End-User Product WIth The Circuitry

5.1   The Digital Interface

The user must determine what kind of A/D interface should be used after the signal processing application circuit.

In general, almost any A/D converter could be connected to the application circuit. However, in a low-power application, the choice of an ADC and a digital processing unit will be determined by power consumption and other features. Because of the low frequency requirements, a high-speed ADC is not needed.

The resolution merits more attention. Even if the magnitude of the errors coming from the sensor package prevents high resolution in terms of absolute pressure, the circuit will still provide a high resolution for a differential measurement. Therefore, a 10- or 12-bit sampling architecture could still make sense. Placing a buffer between the amplifier output and the ADC input and reducing the sampling frequency to the minimum required will minimize the output current required of the amplifier (as mentioned earlier).

Another important detail is the possibility of powering down components during standby times. Therefore, the ADC should have a power-down mode (as most of the current digital processors have).

The following products seem to be suitable:

5.1.1   ADCs

TLV1572

12-bit serial ADC, low power 8 mW at 500 kHz, **auto-powerdown**, 8-pin package, glueless interface, maximum 125 MSPS.

TLV1544

10-bit serial ADC, low power **4 mW**, programmable power down, 4-channel input multiplexer, glueless interface, maximum 85 kSPS.

5.1.2   Mixed-Signal Processor

MSP430

This 16-bit RISC processor is designed for extremely low-power applications (a small battery can power its functions for several years). Its internal **14-bit ADC** will further reduce space requirements compared to external ADCs.

From the MSP430 Metering Application Report (SLAAE10B), the analog impedance can be calculate with:

$$\frac{12}{In\,2^n \, \times \, ADCLK} \tag{47}$$

where n is the resolution in bits ($\leq$14 bits) and $ADCLK$ is the clock speed. A clock speed of 1 kHz and 14-bit resolution would, therefore, require an output resistance of the operational amplifier of less than 27 kΩ.

5.1.3   Resolution

To ensure a high resolution even with an amplifier output voltage very close to the supply, there are at least two useful strategies to consider.

Slow Sampling

Increasing the time during which the ADC S&H capacitor is charged allows a higher impedance of the signal source for a given resolution. Unfortunately, the sample time of an ADC (time the switch to the sampling capacitor is closed) is usually fixed at some value. It is often possible to bypass this time limit, however.

It may be possible to ensure that the ADC input samples only the operational amplifier signal for a larger number of samples (no multiplexing to other channels). This will lead to a voltage on the ADC sampling capacitor that is very close to the ideal operational amplifier output, because the sampling capacitance does not get discharged by the other inputs. Thus, the voltage error in the S&H capacitor decreases with every sample. The disadvantage is obvious on an application in which it is unacceptable for the algorithm to not sample any other channel for a longer time.

Output Buffer

The second possibility is a buffer circuit between the operational amplifier output and the ADC input (figure 5–1).
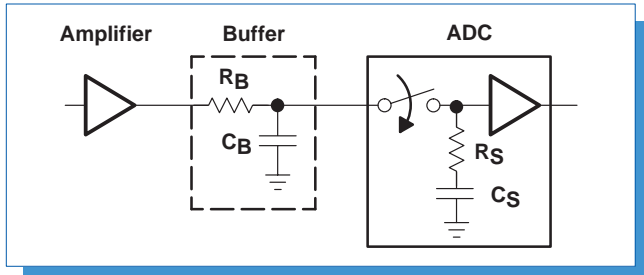

Figure 5–1. Output Buffer

Capacitor C_B stores energy from the signal conditioning amplifier. A constant current is flowing out of the amplifier during the entire S&H time instead of a peak current only at the sampling time. This current charges C_B. When the sample switch closes, the energy will be transferred from the buffer capacitance, C_B, to the sampling capacitance, C_S. To ensure a particular resolution, the buffer has to be about 2^n times larger than the sampling capacitor C_S (n = resolution in bits). Using the 42 pF sampling capacitance of the MSP430 in the calculation, the buffer capacitor will need to be approximately 0.6 μF.

