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Temperature Compensation Methods For The Motorola X-ducer Pressure Sensor Element

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INTRODUCTION

The X-ducer piezoresistive pressure sensor element is a semiconductor device that gives an electrical output signal proportional to the pressure applied to the device. This device uses a unique transverse voltage diffused semiconductor strain gauge which is sensitive to stresses produced in a thin silicon diaphragm by the applied pressure.

Because this strain gauge is an integral part of the silicon diaphragm, there are no temperature effects due to differences in the thermal expansion of the strain gauge and the diaphragm, as are often encountered in bonded strain gauge pressure sensors. However, the properties of the strain gauge itself are temperature dependant, requiring that the device be temperature compensated if it is to be used over an extensive temperature range. The purpose of this Application Note is to illustrate how this temperature compensation can be accomplished, so as to aid the user in applications where temperature compensation is necessary.

The methods discussed here are not the only methods for temperature compensating the X-ducer piezoresistive pressure sensor. They are relatively simple, however, and have been found to be adequate where accuracies of a few percent or less are sufficient. Moreover, they are applicable to the entire product line for the X-ducer pressure sensor element and, in many applications, can provide good performance without consideration of part-to-part variations consistent with the specifications of these devices.

TEMPERATURE CHARACTERISTICS

Figure 1 shows a typical operating curve for an MPX100D pressure sensor element. Other members of this product family which cover different operating pressure ranges exhibit similar behavior. As can be seen from this figure, the output of this device varies with operating temperature. It is this variation with temperature which requires that the device be temperature compensated.

This temperature variation can be characterized in terms of the effect of temperature on (1) the full scale span, which is the change in output over the operating pressure range, and (2) the zero pressure offset, which is the output at zero applied pressure (differential or absolute, depending on the type of the device). The effect of temperature on these two characteristics is specified by the temperature coefficient of value of the full scale span at –40°C and +125°C normalized by the value of the full scale span at 25°C, and the temperature coefficient of offset, which is the slope of the straight line connecting the value of the zero pressure offset at –40°C and +125°C. To properly compensate the device for the effect of temperature, both the full scale span and the zero pressure offset must be temperature compensated.

TEMPERATURE COMPENSATION OF FULL SCALE SPAN

From Figure 1, it is evident that the full scale span of the X-ducer piezoresistive pressure sensor element decreases with increasing temperature. The typical temperature coefficient of span is –0.19%/°C, although this can vary somewhat from part to part. This temperature dependence is one of the better characterized operating parameters, depending on the bulk material properties of the diffused strain gauge. The primary factors which affect the temperature coefficient of span are the sheet resistance and the junction depth of the diffused strain gauge.

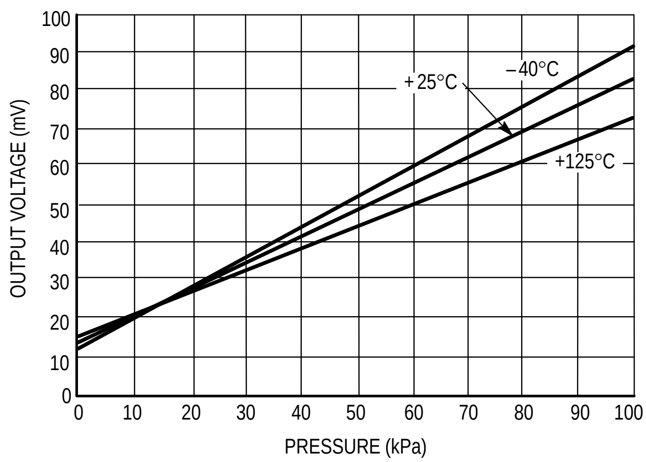

Figure 1. MPX100D Output Voltage versus Applied Pressure (3.0 Volts Excitation)

Since, at any fixed pressure, the output of the X-ducer piezoresistive pressure sensor element is ratiometric to the excitation voltage applied to the device, the most common method for the temperature compensation of full scale span

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temperature in such a manner that it exactly opposes the decrease in full scale span with increasing temperature. Figure 2 shows an experimentally measured curve for the normalized excitation voltage required to compensate the full scale span of an MPX100D pressure sensor element over the temperature range of –40°C to +100°C. This curve is very linear with temperature, the expression for the excitation voltage V_X given in Figure 2 fitting the experimentally measured data with a regression coefficient of 0.99999. In this case, the temperature coefficient required for the excitation voltage in order to compensate the full scale span is +2102 ppm/°C. This value corresponds to a temperature coefficient of span of –2102 ppm/°C, which is on the low end of the specified value for this characteristic. However, the exact value is not important to the present discussion, and many of the design procedures outlined are valid for the entire range specified for the temperature coefficient of span for the X-ducer piezoresistive pressure sensor element.

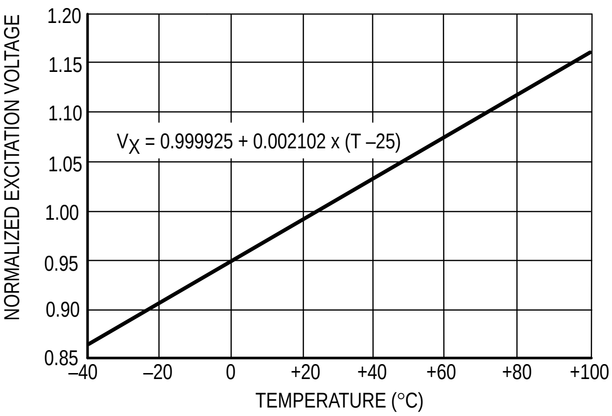


Figure 2. Normalized Excitation Voltage versus Temperature (For Constant Span)

There are many ways of generating a temperature dependent voltage such as that given in Figure 2 for the temperature compensation of full scale span. One of the simplest and most direct methods is to use the temperature characteristics of the resistance of the diffused strain gauge itself. Figure 3 shows the variation in the input resistance of the same device used for Figure 2 over the temperature range –40°C to +100°C. The expression for this resistance, R_X, given in the figure shows a small second order term which causes the temperature coefficient of resistance (TCR) to increase with increasing temperature. The TCR at 25°C is 2405 ppm/°C which agrees well with the specified typical value for the TCR of 0.24%/°C.

