



Application Note

#AN-00MX-001

Accelerometer Fundamentals

Introduction

The MEMSIC accelerometers are a complete dual-axis motion measurement system on a monolithic CMOS IC. The principle of operation of the MEMSIC devices is based on heat transfer by natural convection. The devices measure internal changes in heat transfer caused by acceleration. The devices are functionally equivalent to traditional proof-mass accelerometers.

The proof mass in the MEMSIC sensor is a gas. The gaseous proof-mass provides great advantages over the use of the traditional solid proof mass. The device does not display stiction and particle contamination problems associated with competitive devices and provides shock survival up to 50,000g leading to significantly lower failure rates and lower loss due to handling during assembly. The arrangement necessary for measuring the acceleration effects on heat transfer is described next.

A single heat source, centered in the silicon chip is suspended across a cavity. Equally spaced aluminum/polysilicon thermopiles (groups of thermocouples) are located equidistantly on all four sides of the heat source (dual axis). Under zero acceleration, a temperature gradient is symmetrical about the heat source, so that the temperature is the same at all four thermopiles, causing them to output the same voltage (reference Figure 1 for an illustration of an acceleration sensing sequence).

Acceleration in any direction will disturb the temperature profile, due to free convection heat transfer, causing it to be asymmetrical. The temperature, and hence voltage output of the four thermopiles will then be different. The differential voltage at the thermopile outputs is directly proportional to the acceleration. There are two identical acceleration signal paths on the device, one to measure acceleration in the x-axis and one to measure acceleration in the y-axis (reference the block diagram shown in Figure 2).

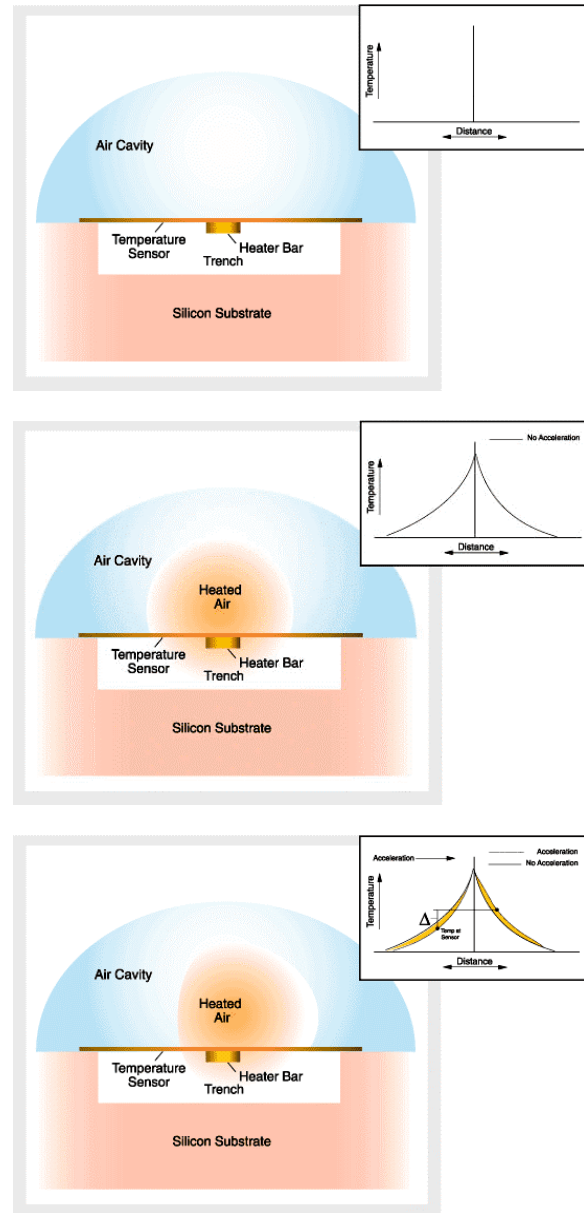


Figure 1: Vertical cross-section showing the sensing sequence



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Acceleration Measurement Range and Accelerometer Outputs

The MEMSIC devices are capable of measuring accelerations with a full-scale range from below $\pm 1.0g$ to above $\pm 100g$. The devices can measure both dynamic acceleration (e.g. vibration) and static acceleration (e.g. gravity).

