INTRODUCTION

Low cost solid state pressure sensor elements have attracted a great deal of attention lately. Although for the bulk of applications it is more economical to use a device which is calibrated by the sensor manufacture, for some very high volume OEM applications a basic sensor element, such as the CCT-4 and CCT-6 can be used. It is when using these uncompensated elements that one needs to be able to understand the various methods for span temperature compensation.

A misconception existing today among many engineers is that the basic piezoresistive pressure sensor elements come in two types-constant voltage and constant current. Although the basic sensor elements are often referred to as either constant current or constant voltage driver sensors, what is really being referred to is the method of span temperature compensation utilized. The two basic methods of compensation for the sensors inherent decrease in sensitivity over temperature are:

- Using the internal characteristics of the die in conjunction with a constant current source, or
- Using thermistors or other similar devices in conjunction with a constant voltage source. This article will explain the difference between the two types of compensation, clarify what is meant by the terms constant voltage and constant current as it applies to piezoresistive pressure sensors, and provide guidelines for which type of die is best for a given application.

GENERAL INFORMATION

Many different types of piezoresistive pressure sensors are available. They cover pressure ranges from below 1 psi to pressures well above 10,000 psi and are available in a variety of package styles and voltage outputs. However, for all integrated solid state piezoresistive sensors the basic operating principle of the sensor element remains unchanged. Figure 1 shows the schematic diagram of a typical solid state pressure sensing element. These devices use diffused or ion implanted resistors in an integral silicon diaphragm to transform the related stress, due to pressure, into an electrical output. The solid state pressure die functions as a wheatstone bridge. As pressure is applied the resistors in the arms of the bridge change by some amount Δ .

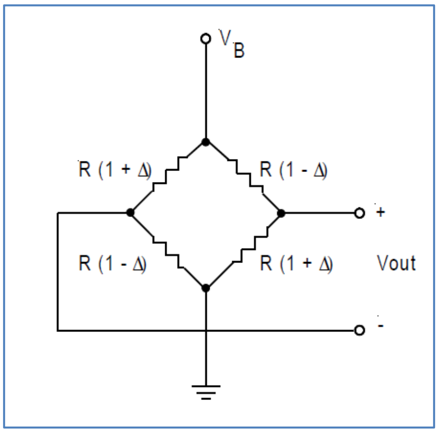


FIGURE 1

Schematic diagram of piezoresistive pressure sensor

The resulting differential output Vo, Is easily shown to be Vo = Vb x Δ. Since the charge in resistance is directly proportional to pressure, Vo can be written as:

Vo=S x P x Vb (+Vos) (1)

Where:

Vo is the output voltage in mV

S is the sensitivity in mV per volt per unit pressure

P is the pressure

Vb is the bridge voltage

Vos is the offset error (the differential output voltage when no pressure is applied).

The offset voltage and the related offset temperature errors can be critical error parameters for some applications. However since the method of excitation, constant current or constant voltage, will not significantly impact these parameters, they will not be covered in this discussion.

Equation 1 is simple and no additional circuitry would be needed for temperature compensation, if not for the fact that the sensitivity, S, changes quite dramatically with temperature. In fact, all piezoresistive die have two inherent characteristics:

- A decrease in sensitivity with increasing temperature, which is referred to as the temperature coefficient of span (TCS).
- An increase in the bridge resistance with temperature, known as the temperature coefficient of resistance (TCR).