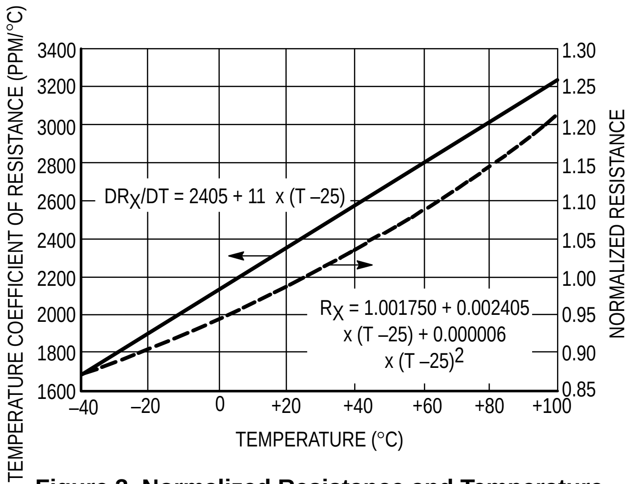


Figure 3. Normalized Resistance and Temperature Coefficient of Resistance versus Temperature

To understand how this temperature variation in the resistance of the X-ducer piezoresistive pressure sensor element can be used to temperature compensate the full scale span of the device, consider a hypothetical case where (1) the input resistance is linear with temperature and (2) the TCR is equal to 2102 ppm/°C. In this special case, if a constant current were to be used to excite the device, the excitation voltage V_X appearing across the diffused strain gauge would match exactly with the *ideal* value required for compensation of the full scale span given in Figure 2. This technique for temperature compensation of full scale span is called self-temperature compensation. There are several difficulties with the practical implementation of self-temperature compensation methods, however, notably the fact that the TCR of the device and the temperature coefficient of span must be exactly equal in magnitude and opposite in sign. In actual practice, there is little chance that this condition will be satisfied.

Because of this, the X-ducer piezoresistive pressure sensor element was intentionally designed so that the TCR of the device would be greater in absolute value than the temperature coefficient of span. Under these conditions, the effective TCR of the sensor element can now be modified by placing additional passive resistive elements either in parallel or in series with the X-ducer. The effect of these passive elements is to reduce the TCR of the network involving these passive elements and the X-ducer piezoresistive pressure sensor element. If the TCR of the X-ducer is greater than that required for perfect self-temperature compensation, the effective TCR of the network can be lowered to a point where self-temperature compensation can be realized. All the methods described herein for temperature compensation of full scale span utilize this approach to achieve self-temperature compensation.

SELF-TEMPERATURE COMPENSATION

As noted in the previous section, to achieve self-temperature compensation using the X-ducer piezoresistive pressure sensor, additional passive resistive components must be placed in a network with the X-ducer to reduce the TCR of the device to the point needed for self-temperature compensation. While there are many such networks, the simplest ones are: (1) a single resistive element in parallel with the X-ducer, and (2) a single resistive element in series with the X-ducer. Here, we will restrict our considerations to these two simple cases. As will be seen, both of these networks can give excellent temperature compensation.

For perfect temperature compensation of the full scale span, the excitation voltage, $V_X(T)$, must match that shown in Figure 2. Therefore, the objective is to obtain an excitation voltage of the form

$$V_X(T) = V_X\, h(T) \qquad (1)$$

where

$$h(T) = 0.999925 + 0.002102 \times (T-25). \qquad (2)$$

To do this, we will place a passive resistive element in either parallel or series with the X-ducer piezoresistive pressure sensor element which has a resistance, R(T), of the form

$$R(T) = R\, g(T) \qquad (3)$$

where g(T) is a function of temperature yet to be defined. The definition is determined by the fact that when this resistive element is placed in either parallel or series with the X-ducer, the temperature variation of the excitation voltage must match that given by Equation 1.

We know that the resistance of the X-ducer, $R_X(T)$ is given by the equation

$$R_X(T) = R_X\, f(T) \qquad (4)$$

where

$$f(T) = 1.001750 + 0.002405 \times (T-25) + 0.00006 \times (T-25)^2. \qquad (5)$$

Therefore, it can be easily shown that for a series resistive element, the function g(T) must be given by

$$g(T) = (R_X/R)\, f(T)\, [(1 + R/R_X)/h(T) - 1]. \qquad (6)$$

Similarly, for a parallel resistive element, the function g(T) must satisfy the relationship

$$g(T) = h(t)f(T)/[(1 + R/R_X)f(T) - (R/R_X)h(T)]. \qquad (7)$$

Figures 4 and 5 show the behavior of the function g(T) for series and parallel compensation resistive elements respectively over the temperature range –40°C to +100°C. Characteristic curves are shown for various resistance ratios, $R:R_X$, of the resistance of the compensation resistive element to the resistance of the X-ducer. We will discuss the significance of these characteristic curves separately for the case of a parallel compensation resistive element and the case of a series compensation resistive element, since different techniques are required to achieve the desired temperature dependence, g(T), for the compensation resistive element.

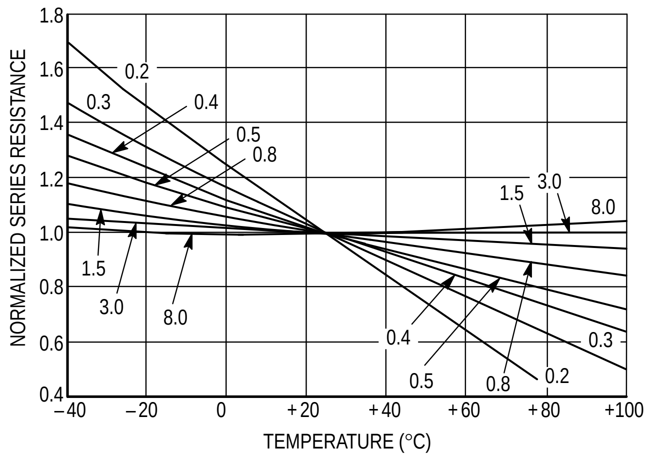


Figure 4. Normalized Series Resistance for "Ideal" Span Temperature Compensation versus Temperature for a Given Resistance Ratio ($R:R_X$)