In addition, this solution requires special attention. The larger the buffer capacitor C_B, the less stable the operational amplifier becomes. To prevent oscillation, the resistance of R_P must be chosen carefully. A large resistance will prevent oscillation but extend the settling time (time until C_B is fully charged).

Because the drive capability of the operational amplifier output is not completely linear with the load impedance (especially as the output voltage approaches the supply voltage) and the voltage through an RC network is exponential, the calculation of R_B and C_B is complicated. A mathematical approach first requires the measured output voltage-termination curve be transformed into a mathematical equation.

It seems to makes sense, instead, to monitor the timing on an oscilloscope and then vary the resistor R_B until the best compromise among amplifier stability, resolution, and settling time is found.

5.2   Power Saving and Power Supply Stability

The power consumption of the sensor is:

$$P \; = \; \frac{U^2}{R_{min\_sensor}} \; = \; \frac{3^2}{4000} \; = \; 2.25 \; mW \tag{48}$$

The power consumption of the operational amplifier (33 μW per channel) is negligible in comparison to that of the sensor. Adding the power consumption of the digital unit and, in the fully automated version, the two error compensation DACs (an additional 4 mW), could cause the total power consumption of the system to be unacceptably high for portable products. Hence, the design should include a power-down function for at least the sensor and the digital units during idle times. While most digital processors have a pin-selectable power-down mode, power must be removed from the pressure sensor and any digital elements that lack a power-down mode.

Another problem in a battery-powered application is its supply voltage instability. A voltage regulator will improve accuracy but the voltage still varies too much at the LSBs of high-resolution (10- or 12-bit) converters. To offset this error, the reference voltage of the ADC should be derived from the power supply (the error will then cancel itself). Two possibilities are:

- Connect the ADC reference pin to the pressure sensor bridge supply voltage.

  or

- Use a resistor divider network instead of Zener diodes to obtain the reference voltage.

5.3   Simplification for μP/DSPs to Calculate the Actual Altitude

Designing a height meter first requires the derivation of the pressure equation into a function in which the pressure is input to calculate the height.

From the equation:

$$p(h2) \; := \; k1 \cdot 2^{k2 \cdot h2} \tag{49}$$

the height is defined by:

$$h(p) \; := \; \frac{In\left(\frac{p}{k1}\right)}{(In(2) \cdot k2)} \tag{50}$$

Most of the processors in small portable devices cannot perform a logarithmic calculation directly. Therefore, an approximated function is required to reproduce the exponential function. One way to do this is to linearize the curve with a straight line.

5.3.1 Two-Point Approximation

The formula for a straight line is the defined by:

$$y(x) = m \cdot x + n \qquad \text{(51)}$$

With two known points, the line is defined, and the slope m and the crossing point n can be calculated (figure 5–2). As all points of the height–pressure function are known, the two points are chosen first. Expecting that the line has to go through the minimum and the maximum height, the approximation gets to:

The slope, m, is:

$$m := \frac{p(x2) - p(x1)}{x2 - x1} \qquad \text{(52)}$$

The crossing point n on the y axis gets:

$$n := p(x1) - m \cdot x1 \qquad \text{(53)}$$
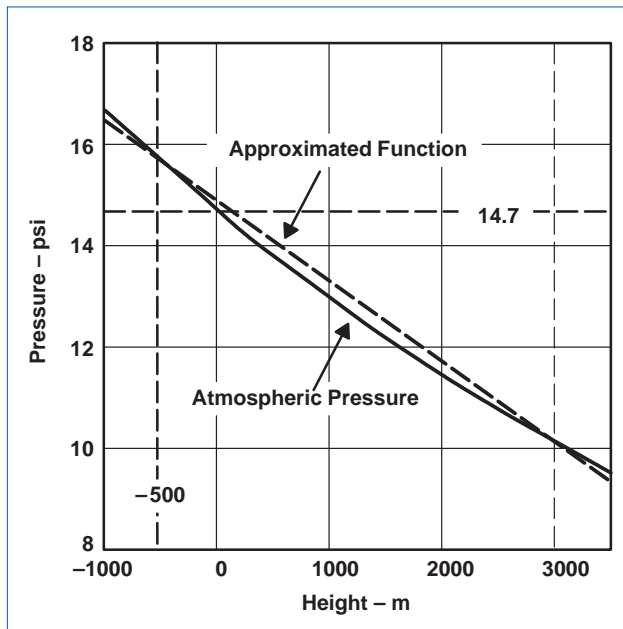
Figure 5–2. Two-Point Approximation

