

# A RUGGED, HIGH PERFORMANCE PIEZORESISTIVE ACCELEROMETER

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Many mid-range shock measurements of 100-2000 g are made with accelerometers incorporating silicon strain gages bonded by epoxy to an inertial mass. These accelerometers are limited by low resonance frequencies, fragility to high overshock conditions, and temperature sensitivity. Endevco has developed a new micromachined silicon microsensor featuring DC to 13 000 Hz frequency response, 10 000 g overshock rating, and -65 to +250°F (-54 to +121°C) operating range. The undamped sensor also offers high sensitivity, excellent linearity, and outstanding repeatability.

### MICROSENSOR DESIGN

The microsensor is fabricated from three layers of silicon (see Figure 1). The inner layer or core consists of the inertial mass, piezoresistive gages, and elastic hinge. The inertial mass is suspended inside an etched rim on the hinge; piezoresistive gages on either side detect motion about the hinge. The outer two layers, base and lid, protect the moving parts from environmental contamination. Recesses are provided in the base and lid to allow the inertial mass to move freely. One edge of the lid is etched through to allow access to the bonding and trimming pads.

In contrast to many other silicon microsensors in which the sensitive axis is perpendicular to the silicon wafer, the sensitive axis on the new sensor lies in the plane of the wafer. The

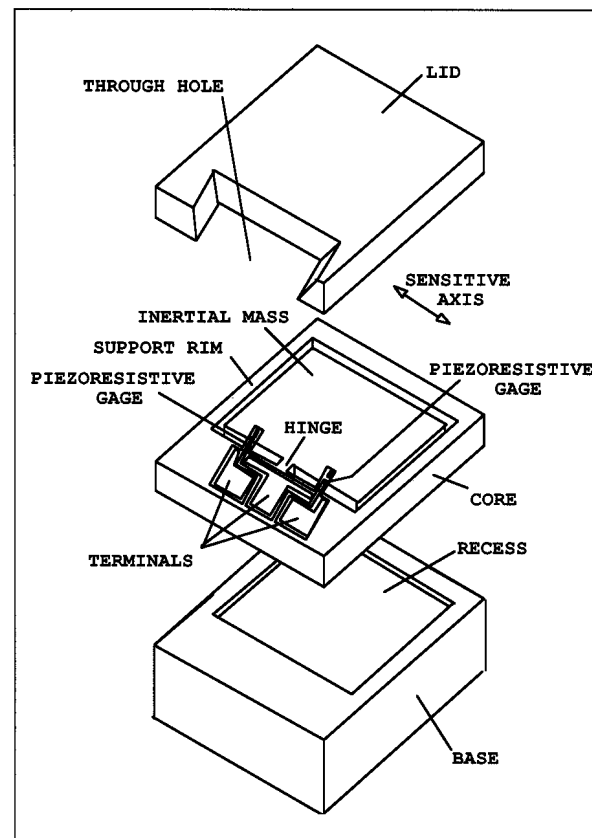
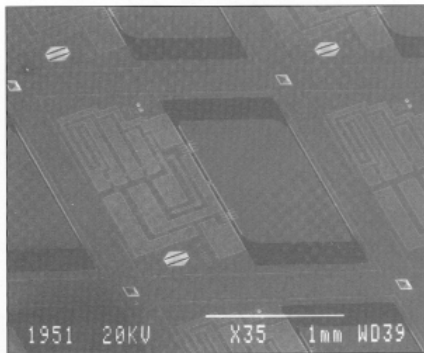


Figure 1. Shown is an exploded view of a new piezoresistive microsensor.

piezoresistive gages, although atomically continuous with the inertial mass and rim, extended freely in space between them. Since the mass, gages, and supporting rim are all formed from a single silicon crystal, the microsensor offers excellent mechanical integrity and repeatability.

When acceleration is applied along the sensitive axis, the inertial mass rotates around the hinge. The piezoresistive gages on either side of the hinge allow the rotation of the inertial mass to create compressive stress on one gage and tensile stress on the other. Because each gage represents a very small amount of silicon, very little strain energy is needed to produce a useful signal. Furthermore, the fraction of resistance change of the piezoresistive gage per unit displacement increases as the length of the gage is reduced. The short gage lengths at appropriate distances from the hinge allow very small displacements to produce very large resistance changes.

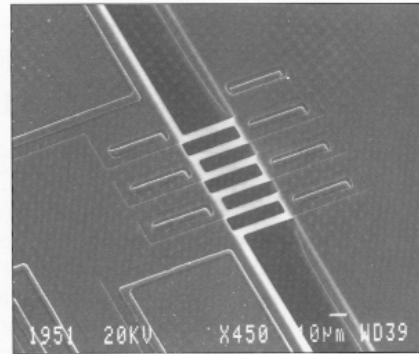
Photo 1 shows the microsensor's inner layer. Because the device is executed in a (110) silicon substrate, it takes the unusual shape of a 70.5° parallelogram. An inverted C-shaped groove on the substrate defines the inertial mass and hinge and undercuts the gages, which extend across the groove between the inertial mass and the support rim as shown in Photo 2.