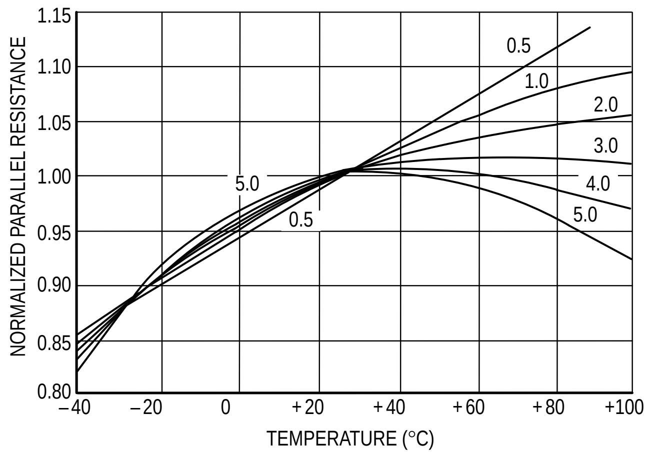


Figure 5. Normalized Series Resistance for "Ideal" Span Temperature Compensation versus Temperature for a Given Resistance Ratio ($R:R_X$)

SPAN COMPENSATION USING A PARALLEL RESISTIVE ELEMENT

The temperature compensation of span using a parallel resistive element can only be accomplished if the X-ducer is excited using a constant current source. If constant voltage excitation is required, the use of a parallel resistive element will not work for this application. Where a constant current source can be employed, however, the use of a parallel resistive element can give very good temperature compensation with very simple circuit components.

From Figure 5, it is apparent that for all practical resistance ratios, $R:R_X$, of the parallel resistive element to that of the X-ducer, a large and positive TCR is required for the parallel resistor. For resistance ratios less than one, this condition is true even at elevated temperatures. Moreover, the TCR of the parallel resistor for $R:R_X$ less than one is a constant to a good approximation for any given resistance ratio $R:R_X$. Figure 6 shows how the TCR of the parallel resistor required for *ideal* span temperature compensation must vary with the resistance ratio, $R:R_X$. This TCR was determined using a least-square regression analysis to determine the slope of the characteristic curves shown in Figure 5 for $R:R_X$ less than one. The magnitude of this TCR is consistent with the use of semiconductor resistors as the parallel resistive element, although it may be necessary to use yet a second zero TCR high value resistor in parallel with the semiconductor resistor to linearize the TCR of this element. Note too that the presence of this linearization resistor will further decrease the effective TCR of the total parallel network and allowance should be made for this effect.

A particularly simple yet effective span temperature compensation can be achieved for temperatures around room temperature by noting in Figure 5 that for resistance ratios, $R:R_X$, between 3.0 and 4.0, the behavior of the parallel resistor approximates that of a zero TCR resistor. Figure 7 shows the span compensation error, determined by the percent deviation of the true excitation voltage from that given in Figure 2, realized using zero TCR resistors as the parallel resistive element. As can be seen from this figure, the use of zero TCR parallel resistors in the resistance ratio range of 3.0 to 4.0 can produce temperature compensation sufficient to limit the span compensation error to less than ±1.0% from 0° to +120°C. While the low temperature compensation is not good, this type of span compensation is very well suited to many applications where the X-ducer is not subject to or required to perform accurately at low temperatures. It should be noted, however, that the totally uncompensated X-ducer has a self-temperature compensation characteristic which gives very good low temperature span compensation. This is also shown in Figure 7. A constant current source must be used with the uncompensated X-ducer to achieve this result, just as in the case of the parallel compensation resistor.

While the use of parallel resistor span temperature compensation can be very simple, yet give very good compensation, this technique is not without its limitations. Thus, the X-ducer itself is a low input impedance device with a typical input resistance of 400-550 ohms. While this low impedance minimizes noise problems, it can impose a heavy drain on a current source in order to obtain excitation voltage levels of 3.0 volts or greater. In addition, if the supply voltage is limited (for example, to 5.0 volts maximum), increases in the resistance of the X-ducer with increasing temperature could create a condition where there is not sufficient voltage across the current source to maintain its operation. Because of these problems, the use of the parallel resistive element span compensation technique is not recommended in applications where the current supply is limited or where there are requirements that the X-ducer be operated at low supply voltages and elevated temperatures.

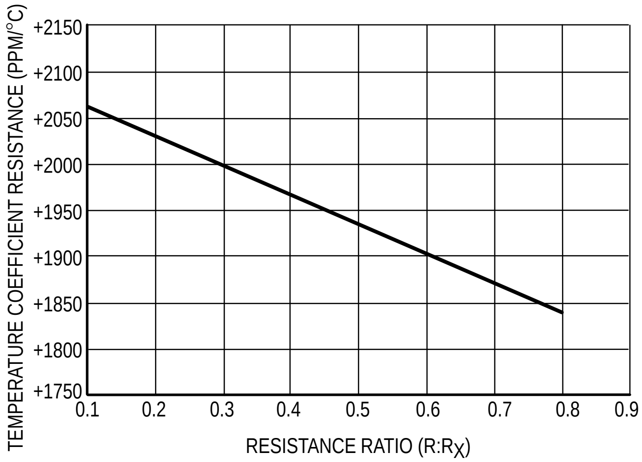


Figure 6. Temperature Coefficient of Resistance for a Parallel Resistance Required for "Ideal" Span Temperature Compensation versus Resistance Ratio ($R:R_X$)

SPAN COMPENSATION USING A SERIES RESISTIVE ELEMENT

Span temperature compensation using a series resistive element assumes that a constant supply voltage is employed. The desired excitation voltage, $V_X(T)$, then appears as a result of the voltage divider network formed by the series resistor and the X-ducer piezoresistive pressure sensor element. While this technique is more complex than that of parallel span compensation, it can provide the highest accuracies and cover the widest range of temperatures. The major reason that the use of a series compensation resistor is more complex than the use of a parallel resistor is that, as can be seen from Figure 4, the TCR of the series resistor must be negative for most resistance ratios, $R:R_X$, of the series resistors to the X-ducer resistance.

