

## Thermal Accelerometers Temperature Compensation

### Introduction

The miniature thermal accelerometers from MEMSIC are very low cost, dual-axis sensors with integrated mixed signal conditioning. The thermal accelerometer operation is based on a convection heat transfer principle that is implemented with no moving parts for superb reliability and ruggedness.

Like all other accelerometer technologies, the thermal accelerometer sensitivity and zero g bias change when exposed to hot and cold temperatures. However, thermal accelerometers display a predictable and repeatable behavior.

The sensitivity decreases with increasing temperature, and the zero g bias may increase or decrease with increasing temperature. Because these temperature characteristics are predictable and repeatable, the user can compensate for these changes using many different compensation methods. In this application note various compensation methods are described. An analog method using a thermistor, a method using the built in temp sensor and a couple of digital methods using micro-controllers. In the conclusion, a comparison of all these methods will be shown.

### Temperature Effects on Sensitivity

Each thermal accelerometer family display the same sensitivity change with temperature. The sensitivity change depends on variations in convection heat transfer that are governed by the laws of physics. Manufacturing variations do not influence the sensitivity change, so there are no unit to unit differences in sensitivity. The sensitivity change is described by the following equation (reference Figure 1):

$$S_i \cdot T_i^{2.67} = S_f \cdot T_f^{2.67}$$

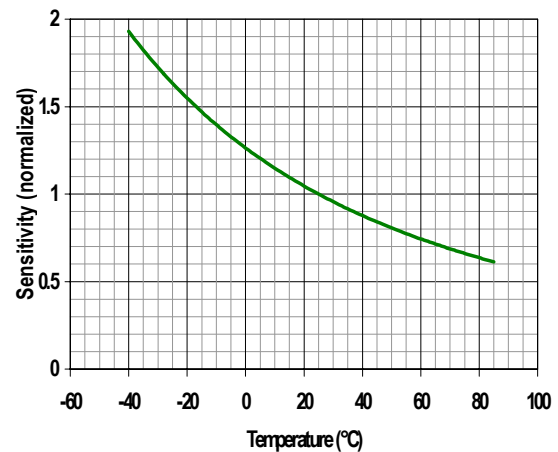


Figure 1 Thermal Accelerometer Sensitivity

where,  $S_i$  is the sensitivity at any initial temperature  $T_i$ , and  $S_f$  is the sensitivity at any other final temperature  $T_f$ , with the temperature values in °K. To put this equation in simple terms, the uncompensated sensitivity is almost double its +25°C value when the accelerometer reaches -40°C, and it is almost half when the device is at +85°C.

The exponent of the temperature term  $T$  will be slightly different for each family of MEMSIC accelerometers (for example Ultra Low Noise devices will display an exponent of 2.81 instead of 2.67).

For applications where sensitivity changes of a few percent are acceptable, the above equation can be approximated with a linear function. Using a linear approximation, an external circuit that provides a gain adjustment of 0.9%/°C would keep the sensitivity within 5% of its room temperature value. For applications that demand high performance, a low cost microcontroller can be used to more accurately implement the above equation. With a microcontroller and this method the sensitivity variation over temperature can be kept well below 1%.

### Temperature Effects on Zero g Bias

The amount that the zero g bias changes with temperature is different for each unit. At extreme temperatures the zero g bias drift is in the order of 0.1g . The magnitude and polarity of this change is usually very similar within each lot of accelerometers. The change can be characterized with the following equation (reference Figure 2):

$$Z = a + b \cdot T + c \cdot T^2$$

where, Z is the zero g bias at any temperature T , and a,b,c are constants characteristic to each accelerometer.