Note 1: In this discussion, for simplicity of notation, the change of a variable with temperature will be designated with a dot (•) over the variable. For example,

$$\frac{\Delta S}{\Delta T} = \frac{\text{Change in Sensitivity}}{\text{Change in Temperature}} = \frac{ds}{dt} = \dot{S}$$

One can better understand how to compensate for this change in sensitivity by looking at the derivative of equation 1 with respect to temperature. Ignoring the VOS term gives:

$$V_o = P\,(S\dot{V}_b + S\,\dot{V}_b) \qquad \text{Note 1}$$

When a sensor is properly compensated the output voltage does not change with temperature. Hence, Vo = 0 and:

$$S\,\dot{V}_b = -\,S\,\dot{V}_b \qquad \text{or} \qquad \frac{\dot{V}_b}{V_b} = \frac{\dot{S}}{S}$$

This equation tells us that in order to compensate for the change in sensitivity with temperature, the bridge voltage must change in equal magnitude in the opposite direction. Therefore, the goal of all compensation schemes shown in this article is to change the bridge voltage with temperature such that the sensitivity will not vary with temperature. This is true regardless of the compensation method used. Some examples of the different compensation techniques are now given.

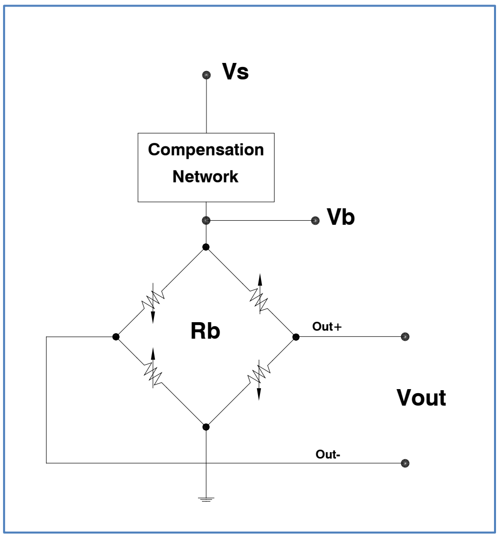


FIGURE 2

Compensation Network and Silicon Pressure Sensor

COMPENSATION TECHNIQUES

As noted previously, due to the effects of TCS, all piezoresistive pressure sensor die will exhibit a decrease in sensitivity with temperature so they will not be properly compensated if a fixed voltage source is placed directly across the bridge. In order so stop, or at least limit, the change in sensitivity with temperature, a compensation network must be utilized.

Typically, the compensation network will take on one of the following forms:

(1) Temperature dependent resistive components

In this method, an additional circuit consisting of resistors and thermistors, or similar components, are most often added by the manufacturer to the pressure sensing die for span compensation. Remembering that the goal of this compensation method is to change the bridge voltage with temperature a simple compensation network can be modeled as follows:

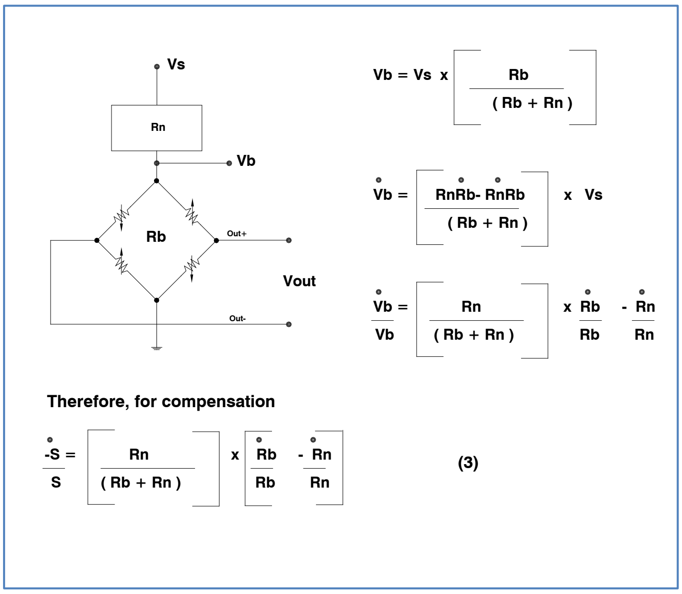


FIGURE 3

Temperature Dependent Compensation

Note, that the correct compensation schema for equation 3 does not involve the power supply voltage. In fact, the output is ratiometric to the supply voltage and devices utilizing this method of compensation can operate over a large input voltage range. Because the device is operated by a voltage source, when this method of compensation is used with a sensor, the end product is often referred to as a constant voltage sensor. The main problem associated with this scheme for low to medium volume applications is that thermistors and resistors, for optimum results, must be individually matched to the sensors. Because low cost, off-the-shelf thermistors are not well controlled, this method really only make sense for very high volume manufacturing where thick film networks with laser trimmed circuits can be utilized.