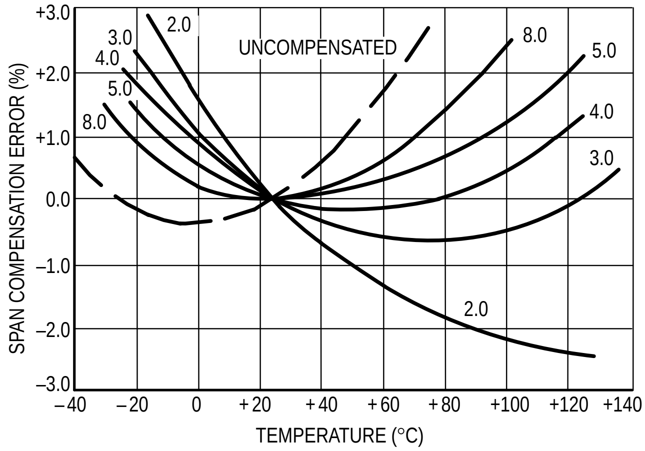


Figure 1. Span Compensation Error versus Temperature for a Given Resistance Ratio (R:R_X) Using Zero TCR Compensation Resistors

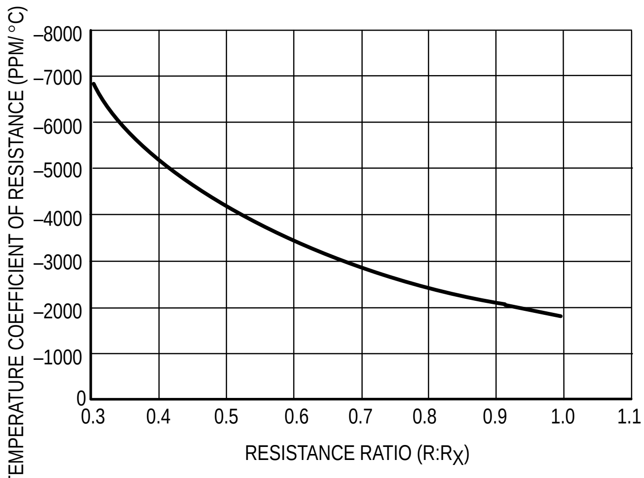


Figure 8. Temperature Coefficient of Resistance for a Series Resistance Required for "Ideal" Span Temperature Compensation versus Resistance Ratio (R:R_X)

There is one particularly simple case for span temperature compensation using a series resistor, that being where the resistance ratio, R:R_X, is near 3.0. From Figure 4 again, it is evident that for this case, a zero TCR resistor will provide good span temperature compensation for temperatures around room temperature. In fact, it can be easily shown that the span compensation error resulting from the use of a zero TCR series resistor is identical to that shown in Figure 7 for span compensation using a parallel zero TCR resistor. However, when this resistor is used in series rather than in parallel, the magnitude of the excitation voltage, $V_X(T)$, actually applied to the X-ducer (and hence the magnitude of the output signal) is considerably reduced due to the dividing of the supply voltage across the series resistor. Much lower current drains can be obtained in this manner, however, and this technique can work well where there is sufficient supply voltage to tolerate the loss in excitation voltage applied to the X-ducer.

To minimize the loss in excitation voltage due to the use of a series resistor for span compensation, it is obvious that the resistance ratio, R:R_X, of the series resistor to the X-ducer should be kept as small as possible. However, referring to Figure 4, it is evident that as the resistance ratio, R:R_X, gets smaller the TCR of the series resistor must become increasingly negative. For values of R:R_X of 0.8 or less, the required TCR of the series resistor closely approximates a constant value, since the characteristic curves shown in Figure 4 are very nearly linear with temperature for ratios of R:R_X less than 0.8. Figure 8 shows the variation in the TCR required for *ideal* span temperature compensation using a series resistor as a function of the resistance ratio, R:R_X. This TCR was determined using a least-square linear regression to determine the slope of the characteristic curves shown in Figure 4 for R:R_X less than or equal to 1.0.

The problem with this approach to span temperature compensation is that negative TCR resistors are not common. The closest approximation to a negative TCR resistor is found in thermistors. These are oxide semiconductor materials which show large, nonlinear decreases in resistance with increasing temperature. Empirically, it has been found that the temperature behavior of these thermistors can best be described by an exponential function of the form

$$R(T) = R(25°C) \exp \beta[1/(T + 273) – 1/298] \quad (8)$$

where the parameter β (which has the units of °K) is equivalent to the TCR for resistors. While a thermistor, itself, is highly nonlinear, a good linear, negative TCR network can be achieved by placing a zero TCR resistor in parallel with the thermistor. The linearity of this parallel network's resistance with temperature and the TCR both depend on the ratio of the parallel resistor to the thermistor as well as the β of the thermistor. Figure 9 shows the effect of different parallel resistance ratios on the temperature dependence of a thermistor with a β of 1250° K. In this case, a linear resistance with a negative TCR is obtained for a resistance ratio of 0.5 or less.

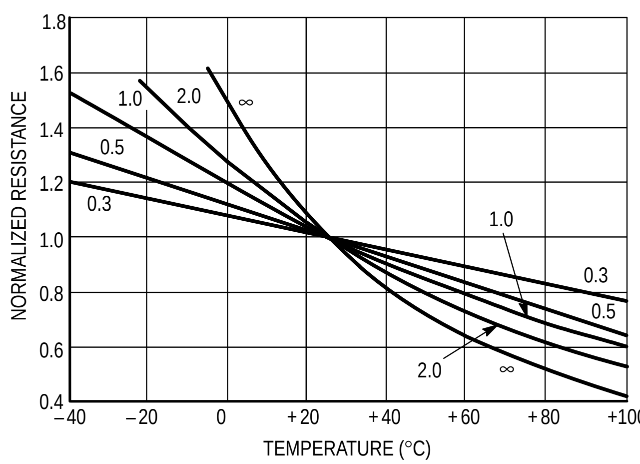


Figure 9. Thermistor:Resistor Parallel Network Normalized Resistance versus Temperature for a Given Resistance Ratio $R_{PARALLEL}$:$R_{THERMISTOR}$ (β = 1250)

For a thermistor of any given β, an appropriate parallel resistance can be determined which will match the TCR of the thermistor: resistor network to the TCR required for *ideal* span temperature compensation given in Figure 8. This can be done using either a trial-and-error approach or a root solving method. Figure 10 shows the results of this calculation for a given set of thermistor β values ranging from

1000°K to 3000°K. From the set of curves given in this figure, for any given resistance ratio $R_{NETWORK}:R_X$ (which determines from Figure 8 the TCR required for *ideal* span compensation), the ratio $R_{PARALLEL}:R_{THERMISTOR}$ can be found for a particular thermistor β which will make the TCR of the thermistor:resistor parallel network equal to the TCR required for span compensation. Figure 11 is a plot of the same data given in Figure 10, only in this case the ratio $R_{PARALLEL}:R_{THERMISTOR}$ is plotted versus the thermistor β for a given resistance ratio $R_{NETWORK}:R_X$. It should be emphasized that both Figures 10 and 11 are based on approximations of linearity and constant TCR's and, because of this, should be used only as guides to the selection of the thermistor:resistor network required for span temperature compensation.