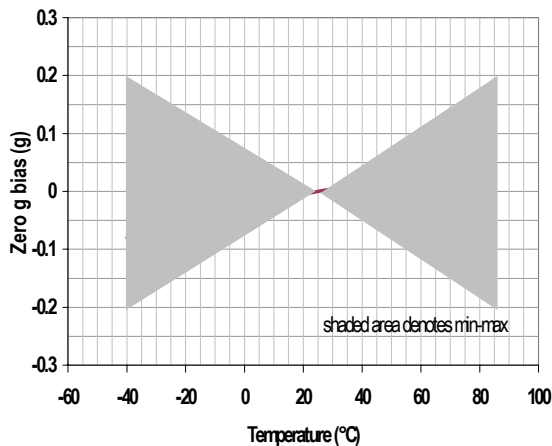


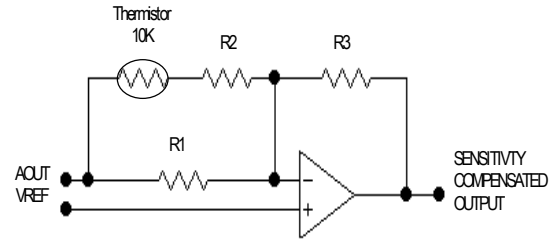
Figure 2 Typical Zero G Bias vs. Temperature

In many applications that require moderate performance at extreme temperatures, a linear approximation of the zero g bias could be applied (i.e. only use constants a,b) . This approximation only requires measuring the zero g bias at two temperature points. The zero g bias calibration is simplified by compromising the temperature correction.

Every application demands compromises between cost and performance. In some designs, even with the additional cost of characterizing and finding the constants the low cost thermal accelerometers will still provide the most cost effective solution.

### Thermistor Compensation of Sensitivity

One relatively simple method for compensating the sensitivity is to use an external temperature sensor or thermistor in the input network of an operational amplifier circuit.



R1	R2	R3	Thermistor	Sensitivity error after temp.comp.
12K	4.3K	4.7K	5K Changzhou ( <a href="http://www.chinahuichang.com">www.chinahuichang.com</a> )	9%
20K	10K	10K	10K Panasonic SMD ( <a href="http://www.panasonic.com">www.panasonic.com</a> )	13%
20K	10K	10K	10K QTI or YSI curve Z ( <a href="http://www.ysi.com">www.ysi.com</a> )	14%

Figure 3 Thermistor Controlled Gain Circuit

Thermistors are readily available that display positive or negative temperature coefficients (PTC or NTC). NTC Thermistors are usually lower cost than PTC types. A simple, low cost circuit like the one shown in Figure 3 using NTC thermistors can be used to compensate sensitivity.

The NTC thermistors display a non-linear change in resistance with temperature that is slightly different from the accelerometer sensitivity non-linear change. Resistors R1 and R2 linearize or change the input resistor network non-linearity so that it approximates the inverse of the behavior of the accelerometer sensitivity.

Different NTC thermistors require a unique input network for optimum compensation. The analytical method to optimize the design of the input network may not be a simple task. One alternate approach is to use a computer model of the network in a program that iteratively increments component values. On each iteration the program checks the network performance across the desired temperature range, until an optimum network is found.



# Application Note

## #AN-00MX-002

The results that can be obtained with this simple circuit are a compromise of cost and performance. In many applications changes of sensitivity of tenths of percent are acceptable. Consider that the net effect of the sensitivity variation is a percentage of the reading, not of the full scale.

For example, in a particular application with  $\pm 2g$  full scale, a 10% sensitivity change due to extreme temperature exposure would cause a 100mg input to be measured as 110mg. The 10mg error represents only a 0.25% of full scale.

The thermistor compensation of sensitivity features unipolar supply operation with a simple implementation and low cost.