5.3.2 Error Over Height:
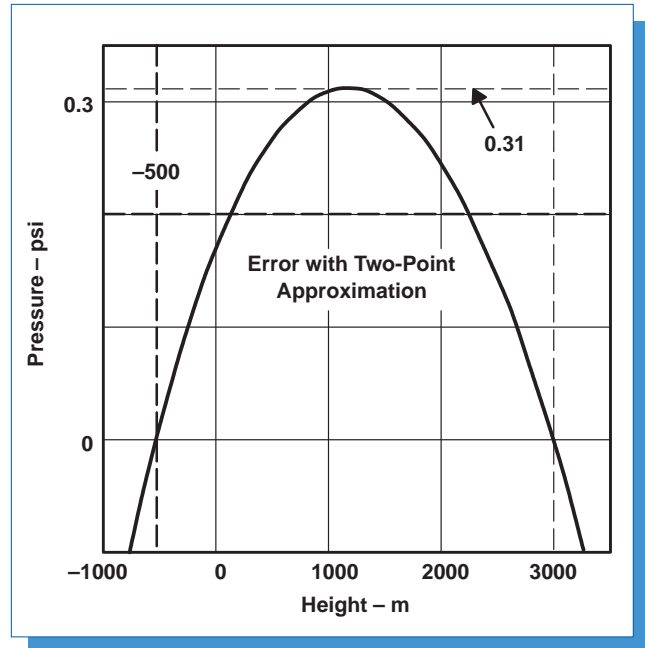
Figure 5–3 shows the two-point approximation error.

Figure 5–3. Error Function with the Two-Point Approximation

5.3.3 Error Correction:

There are two ways to improve the accuracy of the approximated function.

First, moving the two crossing points between the approximated function and the truel pressure function closer together will make the error positive and negative about the true pressure function, and therefore, decrease the amount (figure 5–4).

The second correction can be done with multiple straight lines instead of one — the logarithmic function is cut into pieces and each is approximated with one straight line (figure 5–5).
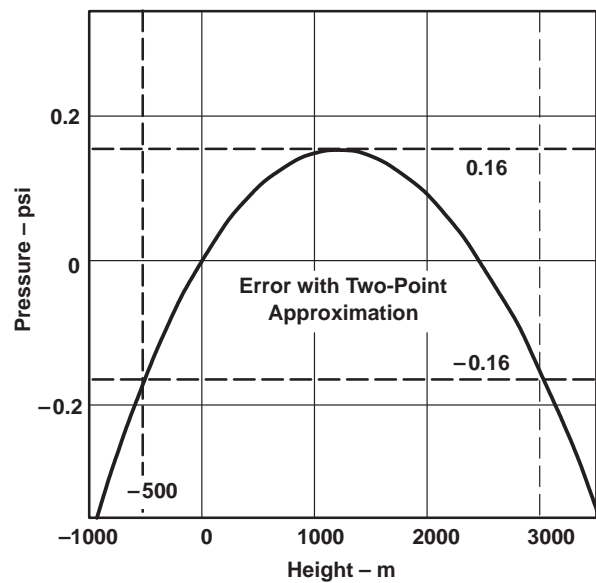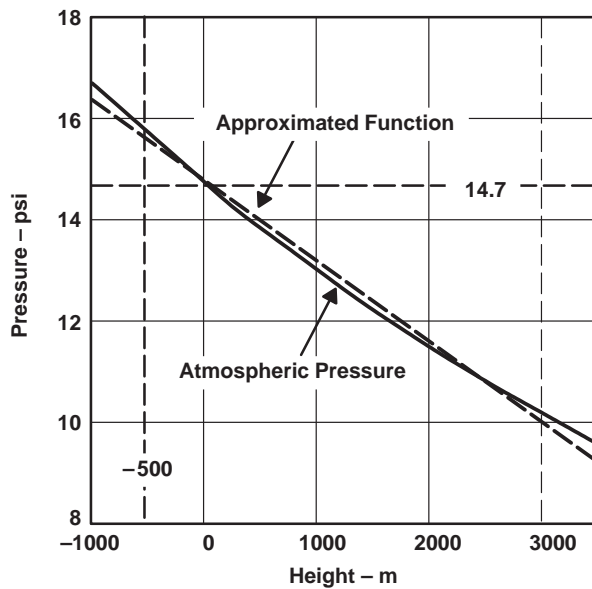