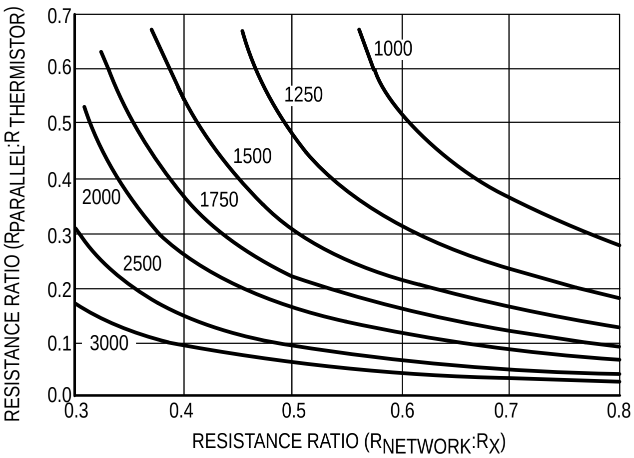


Figure 10. $R_{PARALLEL}:R_{THERMISTOR}$ for Span Temperature Compensation versus $R_{NETWORK}:R_X$ for a Given Thermistor Beta

SAMPLE CALCULATIONS OF SPAN COMPENSATION USING THERMISTORS

Since the results given in Figures 10 and 11 may appear somewhat confusing at first, it is worthwhile to illustrate the use of the figures with some examples. Thus, consider the following problem:

Problem: A MPX100D X-ducer has an input resistance of 450 ohms at 25°C and a temperature coefficient span of –0.21%/°C. It is required that the excitation voltage on the X-ducer be 4.0 volts at 25°C. The supply voltage is 6.0 volts. Select a thermistor:resistor parallel network which will temperature compensate the span of the X-ducer when placed in series with the X-ducer.

Solution: In order for the excitation voltage to be 4.0 volts with a 6.0 volts supply voltage, the resistance ratio $R_{NETWORK}:R_X$ must be equal to 0.5. Since the X-ducer has a resistance of 450 ohms, this means that the thermistor: resistor parallel network must have a resistance of 225 ohms. Referring to Figure 10, for a resistance ratio of 0.5, it can be seen that there is an infinite number of networks which satisfy the TCR requirement for span compensation, depending on the β of the thermistor. Since the choice of this β is arbitrary, we will select a thermistor with a β of 1250°K. In this case, Figure 10 shows that a resistance ratio of $R_{PARALLEL}:R_{THERMISTOR}$ equal to 0.485 is required to give the TCR required for span temperature compensation.

Figure 12 shows a plot of the span compensation error resulting from this choice of thermistor β and parallel resistance ratio. Also shown in this figure is the span compensation error for resistance ratios, $R_{PARALLEL}:R_{THERMISTOR}$, equal to 0.45 and 0.52. As can be seen from this figure, the value of 0.45 for the parallel resistance ratio gives an even better temperature compensation than does the value of 0.485 selected using Figure 10. Therefore, it can be concluded that a thermistor of β equal to 1250°K and 25°C resistance of 725 ohms in parallel with a 326 ohm resistor will give good span compensation when placed in series with the MPX100D X-ducer.

It is important to note in the above example that although the results of Figure 10 gave a value of 0.485 for the parallel resistance ratio, the span compensation error plot showed that a value of 0.45 gave even better span compensation. This reflects the approximate nature of the results given in Figure 10 and emphasizes the importance of the span compensation error plot. The results of Figure 10 should only be used as a guide to the selection of the approximate values required for span compensation. The actual compensation values should be selected by evaluating the span compensation error for all values in the vicinity of that selected from Figure 10. Figures 13 and 14 show the effect of variations in the ratio $R_{NETWORK}:R_X$ and the β of the thermistor respectively on the span compensation error. While these effects are not large, they can be significant where high accuracy is required.

Problem: A MPX200A X-ducer has a resistance of 480 ohms at 25°C and a temperature coefficient of span of –0.19%/°C. A thermistor is available which has a resistance of 900 ohms at 25°C with a β of 1500°K. It is desired to have an excitation voltage of 3.5 volts on the X-ducer at 25°C when the device is compensated by a series network using this thermistor. The supply voltage is 5.0 volts. Determine the value of the resistor to be placed in parallel with this thermistor to obtain span temperature compensation.

Solution: To obtain an excitation voltage of 3.5 volts at 25°C, the resistance ratio $R_{NETWORK}: R_X$ must be equal to 0.43. Since the X-ducer has a resistance of 480 ohms at 25°C, the network resistance must be equal to 206 ohms. The parallel resistor required to give this value when used with the 900 ohm thermistor is 267 ohms. Therefore, the resistance ratio, $R_{PARALLEL}: R_{THERMISTOR}$, is equal to 0.30. Referring to Figure 10, a problem is immediately obvious, since this figure indicates that for a β of 1500°K, the required resistance ratio, $R_{PARALLEL}:R_{THERMISTOR}$, must be equal to 0.49 for $R_{NETWORK}: R_X$ equal to 0.43. From Figure 11, we can see that the β of the thermistor is too low, a value of approximately 2000°K being indicated by this figure.

Therefore, an inconsistent set of values has been selected for this X-ducer. However, note that the temperature coefficient of span of the X-ducer is –1900 ppm/°C, whereas the results given in Figures 10 and 11 assume a value of –2100 ppm/°C. Therefore, we should not be hasty in drawing any firm conclusions at this point. In fact, a span compensation error plot using these values gives a maximum error of +2.11% at –40°C and shows an error of less than ±0.50% from 0°C to +125°C. Thus the available thermistor can give good temperature compensation of span for this X-ducer over a limited range of temperature.