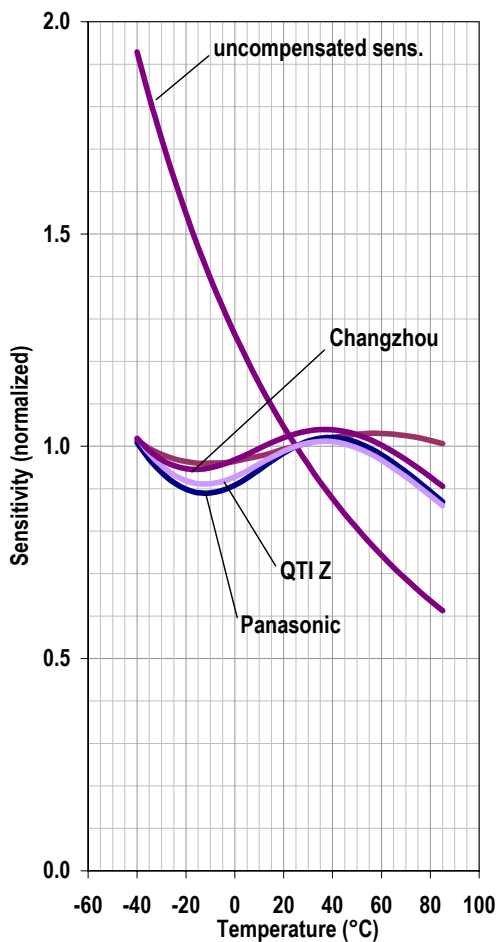


Fig.4 Compensation with different thermistors

### Output Zero g Offset Change With Temperature

Like all other accelerometer technologies, each MEMSIC accelerometer will display a unique change in zero g offset with temperature. The amount of change that is acceptable will be different for each application. The standard MEMSIC products display a typical change of  $\pm 2mg/^\circ C$ , and the newer Ultra Low Noise versions display drifts below  $\pm 1mg/^\circ C$ .

For high accuracy applications, where the zero g offset changes are not acceptable, the user must individually characterize the units and compensate accordingly.

The compensation requires individual calibration because the magnitude of the zero g offset change over temperature is different for each unit. To compensate the drift, a calibrated temperature dependent signal equal in magnitude but with opposite polarity to that of accelerometer drift is added to the accelerometer output. The circuit in Figure 5 shows a circuit example applying an analog linear compensation technique. In this circuit the accelerometer temperature sensor output is added to or subtracted from the accelerometer output.

The calibration sequence is: start at room temperature with the 100K potentiometer set so that its wiper is at  $V_{ref}$ . Next, soak the accelerometer at the expected extreme temperature and observe the direction of the drift. Then set the switch to the non-inverting input if the drift is negative or vice versa. Finally, adjust the 100K potentiometer while monitoring the circuit output, until the zero g offset drift is removed.

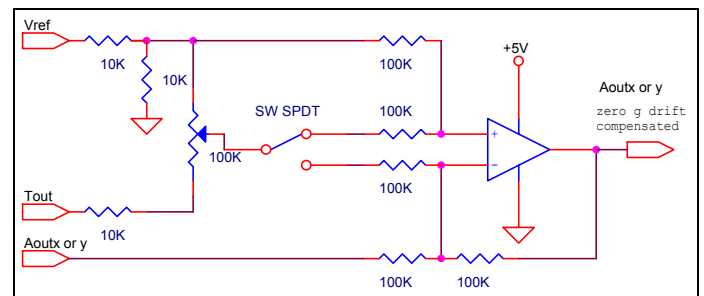


Figure 5: Zero g Offset Temperature Compensation Circuit

### All Digital Compensation

A very effective way for temperature compensation of both sensitivity and zero g is by using a mcu (micro controller unit). Many low cost 8 bit mcu's are available today that feature integrated a/d (analog to digital converters) with resolutions ranging from 8 to 12 bits and with ample program memory. Additional features that simplify the design and enhance the mcu application are integrated oscillators and re-programmable memory (flash).

A block diagram for the all digital compensation is shown in figure 6. For analog output accelerometers the acceleration signal may need amplification if the application's g range is low. The temperature signal can typically be used without amplification.