(2) Fixed TC compensation

This compensation technique consists of using diodes or other active components which have a fixed voltage change with temperature. The mathematical model is similar to the model shown in method (1). Assuming that the voltage across the compensation network, VN, is equal:

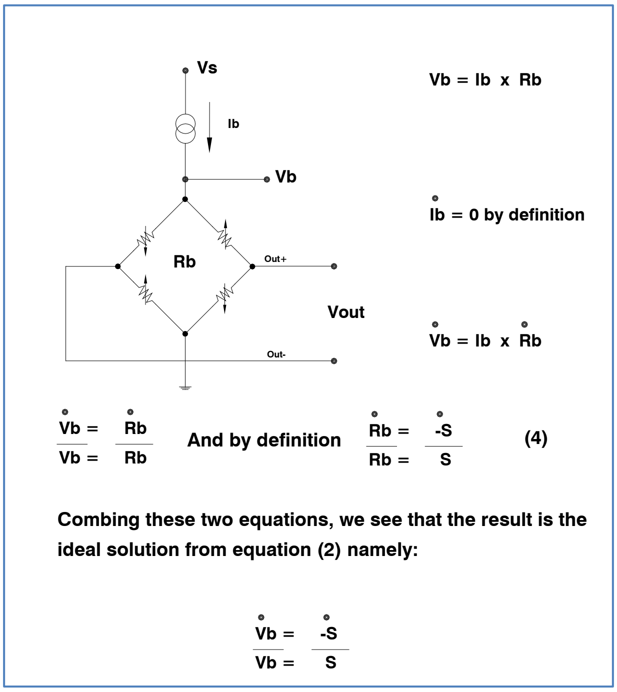


FIGURE 4

Schematic Diagram of Piezoresistive Pressure Sensor

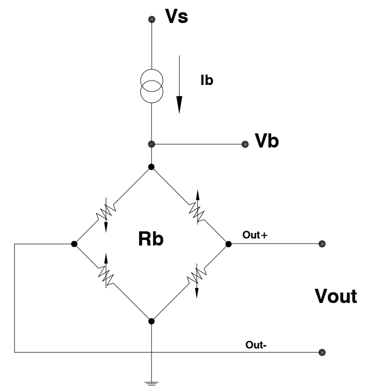
However, one major difference does exist between this method and the previous method. Since VN and VN are fixed properties of the diode (or other active device used) and these are not ratiometric to the supply voltage, Vs, this compensation method performs well at only one particular value of the supply voltage. Any variation in supply voltage will cause an error in the span TC compensation. Again, because a voltage source is used, this method also yield what is typically referred to as a constant voltage sensor.

The one advantage of this simple scheme is that low cost, off-the-shelf diodes and transistors are readily available with fairly well known temperature characteristics so that this compensation method can easily be added by the end user.

(3) Current source compensation, TCR = -TCS

The exact value of the TCR and TCS in the die considered thus far have not been of particular concern because the components that were added, compensated the sensor for any reasonable value of TCR and TCS found in piezoresistive sensors.