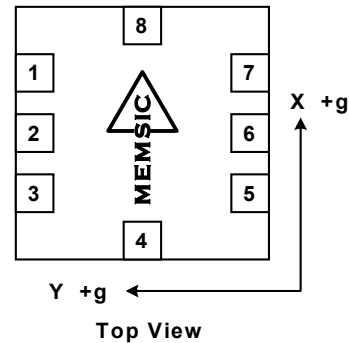
The devices can provide analog or digital output voltages. Analog output voltages are available in absolute and ratiometric mode. The absolute output voltage is independent of the supply voltage, while the ratiometric output voltage is proportional to the supply voltage. The digital outputs are signals with duty cycles (ratio of pulse width to period) that vary with acceleration.

The resolution, or the smallest detectable increment in acceleration is defined by the signal noise. For the MEMSIC accelerometers the typical noise floor is below $1mg/\sqrt{Hz}$, allowing sub milli-g signals to be measured at very low frequencies.

The frequency response, or the capability to measure fast changes in acceleration is defined by design. For these devices the -3dB rolloff occurs at above 30 Hz but is expandable to >160 Hz (reference Application Note AN-00MX-003).

Packaging and Operating Range

The accelerometers are available in a low-profile LCC surface mount package (2.00 mm height). They are hermetically sealed and are operational over a $-40^{\circ}C$ to $+105^{\circ}C$ temperature range.



Pin Description: LCC-8 Package

Pin	Name	Description
1	T _{OUT}	Temperature (Analog Voltage)
2	A _{OUTY}	Y-Axis Acceleration Signal
3	Gnd	Ground
4	V _{DA}	Analog Supply Voltage
5	A _{OUTX}	X-Axis Acceleration Signal
6	V _{ref}	2.5V Reference
7	Sck	Optional External Clock
8	V _{DD}	Digital Supply Voltage

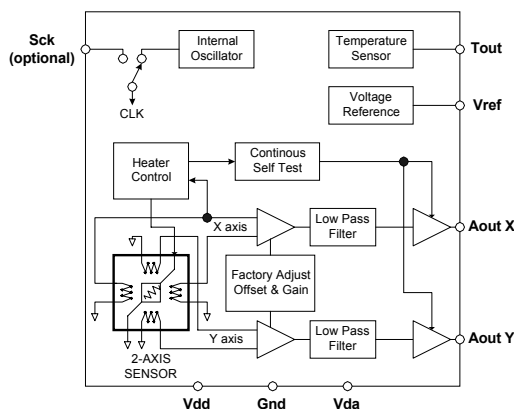


Figure 2: Typical Block Diagram

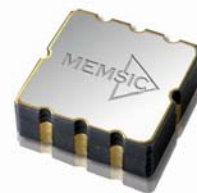


Figure 3: Sample package and pin-outs



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Pin Descriptions

V_{DD} – This is the supply input for the digital circuits and the sensor heater. The DC voltage should be between 2.70 and 5.5 volts.

V_{DA} – This is the power supply input for the analog amplifiers.

Gnd – This is the ground pin.

A_{OUTX} – This pin is the output of the x-axis acceleration sensor. The user should ensure the load impedance is sufficiently high as to not source/sink >100µA typical. While the sensitivity of this axis has been programmed at the factory to be the same as the sensitivity for the y-axis, the device can be programmed for non-equal sensitivities on the x- and y-axes.

A_{OUTY} – This pin is the output of the y-axis acceleration sensor. The user should ensure the load impedance is sufficiently high as to not source/sink >100µA typical. While the sensitivity of this axis has been programmed at the factory to be the same as the sensitivity for the x-axis, the device can be programmed for non-equal sensitivities on the x- and y-axes.

T_{OUT} – This pin is the buffered output of the temperature sensor. The voltage at T_{OUT} is an indication of the die temperature. This voltage is useful as a differential measurement of temperature from ambient and not as an absolute measurement of temperature. After correlating the voltage at T_{OUT} to 25°C ambient, the change in this voltage due to changes in the ambient temperature can be used to compensate for the drift over temperature of the accelerometer offset and sensitivity. Please refer to the section on Output Changes With Sensitivity Over Temperature for more information.

Sck – The standard product is delivered with an internal clock option (800kHz). **This pin should be grounded when operating with the internal clock.** An external clock option, between 400kHz and 1.6MHz, can be special ordered from the factory.

V_{ref} – A reference voltage is available from this pin. It is set at 2.50V typical and has 100µA of drive capability.

Output Sensitivity Changes with Temperature

Each family of thermal accelerometer displays the same sensitivity change with temperature. The sensitivity change depends on variations in 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 change. The sensitivity change for standard accelerometers, is governed by the following equation (and shown in Figure 4 in °C):

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

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. 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).