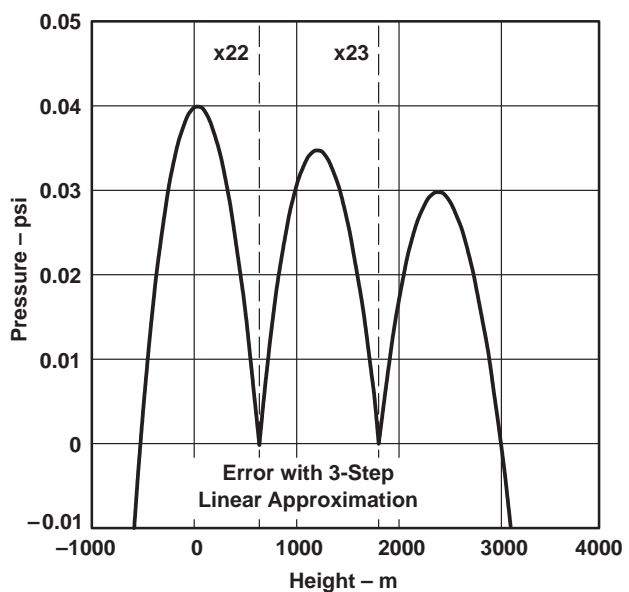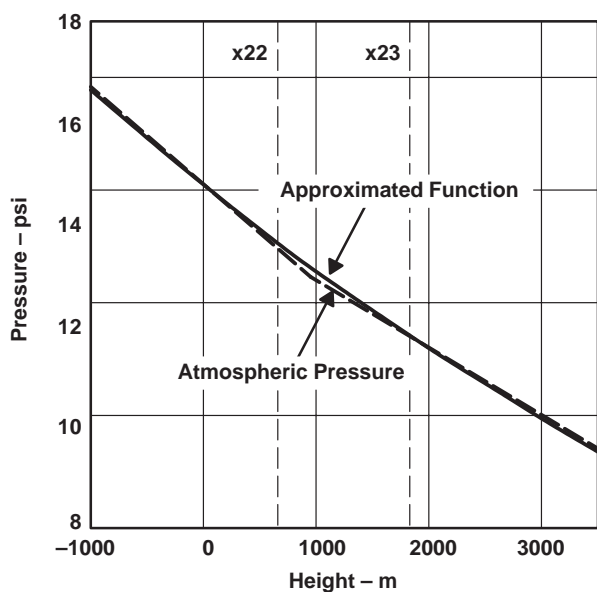**Figure 5–4. Error Reduction by Changing the Crossing Points**

Figure 5–5. Three-Point Approximation

Low-Power Signal Conditioning for a Pressure Sensor

Figure 5–6 shows all errors from a one-, two-, and three-point linear approximation. It is likely that the user range is precise enough when using 2 or 3 points to fulfill accuracy requirements for an inexpensive height meter.