However, the pure current source compensation scheme has a specific requirement: The TCR must be equal in absolute magnitude and opposite in sign with the TCS (TCR = - TCS). Given this characteristic, the die will obtain optimum performance over temperature when operated from a constant current source. The model is shown below:



$V_b = I_b \times R_b$

$\dot{I}_b = 0$ by definition

$\dot{V}_b = I_b \times \dot{R}_b$

$$\frac{\dot{V}_b}{V_b} = \frac{\dot{R}_b}{R_b}$$ And by definition $$\frac{\dot{R}_b}{R_b} = \frac{-\dot{S}}{S} \quad (4)$$

Combing these two equations, we see that the result is the ideal solution from equation (2) namely:

$$\frac{\dot{V}_b}{V_b} = \frac{-\dot{S}}{S}$$

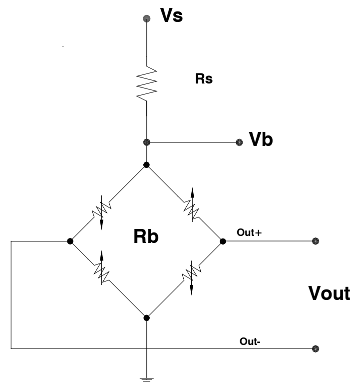
FIGURE 5

Constant Current Compensation

In the final form shown in equation 4 the answer involves only the bridge resistance change with temperature, TCR, and the change in sensitivity, TCS. As the sensitivity is reduced with increasing temperature, the bridge voltage increases thus canceling any change in sensitivity. Such a system is often referred to as self-compensating, and because the die is operated from a constant current source the die is often referred to as constant current sensor.

(4) TCS smaller than TCR compensation

This is one of the more common types of solid state sensor die available today. In this product, the TCR is slightly larger than the TCS in absolute magnitude, and span temperature compensation can be adjusted by adding a single resistor in series with the sensing element if voltage excitation is used. This device can also be used with a true constant current source and span TC can be adjusted by adding a single resistor in parallel with the bridge to effectively reduce the TCR of the device. When using this device with a constant voltage source, a large resistor must be added to the network so a “quasi” constant current sources provides power to the sensor. The mathematical model is shown below.



$$\frac{\dot{V_b}}{V_b} = \left[\frac{R_s}{(R_s + R_b)}\right] \times \frac{\dot{R_b}}{R_b} - \frac{\dot{R_s}}{R_s} \qquad (5)$$

It is assumed that the temperature coefficient of the discrete resistor is negligible, < 50ppm/°C. Then

$$\frac{-\dot{S}}{S} = \left[\frac{R_s}{(R_s + R_b)}\right] \times \frac{\dot{R_s}}{R_s} \qquad (6)$$

FIGURE 6

TCR > TCS Compensation

For proper span compensation the magnitude of RB/RB must be larger than the magnitude of S/S by a factor of RB + RS/RS. This rule is not strictly adhered to in cases where the temperature range is small and some span TC can be tolerated. Again, because a "quasi" current source is constructed for excitation, this type of die is often referred to as a constant current sensor.

Other types of span temperature compensation do of course exist but the four examples shown here are the most common. It should also be noted that no matter which type of excitation is used, constant voltage or constant current, what is really being referred to with the terms constant current and constant voltage sensors is the type of span compensation that the particular die best utilizes. The next section may offer some guidance in choosing which type of span compensation, and hence which type of sensor, is best for a particular application by listing some of the pros and cons of each type described above.

ADVANTAGES AND DISADVANTAGES

Choosing the sensor which is best for any given application typically requires weighing a number of factors. Parameters which need to be considered are: temperature range of the system, amount of temperature error which the system can tolerate, environment, number of additional components which are added to the circuit, size limitations, design time which needs to be allotted to the compensation scheme, cost, etc. So, suggesting a "one sensor for all designs" is not possible and hardly the intent of this article. Instead, let's consider just the types of compensation discussed and some of the advantages and disadvantages of each.