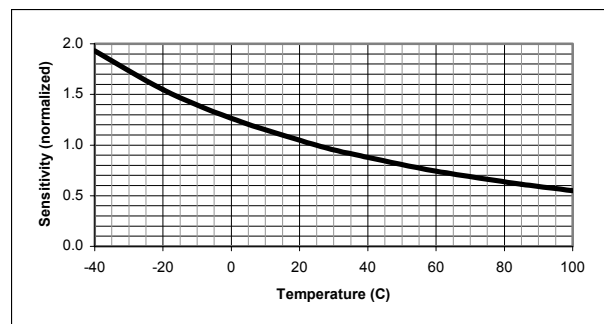


Figure 4: Thermal Accelerometer Sensitivity

In gaming applications where the game or controller is typically used in a constant temperature environment, sensitivity may not have to be compensated for in hardware or software. Any compensation for this effect could be done instinctively by the game player.

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 2.6% of its room temperature value over a 0°C to +50°C range.



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For applications that demand high performance, a low cost microcontroller can be used to implement the above equation. A reference design using a Microchip MCU (p/n 16F873/04-SO) and MEMSIC developed firmware is available by contacting the factory. With this reference design, the sensitivity variation over the full temperature range (-40°C to +105°C) can be kept below 3%. In addition, an MXEB-232-001 evaluation board with an RS-232 connection is available through the MEMSIC web site at www.memsic.com. This evaluation board includes additional features beyond sensitivity compensation over temperature.

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 $\pm 2\text{mg}/^\circ\text{C}$, and the newer Ultra Low Noise versions display drifts below $\pm 1\text{mg}/^\circ\text{C}$.

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.

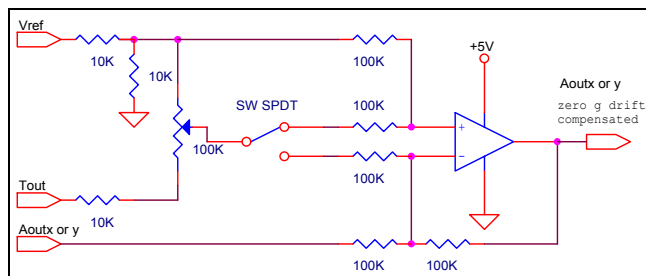


Figure 5: Zero g Offset Temperature Compensation Circuit

Various digital compensation techniques can be applied using a similar concept. Digital techniques can provide better compensation because they can compensate for non-linear zero g offset vs. temperature. A microcontroller or microprocessor would perform the compensation. The acceleration signal and the temperature signal would be digitized using an analog to digital converter. Like in the analog compensation, the first step is to test and characterize the zero g drift. The purpose of the characterization is to create a look up table or to estimate a mathematical representation of the drift. For example, the drift could be characterized by an equation of the form:

$$\text{Drift} = a \cdot \text{Temperature}^2 + b \cdot \text{Temperature} + c$$

where a,b,c are unique constants for each accelerometer. In normal operation the processor calculates the output:

$$\text{Compensated Output} = \text{Acceleration} - \text{Drift}.$$

For a more detailed discussion of temperature compensation reference MEMSIC Application Note #AN-00MX-02.

Discussion of Tilt Applications and Minimum Resolution

Tilt Applications: One of the most popular applications of the MEMSIC accelerometer product line is in tilt measurement. An accelerometer uses the force of gravity as an input to determine the position of an object.

A MEMSIC accelerometer is most sensitive to changes in position, or tilt, when the accelerometer's axis is perpendicular to the force of gravity, or parallel to the Earth's surface. Similarly, when the



accelerometer's axis is parallel to the force of gravity (perpendicular to the Earth's surface), it is least sensitive to changes in tilt. Since a dual-axis accelerometer from MEMSIC is not cost prohibitive compared to a single-axis unit, as is true with nearly all competitors' products, using a dual-axis accelerometer can provide high sensitivity to changes in tilt for all angles.

Table 1 and Figure 6 illustrate the changes in the X- and Y-axes as the unit is tilted from +90° to 0°. Notice that when one axis has a small change in output per degree of tilt (in mg), the second axis has a large change in output per degree of tilt. With triangulation, this permits low cost accurate tilt sensing to be achieved with the MEMSIC device.