**Photo 1.** Piezoresistors bridge the gap between the inertial mass and support rim in the inner layer of the microsensor.

Each gage is a series of six boron-doped silicon bridges measuring  $1.3 \times 10^{-10}$  cc.

Five trimming resistors on the silicon core are serially connected to the gage; they appear in Photo 1 as four thin bridges between five metal



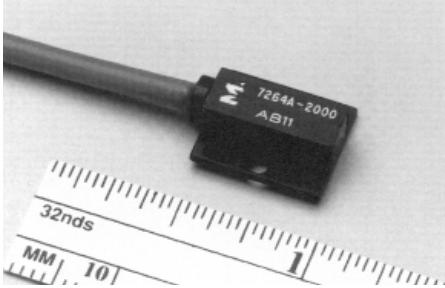
**Photo 2.** Each of the gages is a serpentine of six thin bridges.

pads. A trimming resistor can be activated by blowing out the associated fuse with a current pulse; the resistors in this device are used to trim the zero balance of the strain gage bridge.

## PERFORMANCE

The microsensor and bridge completion resistors are connected on a ceramic substance in a half-active, half-passive Wheatstone bridge. The half-passive portion consists of  $500 \Omega \pm 1\%$  resistors that allow shunt calibration. The number of interconnections has been minimized for improved reliability and quality. After the sensor is in place and electrically connected, the board is mounted in a red anodized aluminum housing. A 4-wire 32 AWG cable is connected to the board, and assembly is completed with an engraved housing lid as shown in Photo 3. The final accelerometer, Model 7264A-2000, measures 0.48 by 0.40 by 0.18 in. (12.2 by 10.2 by 4.6 mm) and weighs only 0.8 g.

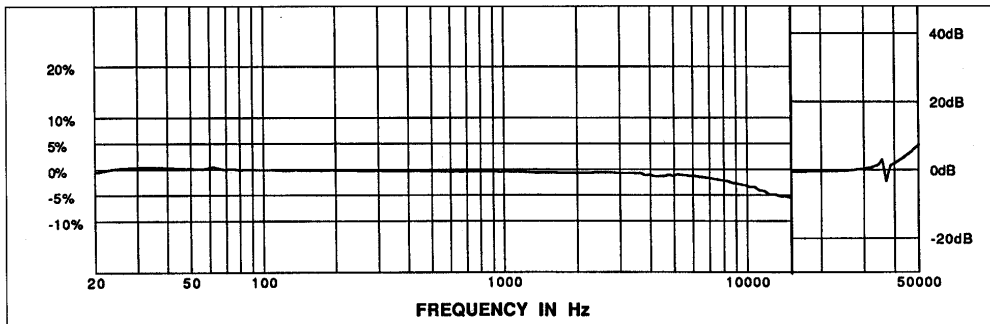
Testing has confirmed the accelerometer's linearity, resonance frequency, frequency re-



**Photo 3.** The Model 7264A-2000 Accelerometer includes the new microsensors packaged in a red anodized housing with integral cable.

response, thermal zero and sensitivity shifts, transverse sensitivity, and shock survivability.

resonance frequency. Figure 2 demonstrates the flat response within  $\pm 5\%$  to 13 000 Hz which corresponds to a resonance frequency of 65 000 Hz. Another design improvement was to place the center of gravity in line with mounting holes and at the center of the accelerometer, making frequency response measurements easier and more accurate. For a typical triaxial shock measurement application, three accelerometers are mounted on a block as shown in Figure 3. The new design minimizes total test setup time and measurement errors because the centers of gravity of these three accelerometers intersect at the center of the block.



**Figure 2.** A typical frequency response of the packaged microsensors is  $\pm 5\%$  to 13,000 Hz.

Table 1 compares the new design's performance to that of other piezoresistive shock accelerometers.

As previously noted, one key characteristic of this accelerometer is a wider frequency response range that is directly related to the

Shock testing has demonstrated the accelerometer's survivability at 10000 g which improves reliability and eliminates concern over handling damage during installation and removal. This ruggedness is a product of silicon's excellent yield strength and a relatively high piezoresistive coefficient. The