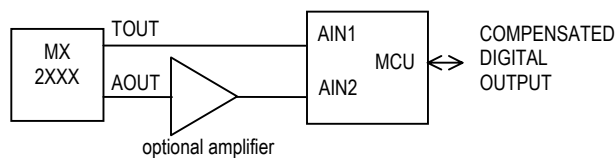


Figure 6 All digital compensation block diagram

The acceleration signal room temperature full scale output must be set so that it won't exceed the a/d full scale range when exposed to low temperatures. For example, in an application with operating range down to  $-40^{\circ}\text{C}$ , the a/d range should be about 2.5 times the accelerometer room temperature full scale output.

Once the acceleration and temperature are digitized, the sensitivity correction in the mcu is relatively simple. From the sensitivity equation it is known that:

$$S_i = S_r \frac{T_f^{2.67}}{T_i^{2.67}}$$

So to correct sensitivity the mcu program would multiply the digitized AOUT by the ratio of the digitized temperature (in  $^{\circ}\text{K}$ ), or:

$$A_{\text{OUTcompensated}} = A_{\text{OUT}} * (T_{\text{OUT}}^{2.67} / T_{25^{\circ}\text{C}}^{2.67})$$

But implementing the above exponential function in an 8 bit mcu would consume a significant portion of the typical device resources (memory and processing time) that are needed for data communications and other tasks (i.e. zero g bias compensation). One way to conserve mcu resources is to use a look up table. Another way is to approximate the above equation to a simpler function that only involves addition and multiplication. One such an approximation would be:

$$A_{\text{OUTcompensated}} = A_{\text{OUT}} * (d + e * T_{\text{OUT}} + f * T_{\text{OUT}} * T_{\text{OUT}})$$

where d, e, f are calculated constants that depend on the a/d resolution, the a/d voltage reference, and the temperature sensor scale factor. These constants can be calculated using curve fitting, typically available in spreadsheet programs. One method for the calculation is to tabulate the inverse of the known sensitivity vs. temperature (in the proper units), and then run the spreadsheet trend characterization or polynomial curve fitting feature.

Another consideration with implementing the above equation in an 8 bit mcu, is that floating point math is required to obtain the best possible compensation. Constants d,e,f, will vary greatly in magnitude, so 16 bit integer math does not provide enough numerical range to execute the equation. Most mcu vendors have the necessary floating point math program libraries available.

In applications with limited operating temperature range, the above approximation can be further simplified by dropping the last term (setting  $f=0$ ). The trade off is a slightly larger sensitivity error, but the programmer can implement the correction using simpler integer math and therefore reduce the mcu memory requirement (and the mcu cost). Table 1 shows some examples of the all digital sensitivity compensation using different a/d parameters. In the calculation of the constants shown in Table 1 the accelerometer temperature sensor with 1V output at  $25^{\circ}\text{C}$  and  $5\text{mV}/^{\circ}\text{C}$  scale was used. The all digital compensation of zero g bias can be performed with the following equation:

$$A_{\text{OUTcompensated}} = A_{\text{OUT}} - (a + b * T_{\text{OUT}} + c * T_{\text{OUT}} * T_{\text{OUT}})$$

where the a, b, c are constants characteristic to each accelerometer. To determine the values of these constants, each accelerometer is taken to three different temperatures, preferably evenly spread across the desired temperature span. The zero g bias and the temperature are recorded at each temperature. The data collected AOUT0, TOUT0, AOUT1, TOUT1 and AOUT2, TOUT2 is used in a quadratic interpolation (or LaGrange polynomial) to determine a, b and c as follows:

$$\begin{aligned} r_0 &= A_{\text{OUT}0} / ((T_{\text{OUT}0} - T_{\text{OUT}1}) * (T_{\text{OUT}0} - T_{\text{OUT}2})) \\ r_1 &= A_{\text{OUT}1} / ((T_{\text{OUT}1} - T_{\text{OUT}0}) * (T_{\text{OUT}1} - T_{\text{OUT}2})) \\ r_2 &= A_{\text{OUT}2} / ((T_{\text{OUT}2} - T_{\text{OUT}0}) * (T_{\text{OUT}2} - T_{\text{OUT}1})) \\ a &= r_0 * T_{\text{OUT}1} * T_{\text{OUT}2} + r_1 * T_{\text{OUT}0} * T_{\text{OUT}2} + r_2 * T_{\text{OUT}0} * T_{\text{OUT}1} \\ b &= -r_0 * (T_{\text{OUT}1} + T_{\text{OUT}2}) - r_1 * (T_{\text{OUT}0} + T_{\text{OUT}2}) - r_2 * (T_{\text{OUT}0} + T_{\text{OUT}1}) \\ c &= r_0 + r_1 + r_2 \end{aligned}$$