In the example presented above, a situation was encountered where the problem was overdetermined. It was not possible to satisfy the conditions for span compensation required by Figure 10 using the values given in the problem. To avoid situations like this, Figure 10 can be modified to show the interdependence between the two resistance ratios, $R_{NETWORK}:R_X$ and $R_{PARALLEL}:R_{THERMISTOR}$, when both the resistance of the thermistor and the resistance of the X-ducer are given. Figure 15 shows the same data as Figure 10, only with the addition of isocontours for constant resistance ratios $R_{THERMISTOR}:R_X$ (the dashed lines in the figure). To illustrate the use of this figure, consider the following problem:

Problem: An MPX50D X-ducer has a resistance of 470 ohms at 25°C and a temperature coefficient of span of –0.20%/°C. A thermistor is available which has a resistance at 25°C of 1100 ohms and a β of 1250°K. Determine the value of the excitation voltage, V_X, at 25°C and the parallel resistor required to span compensate this device.

Solution: The ratio $R_{THERMISTOR}: R_X$ for this case is equal to 2.3. Referring to Figure 15, for a β of 1250°K, the curve for the ratio $R_{THERMISTOR}:R_X$ equal to 2.3 would cross the compensation curve at the approximate values of $R_{PARALLEL}:R_{THERMISTOR}$ equal to 0.33 and $R_{NETWORK}:R_X$ equal to 0.58. Using a span compensation error plot, it is found that the best span compensation occurs at the values $R_{NETWORK}:R_X$ equal to 0.58 and $R_{PARALLEL}:R_{THERMISTOR}$ equal to 0.31. The resulting compensation error is 1.13% at –40°C and less than ±0.8% between –20°C and +125°C. The excitation voltage on the X-ducer for these values is equal to 63% of the supply voltage and the required parallel resistor is equal to 341 ohms.

As in the first example, the span compensation error plot revealed that the resistance ratios required for *ideal* span temperature compensation as determined from Figure 15 were not the optimal values. In this case, this is probably due to the fact that we had to infer where the isocontour for the ratio $R_{THERMISTOR}: R_X$ equal to 2.3 was located since the nearest value was 2.5. This demonstrates again the value of using the span compensation error plot as the means for determining the proper span compensation conditions.

Summarizing the results of this section, several general features associated with the use of thermistors to span compensate the X-ducer piezoresistive pressure sensor element can be noted.

(1) When both the X-ducer and the thermistor have fixed resistance values, there is only one excitation voltage (as a percent of the supply voltage) and one parallel resistance value which will give the proper span temperature compensation for a given β.

(2) The shape of the compensation curves shown in Figure 10 indicate that the best compensation can be achieved at low values for the resistance ratio $R_{NETWORK}: R_X$, since variations in the resistance ratio $R_{PARALLEL}:R_{THERMISTOR}$ result in less deviation from the *ideal* span compensation curve.

(3) As can be seen in Figures 12, 13, and 14, the span compensation error is generally a sigmoidal curve. Increasing either of the required resistance ratios or the β of the thermistor tends to rotate this sigmoidal curve in a counter-clockwise direction about the 25°C point.

(4) The use of low β thermistors tends to give better span temperature compensation. This follows to some degree from the conditions noted in (2) above.

(5) A span compensation error plot should always be used to verify the selected resistance ratios for span compensation, particularly if high accuracy is required.

OFFSET VOLTAGE TEMPERATURE COMPENSATION

One of the primary reasons for the use of the transverse voltage piezoresistive strain gauge found in the X-ducer is that it provides an electrical signal from a single diffused resistive element. Unlike the more conventional piezoresistive pressure sensor devices which employ a Wheatstone bridge, the transverse voltage strain gauge does not have to be matched with other diffused resistors in either its resistance or its temperature coefficient of resistance. Therefore, the zero pressure offset voltage and the temperature coefficient of this offset voltage depend only on the resolution limits of photolithography, which can be very accurately controlled with the technology available within the semiconductor industry.

Indeed the offset voltage of the X-ducer and its temperature coefficient are very well controlled, the offset voltage typically ranging between 0 and 20 millivolts and the temperature coefficient of the offset typically being on the order of ±15 microvolts/°C when the X-ducer is excited at a constant 3.0 volt. Both of these characteristics can vary, however, and provision must be made for the temperature compensation of the offset voltage as well as the span if high accuracy is required over an extended temperature range.

Even in those cases where the temperature coefficient of offset is acceptably small, provision must generally be made for offset temperature compensation for other reasons. Thus, consider Figure 16 which shows schematics for the span temperature compensation methods discussed in the previous sections.

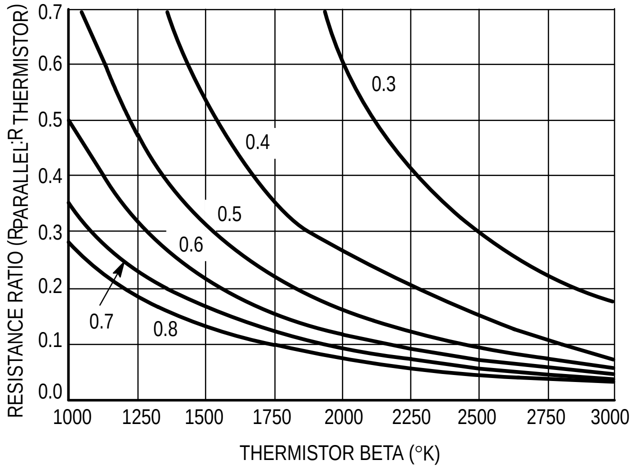


Figure 11. $R_{PARALLEL}$:$R_{THERMISTOR}$ for Span Temperature Compensation versus Thermistor Beta for a Given $R_{NETWORK}$:R_X