- NOTE

The simplest solution for compensating any nonlinearity of the whole application is to apply different pressures, take a measurement at each pressure, and store the result for every measurement in a table. The linear approximation algorithm will then give relatively accurate results.
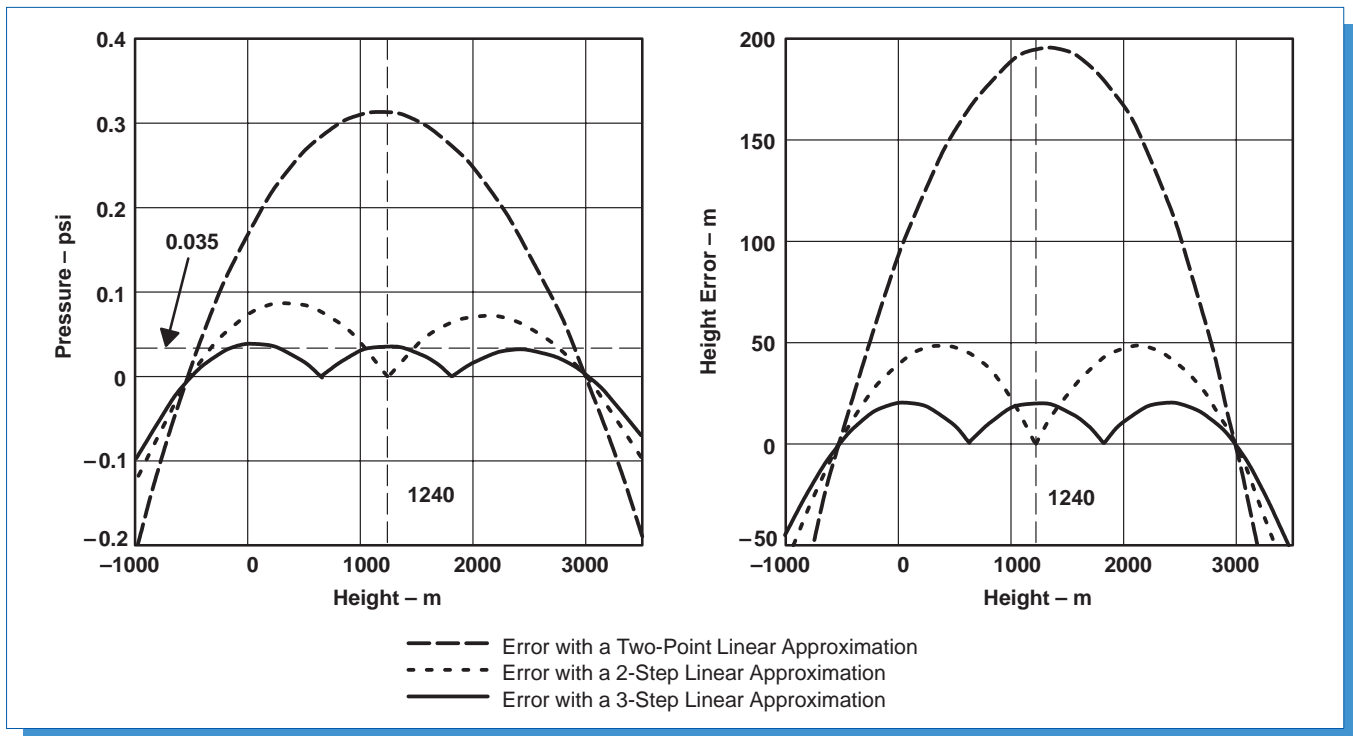

Figure 5–6. Error Correction Effect of the Pressure and Height Result

6   Appendix

6.1   Note on the TLV5616 DAC

This note is based on a test of a TLV5616 sample. This device has a internal gain of 2 and therefore doubles the reference voltage with a full-scale output. Setting the DAC input (digitally) to the maximum will output a voltage of 2 times V_{REF}. The data sheet limits the magnitude of the reference voltage to 1.3 V (for a 3 V system), which is equivalent to an output of 2.6 V.

The result of this test shows that the output limitation of the 2.6 V in a 3-V system is well within the limit. Typically, if the reference voltage of the DAC gets close to $V_{CC}/2$ or exceeds it, a loss of gain will be experienced. However, knowing this loss still allows reaching an output voltage very close to the supply voltage. Since the accuracy of the application system increases with the magnitude of the bridge supply voltage, it might be worth exceeding the limit.

Figure 6–1 shows the result of a reference voltage variation of the DAC and its output. As the graph shows, the TLV5616 drives the bridge up to 2.95 V without any problem. The only correction needed is setting the reference voltage a bit higher than theoretically determined.