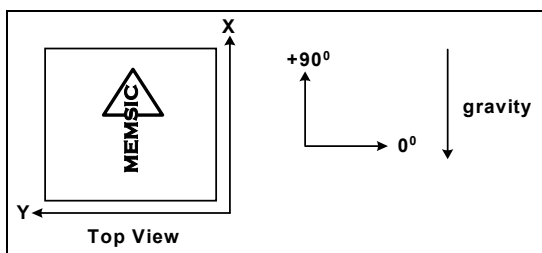


Figure 6: Accelerometer Position Relative to Gravity

X-Axis Orientation To Earth's Surface (°)	X-Axis		Y-Axis	
	X Output (g)	Change/ ° of tilt (mg)	Y Output (g)	Change/ ° of tilt (mg)
90	1.000	0.15	0.000	17.45
85	0.996	1.37	0.087	17.37
80	0.985	2.88	0.174	17.16
70	0.940	5.86	0.342	16.35
60	0.866	8.59	0.500	15.04
45	0.707	12.23	0.707	12.23
30	0.500	15.04	0.866	8.59
20	0.342	16.35	0.940	5.86
10	0.174	17.16	0.985	2.88
5	0.087	17.37	0.996	1.37
0	0.000	17.45	1.000	0.15

Table 1: Changes in Tilt for X- and Y-Axes

Minimum Resolution: The MEMSIC accelerometer product line is capable of resolving less than 1° of tilt angle. The typical rms noise floor for the standard products is specified at $1mg/\sqrt{Hz}$.

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When using a simple RC low pass filter to reduce the noise by limiting the bandwidth, the noise floor of the MEMSIC accelerometer can be calculated by the following equation:

$$\text{Noise (rms)} = (1mg / \sqrt{Hz}) \times (\sqrt{BW \times 1.6})$$

At 10 Hz, the noise will be:

$$\text{Noise (rms)} = (1mg / \sqrt{Hz}) \times (\sqrt{4 \times 1.6}) = 2.5mg$$

The peak-to-peak value of this noise will be the rms value $\times \sqrt{6.6}$ or 16.7mg for a 4 Hz bandwidth. Based on the numbers in table 1 shown for a dual axis accelerometer and the high sensitivity of the $\pm 1g$ and $\pm 2g$ units, MEMSIC devices are capable of resolving less than 1° of tilt at all possible angles.

External Filters

AC Coupling: For applications where only dynamic accelerations (vibration) are to be measured, it is preferable to ac couple the accelerometer output as shown in Figure 7. The advantage of ac coupling is that zero g offset variations from part to part and zero g offset drift over temperature can be eliminated. Figure 7 is a HPF (high pass filter) with a -3dB breakpoint given by the equation: $f = 1/2\pi RC$. In

many applications it may be desirable to have the HPF -3dB point at a very low frequency in order to detect very low frequency accelerations. Sometimes the implementation of this HPF may result in unreasonably large capacitors, and the designer must turn to digital implementations of HPFs where very low frequency -3dB breakpoints can be achieved.

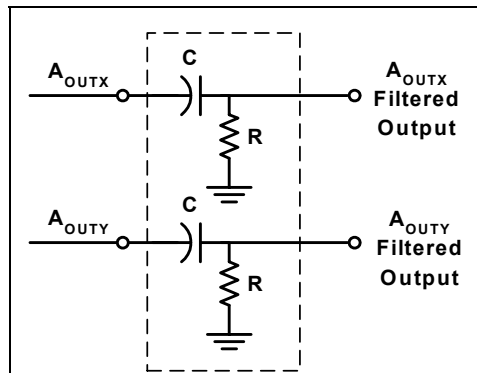


Figure 7: High Pass Filter

Low Pass Filter: An external low pass filter is useful in low frequency applications such as tilt or inclination. The Low Pass Filter band limits the noise and improves the resolution achievable with the accelerometer. When designing with MEMSIC



rationetric output accelerometers (MXRxxxx series), it is highly recommended that an external, 200 Hz low pass filter be used to eliminate internally generated periodic noise that is coupled to the outputs of the accelerometer. The low pass filter shown in Figure 8 has a -3dB breakpoint given by the equation: $f = \frac{1}{2\pi RC}$. For the 200 Hz ratiometric output device filter, $C=0.1\mu\text{F}$ and $R=8\text{k}\Omega$, $\pm 5\%$, $1/8\text{W}$.