a/d resolution	a/d voltage reference	Application Temperature range	mcu math library required	d constant	e constant	f constant	Sensitivity error after temp.comp.
12 bits	2.5 V	-40°C to +85°C	Floating point	$2.0933 \cdot 10^{-1}$	$-1.3843 \cdot 10^{-4}$	$1.4889 \cdot 10^{-6}$	0.3%
12 bits	5.0 V	-40°C to +85°C	Floating point	$1.8816 \cdot 10^{-1}$	$-2.2827 \cdot 10^{-4}$	$3.7898 \cdot 10^{-7}$	0.4%
8 bits	5.0 V	0°C to +70°C	Fixed point	$-9.2673 \cdot 10^{-1}$	$3.7753 \cdot 10^{-2}$	0	1.9%
8 bits	2.5 V	0°C to +70°C	Fixed point	$-9.0149 \cdot 10^{-1}$	$1.8691 \cdot 10^{-2}$	0	2.8%

Table 1. All Digital Sensitivity Compensation Examples

This process can be automated, to provide for a very accurate and simple compensation of the zero g bias. For example a PC (personal computer) can be used to control a temperature chamber, communicate with the mcu, and to calculate the constants. After calculating the constants, the PC would download the constants to the mcu memory. Some mcu's feature built in eeprom (electrically erasable programmable read only memory) that can be serially accessed, providing a convenient method for permanent storage of the compensation constants.

For applications with less demanding zero g bias vs. temperature performance, or applications with reduced temperature range, the above compensation can be simplified by only recording zero g bias data at two temperatures. In this case the third term in the equation is eliminated ( $c=0$ ), resulting in a simple linear approximation compensation.

The all digital compensation of zero g bias provides an excellent enhancement for applications demanding very stable zero g performance (i.e. inclinometry). With this compensation method the zero g bias changes due to temperature can be reduced to a range of a few milli-g's. Additional features of this compensation are that 8 bit mcu's are available in very small surface mount packages, with pin counts as low as 8 (i.e. Microchip 12CXXX family, www.microchip.com), and can be configured to consume very low power.

One limitation of this compensation method in some applications may be frequency response. The time required to process the compensation (or latency) may be too long for certain applications. To overcome this limitation a faster processor will provide improvement, but a slightly different compensation method using both analog and digital components will completely eliminate this limitation, and it is described next.

### Enhanced Digital Compensation with Analog Output

In this compensation method, digitally controlled potentiometers (DIG-POT) are used to periodically adjust the sensitivity and the zero g bias. As in the all digital method, an 8 bit mcu with built in a/d can be used to monitor the accelerometer's temperature sensor. The mcu program uses similar equations to those presented in the all digital method, but instead of multiplying or adding to the digitized  $A_{OUT}$  signal, the program dynamically adjusts the digital potentiometer settings. A block diagram is shown in figure 7.

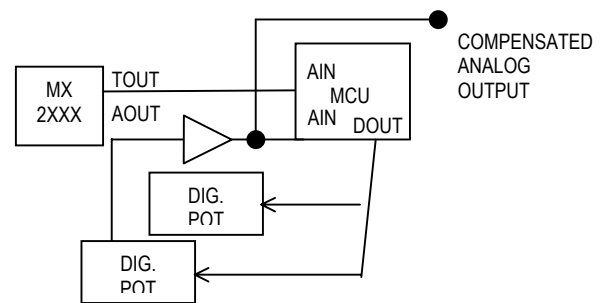


Figure 7: Better digital compensation block

The digital potentiometer sensitivity adjustment is also implemented with a second order polynomial approximation. The polynomial is of the form:

$$\text{SENS. POT SETTING} = d + e * \text{TOUT} + f * \text{TOUT} * \text{TOUT}$$

where d, e, f are the characteristic sensitivity constants. To calculate the constants the same method described in the all digital compensation can be used. In a spreadsheet program, tabulate the compensating potentiometer settings vs. temperature in the proper units, and then calculate the polynomial constants.