(1) TCR > TCS compensation

As mentioned before this is probably the most common type of pressure sensor die sold. At first glance, this appears to be the perfect solution, simply by adding an addition resistor the span temperature compensation can be accomplished. However, drawbacks do exist when using this type of die over wide temperature ranges or in high accuracy applications. If equation 6 is solved for Rs, we can see some of the shortcomings.

$$Rs = Rb \frac{(-TCS)}{TCR + TCS} \qquad \text{Where } TCS = \frac{\dot{S}}{S} \qquad \text{and } TCR = \frac{\dot{Rb}}{Rb}$$

In order to select the proper value of series resistor, Rs, the bridge resistance, RB, as well as the TCR and the TOS must be known. And unless each die is characterized, the typical values must be used. Using the typical values could result in span temperature errors of a few of hundred ppm/°C. Also, because the TCR usually exceeds the /TCS/ by less than 50 %, the resistance of the series resistor, R5, is larger than the bridge resistance, RB, resulting in a lower voltage across the bridge and hence a lower overall sensitivity. Less obvious with a TCR > TCS type of die are the second order effects inherent in the die itself. These second order effects can potentially limit the useful temperature range to 25°C ±15°C.

Also, it should be noted that Vos and Vos, while not the topic of this discussion, must also be compensated for accuracy over a wider temperature range. Therefore, additional components will be necessary, along with extensive testing by the end user of a TCR > TCS die if high accuracy is required.

(2) TCR = - TCS compensation

Unfortunately, this method of compensation has many of the same drawbacks at the single resistor method shown above. The overall sensitivity of the device can be reduced due to the voltage drop across the current source. Although there are fewer variables affecting the TCS, second order effects again limit the compensated temperature range of this device, to typically 25°C ± 25°C for reasonable accuracies. And, again Vos and Vos are not compensated in this method. This method is best where one does not want to individually characterize the sensor devices and accuracies of 1 % to 2 % over 50°C are acceptable.

(3) Fixed TC compensation

This method of compensation has been used as an integrated solution in the past, but is seldom used today because it has the same disadvantages of the above compensation schemes and in addition must be operated from a specific voltage. However, this method does allow the user to use a die with less specific TCR and TCS characteristics. But some forethought is required. Because the power supply is a fixed voltage, characterization over temperature of both the die and the fixed TC device used is strongly recommended to assure that the compensation method will meet the user demands. Variations in the exact TC values of the die and the fixed TC device used may cause some TC error. The overall temperature range of this type of die is again usually limited to 25°C ± 25°C.

Also, because the die and the compensation circuit are not located in the same physical place, this type of design has the added disadvantage in that the die and the compensation network might be at different temperature. However, few systems experience a drastic change in temperature in a short period of time, so the difference in temperature between the die and the compensation circuit are usually small.

(4) Temperature dependent resistive components

By using this type of compensation scheme the sensor can be operated over a large input voltage range, while the output voltage remains ratiometric to this supply voltage. This type of span TC compensation is the optimum solution if the user is running very high volumes and can individuality test and laser trim each device to exact tolerances. In addition then, one can adjust the sensitivity to a very narrow range as well as compensate for Vos and Vos.This method with individual trimming also allows the designer to compensate for second order effects to the die, thus yielding a wider temperature range, -20°C to 70°C (with somewhat reduced performance the temperature range is -40°C to 100°C).

The trade-off for this improved performance is the cost and an over-all increase in the package size of the sensor, since the compensated sensor contains not only the die, but also a thick film compensation circuit. Again, because the die and the compensation network are not located in the same physical location, the die and the compensation network may be at different temperatures, causing some of the problems described in (3) above. However, for the user who cannot individually test and laser trim, this option is probably the least attractive where discrete components must be used.

CONCLUSION

Piezoresistive pressure sensors are often referred to as either constant current or a constant voltage sensor. However, what is really being referred to is the type of span temperature compensation that the die is utilizing.

Although other factors need to be considered, two of the main considerations when choosing to use a low cost basic pressure sensor element are: the operating temperature range of the system and accuracy required. Once these considerations have been established, the actual choice of sensors will be simplified. There is no "cure all" sensor die however, and all die must be compensated for temperature effects. And, although span temperature compensation was the primary variable of concern in this note, for any application where high accuracy over temperature is required, offset shifts with temperature also must be accounted for.

Of course, for all applications except very high volume ones, a sensor which is compensated by the manufacturer is generally the most cost effective solution. A variety of these products are available including those which add span and offset compensation calibration networks and even full amplification to the basic sensor die.