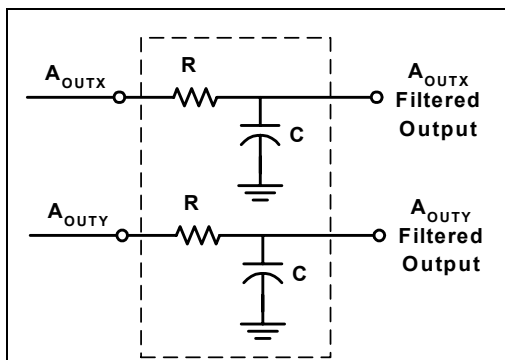


Figure 8: Low Pass Filter

Using MEMSIC Accelerometers in Very Low Power Applications

In applications with power limitations, power cycling can be used to extend the accelerometer operating time. One important consideration when power cycling is that the accelerometer turn on time limits the frequency bandwidth of the accelerations to be measured. For example, operating at 2.7V the turn on time is 40mS. To double the operating time, a particular application may cycle power ON for 40mS, then OFF for 40mS, resulting in a measurement period of 80mS, or a frequency of 12.5Hz. With a frequency of measurements of 12.5Hz, accelerations changes as high as 6.25Hz can be detected. Power cycling can be used effectively in many inclinometry applications, where inclination changes can be slow and infrequent.

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Extending the Frequency Response

The response of the thermal accelerometer is a function of the internal gas physical properties, the natural convection mechanism and the sensor electronics. Since the gas properties of MEMSIC's mass produced accelerometer are uniform, a simple circuit can be used to equally compensate all sensors.

In most applications the compensating circuit does not require adjustment for individual units.

A simple compensating network comprising two operational amplifiers and a few resistors and capacitors provides increasing gain with increasing frequency (see Figure 9). The $14.3\text{k}\Omega$ and the $5.9\text{k}\Omega$ resistors along with the non-polarized $0.82\mu\text{F}$ capacitors tune the gain of the network to compensate for the output attenuation at the higher frequencies. The other resistors and capacitors provide noise reduction and stability.

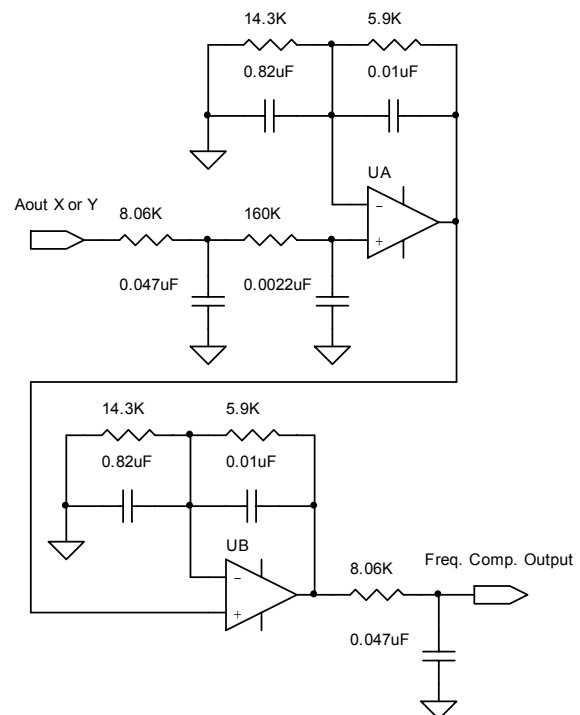


Figure 9: Frequency Response Extension Circuit



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The accelerometer response (bottom trace), the network response (top trace) and the compensated response (middle trace) are shown in Figure 10. The amplitude remains above -3dB beyond 160 Hertz, and there is useable signal well after this frequency.

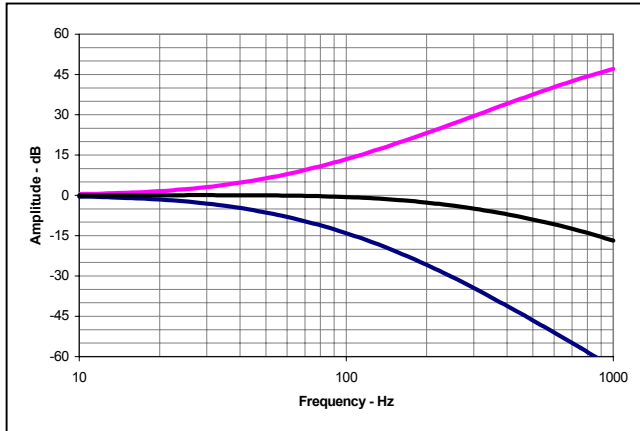


Figure 10: Amplitude Frequency Response

Conclusion

MEMSIC accelerometers provide the most reliable solution in acceleration sensing at a very low cost.