Implementing the sensitivity adjustment network requires a differential gain amplifier like the one shown in figure 8. A well matched dual digital potentiometer will provide good linear control of gain. Additional resistors in series with the potentiometers could be used to enhance the resolution of the sensitivity adjustments.

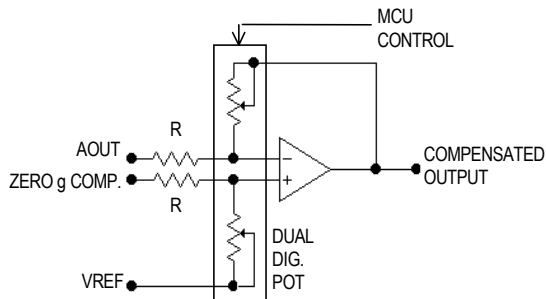


Figure: 8 Sensitivity adjust circuit

The zero g bias is similarly compensated. The compensation is of the same form as the sensitivity:

$$\text{ZERO g POT SETTING} = a + b * T_{OUT} + c * T_{OUT} * T_{OUT}$$

To determine the constants a, b, c the accelerometer is taken to three temperatures. At each temperature the zero g digital potentiometer is trimmed for no offset, and the potentiometer setting is recorded. Also  $T_{OUT}$  is recorded at each temperature. Once the data is collected, the constants a, b, c can be calculated as described in the all digital compensation method. Again, test automation can greatly simplify this compensation process.

In the implementation of the zero g bias network, a dual digital potentiometer can be used to enhance the adjustment resolution. A network like the one shown in figure 9 could provide very high resolution adjustments. In this circuit resistors R3, and R4 are chosen so that one potentiometer provides a coarse adjustment while the other provides a fine adjustment. If each potentiometer has 8 bit resolution, and the potentiometer settings are near the center of the range, zero g bias compensation with 16 bit resolution can be achieved.

Since environmental temperature changes are usually very slow in most application, the digital potentiometer adjustments can be set to occur at low

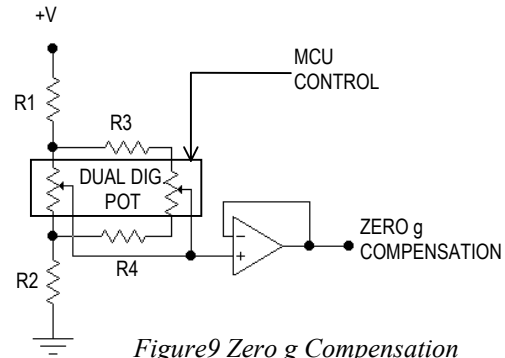


Figure9 Zero g Compensation

rates. One benefit of low update rates, is lower mcu power consumption. The mcu can be operated with an oscillator at a few kilohertz, and this will greatly reduce the power requirement.

The enhanced digital temperature compensation provides excellent results in the most demanding applications. Even with the number of additional components, it provides a very cost effective solution.

Method	Approx. Component Cost	Performance achievable
Analog (thermistor)	Lowest cost	5% - 15 %
Digital (mcu)	Low cost	0.5% - 5%
Analog & Digital (mcu with dig.pot.)	Medium cost	<0.5%

Table 2. Temperature compensation comparison

### Conclusion

Table 2 provides an overview of the methods presented in this application note and some tradeoffs of approximate cost vs. performance.

In summary, many temperature compensation methods can be used to enhance the performance of MEMSIC thermal accelerometers to meet the requirements of the most demanding applications.