Example: increasing the DAC2 reference voltage to 1.6 V will not allow the software to calculate the actual output voltage. But in stepping through the software calibration steps, the bridge will be driven with up to 2.95 V when required. Fortunately, this application is not dependent on the knowledge of the absolute output of DAC2 nor DAC1. The only importance comes with the correct table value for DAC1 and DAC2 (see 4.3.2 *Fully Automatic Calibration*).
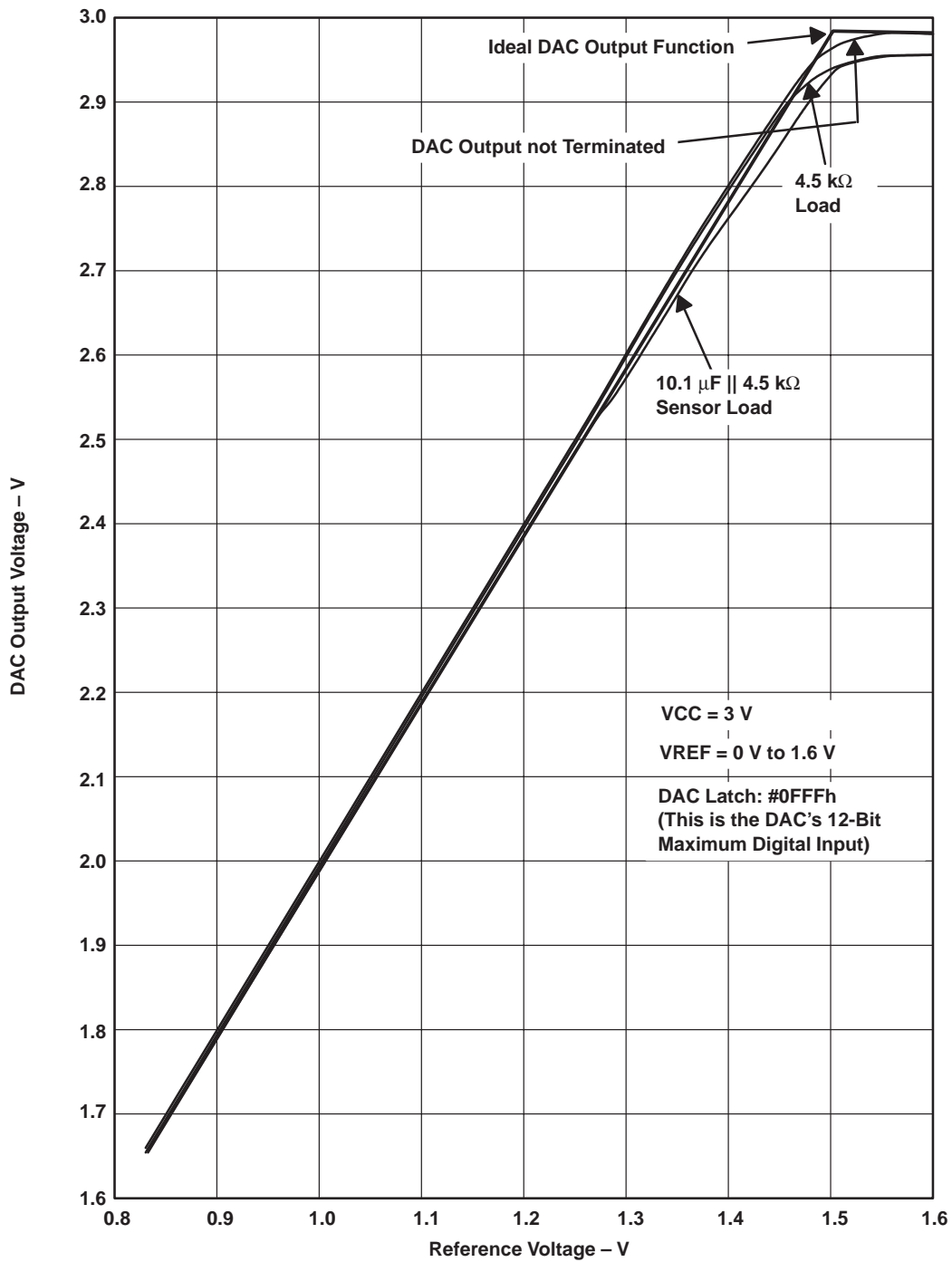
Figure 6–1. TLV5616 Output Voltage In Relation to Reference Voltage

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