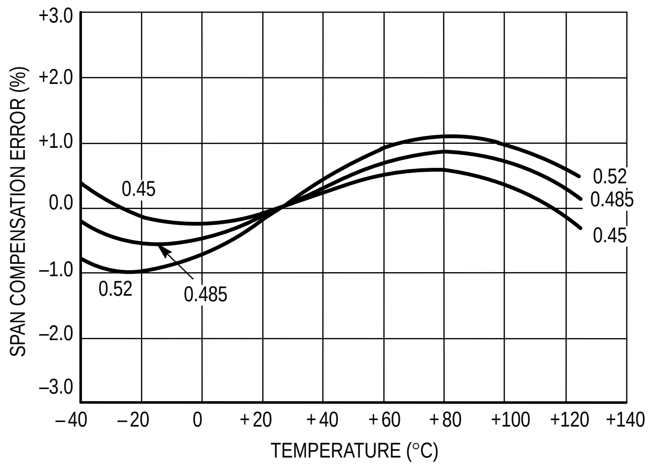


Figure 12. Span Compensation Error versus Temperature ($R_{NETWORK}$:R_X = 0.5, β = 1250) for a Given Resistance Ratio $R_{PARALLEL}$:$R_{THERMISTOR}$

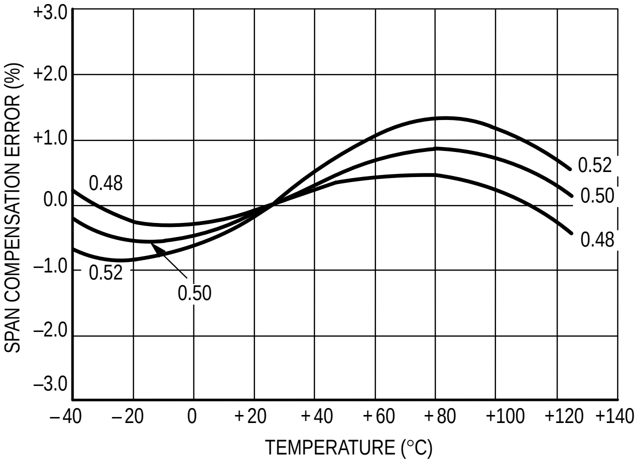


Figure 13. Span Compensation Error versus Temperature $R_{PARALLEL}:R_{THERMISTOR}$ = 0.485 β = 1250 for Given Resistance Ratio $R_{NETWORK}:R_X$

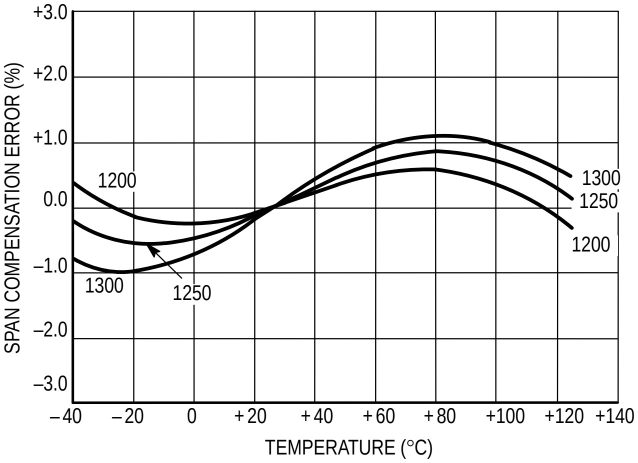


Figure 14. Span Compensation Error versus Temperature ($R_{PARALLEL}:R_{THERMISTOR}$ = 0.485) ($R_{NETWORK}:R_X$ = 0.50) for a Given Thermistor Beta

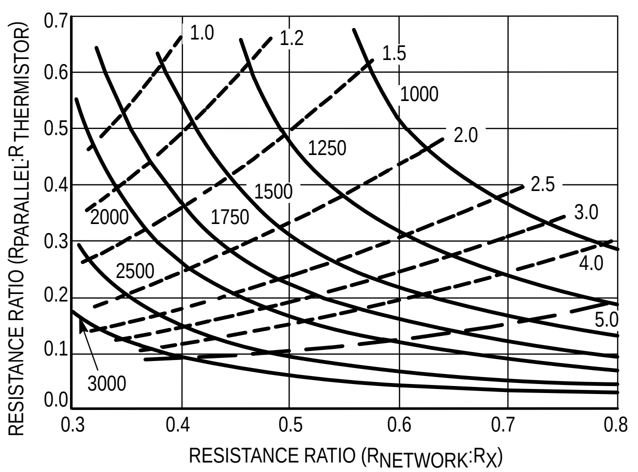


Figure 15. $R_{PARALLEL}:R_{THERMISTOR}$ for Span Temperature Compensation versus $R_{NETWORK}:R_X$ for a Given $R_{THERMISTOR}:R_X$

In all these cases, span temperature compensation is accomplished by introducing a temperature dependent excitation voltage, $V_X(T)$, which increases with increasing temperature to compensate for the decrease in span with increasing temperature. However, the zero pressure offset voltage is proportional to the excitation voltage applied to the X-ducer just as is the span. Therefore, the process of temperature compensating span automatically introduces a positive temperature component into the temperature dependence of the offset voltage.

This problem can be minimized by restoring to a balanced span compensation network such as is shown in Figure 17. In this example, the span compensation is split between the top and the bottom of the X-ducer. This results in the common mode voltage at the output of the X-ducer remaining constant over temperature, since the transverse voltage strain gauge acts as a simple voltage divider in the absence of any applied pressure. However, if amplification of the output signal of the X-ducer is required, additional temperature effects can be introduced in the associated circuitry by, for example, the temperature coefficient of the offset voltage of operational amplifiers. Because of these considerations, the general approach to the temperature compensation of the offset voltage of the X-ducer has been to temperature compensate the system rather than the X-ducer piezoresistive pressure sensor element itself.

The simplest method for accomplishing this system offset voltage temperature compensation is to utilize the temperature dependent voltage, $V_X(T)$, already present in the system as a result of the span temperature compensation process. Figure 18 shows a generalized circuit diagram for the signal conditioning of the X-ducer piezoresistive pressure sensor element which incorporates both span and offset temperature compensation. Both positive and negative temperature coefficients of offset can be accommodated, depending on which input of differential amplifier OA_2 is connected to the temperature dependent excitation voltage, $V_X(T)$. This circuit is quite simple, consisting of a buffer amplifier (OA_1) which amplifies the differential output of the X-ducer and minimizes the loading of these outputs (this is important due to the high output impedance of the X-ducer which is on the order of 1.0 kΩ), and a summing amplifier (OA_2) which provides for the adjustment of both span and offset as well as incorporating temperature compensation of the offset voltage. In general, the major gain stage should be in the buffer amplifier (OA_1), since the temperature coefficient of the amplifier offset voltage will also be amplified and can be compensated for by the summing action of OA_2. The summing amplifier (OA_2) should provide only enough gain to allow for the adjustment of span and offset, since it will amplify its own temperature coefficient of offset as well as any higher order temperature dependent voltages which can not be compensated for by the linearly temperature dependent voltage, $V_X(T)$.

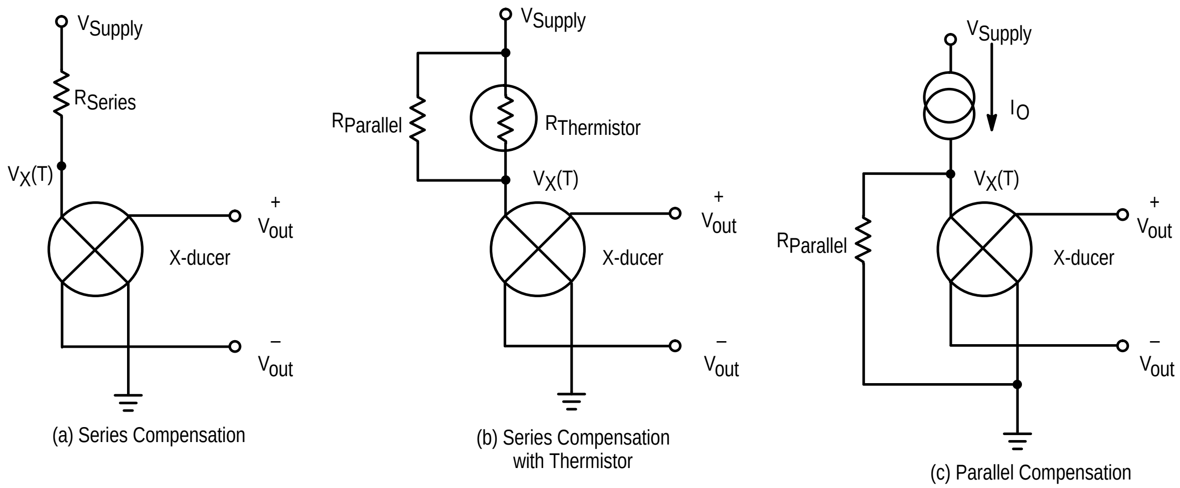


Figure 16. Schematic for Span Temperature Compensation Methods

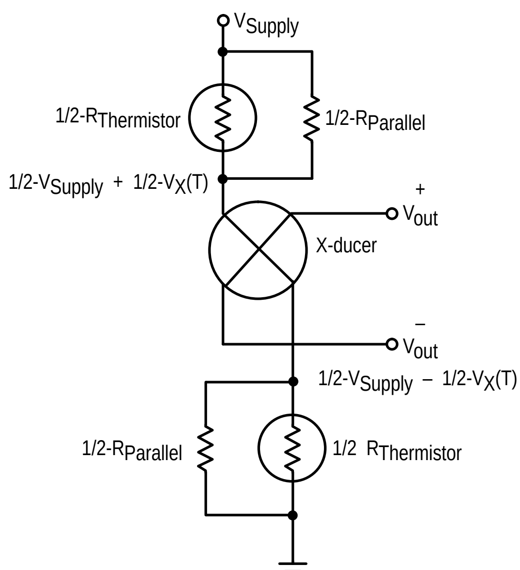
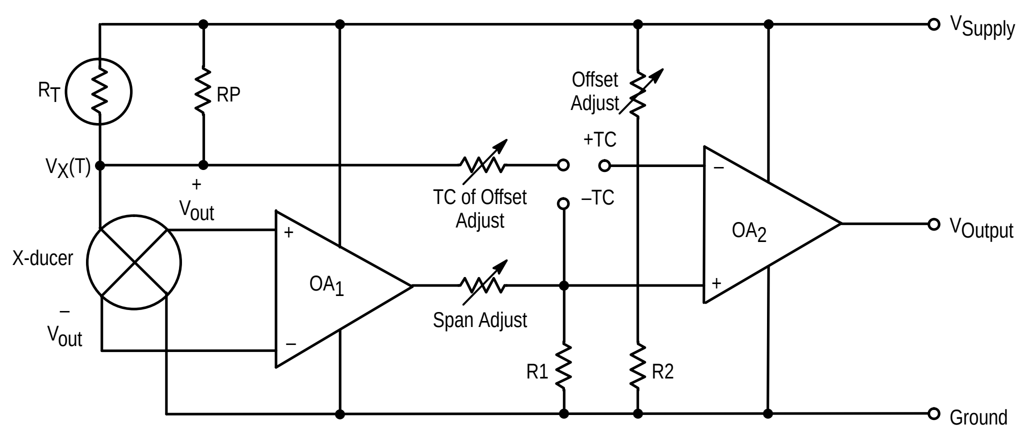


Figure 17. Balanced Series Span Compensation Using Two Thermistor:Resistor Parallel Networks

SUMMARY

Temperature compensation of both span and offset voltage for the X-ducer piezoresistive pressure sensor can be accomplished using relatively simple passive elements to generate temperature dependent voltages which act in a manner counter to the temperature characteristics of the X-ducer. These techniques are capable of providing accuracies of better than ±1% over a temperature range from –40°C to +125°C. Span temperature compensation elements can be selected using design guides presented in the previous sections of this note. The temperature compensation of the offset voltage is less well defined, but should generally be considered from a system viewpoint unless very costly circuits can be accepted.

While the computational methods used in this Application Note may appear laborious, they are well worthwhile. In fact, they are not that difficult. The calculations used in this note have been performed on a programmable hand calculator.



NOTE: OA_1 and OA_2 are generalized differential amplifiers employing negative feedback gain and stabilization.

Figure 18. Generalized Signal Conditioning Circuit for the X-ducer Piezoresistive Pressure Sensor Element, Including Span and Offset Temperature Compensation

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