Table 1 Accelerometer Performance Comparison		
	(Model 7264A-2000)	Existing Accelerometers
Range	2000 g	2000 g
Sensitivity (typ.)	0.20 mV/g	0.10 to 0.25 mV/g
Linearity (max.)	2%	3%
Mounted resonance frequency	65 kHz	25 kHz
Frequency response ( $\pm 5\%$ , typ.)	0 to 13 kHz	0 to 4 kHz
Transverse sensitivity (max.)	3% (1% option available)	3% (1% option available)
Zero measurand output (max.)	$\pm 25$ mV	$\pm 50$ mV
Operating temperature range	$-65^{\circ}\text{F}$ to $+250^{\circ}\text{F}$ ( $-54$ to $+121^{\circ}\text{C}$ )	$0^{\circ}$ to $+150^{\circ}\text{F}$ ( $-18$ to $+66^{\circ}\text{C}$ )
Thermal zero shift	$\pm 2$ mV, $-65^{\circ}\text{F}$ to $+250^{\circ}\text{F}$	$\pm 40$ mV, $0^{\circ}\text{F}$ to $+150^{\circ}\text{F}$
Thermal sensitivity shift	$-0.04\%/^{\circ}\text{F}$ , $-65^{\circ}\text{F}$ to $+250^{\circ}\text{F}$ ( $-54$ to $+121^{\circ}\text{C}$ )	$\pm 0.05\%/^{\circ}\text{F}$ , $0^{\circ}\text{F}$ to $+150^{\circ}\text{F}$ ( $-18$ to $+66^{\circ}\text{C}$ )
Shock survivability	10 000 g	5000 g
Weight	0.8 gm	1 gm - 5 gm

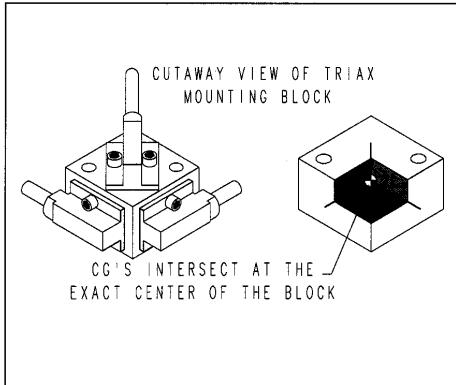


Figure 3. Measurement of the 3-orthogonal axis is accomplished on a triaxial block.

sensor design stress levels can therefore be kept low while maintaining an excellent

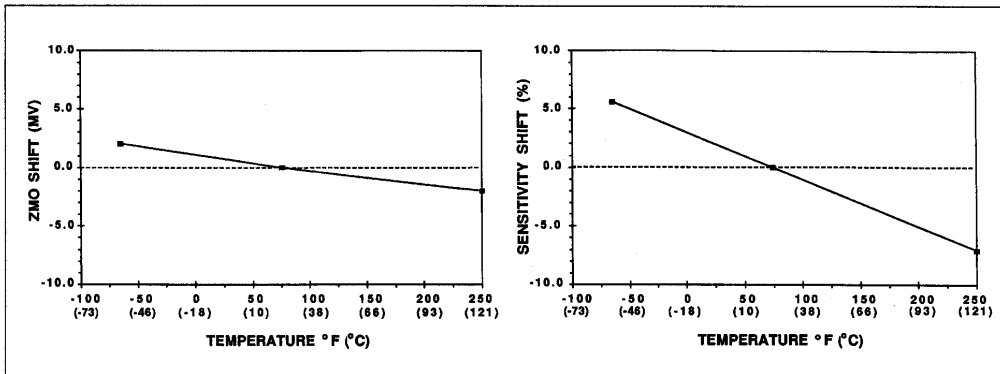


Figure 4. Thermal zero shift is much improved and temperature correction for this linear thermal sensitivity shift can be accomplished with a resistor.

signal-to-noise ratio. The Model 7264A-2000 Accelerometer offers a typical sensitivity of 0.2 mV/g with a 10 VDC excitation.

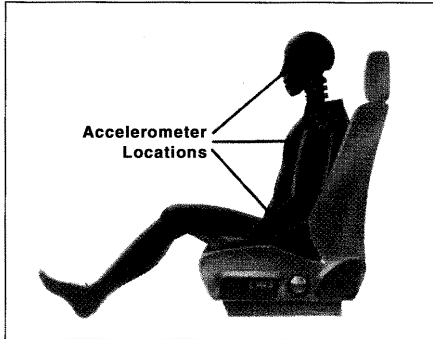
Piezoresistive accelerometer designs with discrete, epoxy-bonded strain gages tend to have undesirable output temperature coefficients; because they are manufactured separately, the gages require individual thermal testing and parameter matching. The new microsensor eliminates this problem by fabricating both gages at the same time and placing them in close proximity. Micromachining technology also offers fabrication tolerance control in the micron range.

The gages are well-matched in temperature coefficients, electrical properties, and physical dimensions. Close proximity also minimizes the effects of thermal transients, improving the thermal performance over a -65 to +250°F (-54°C to +121°C) temperature range. Typical curves of the sensor's thermal zero shift and thermal sensitivity shift are shown in Figure 4. The thermal zero shift over this expanded temperature range is typically  $<\pm 2$  mV and the thermal sensitivity shift is linear and consistently  $<0.04\%/^{\circ}\text{F}$  ( $<0.08\%/^{\circ}\text{C}$ ). Because the microsensor is undamped, its damping ratio remains fairly constant over the temperature range, resulting in a stable frequency response versus temperature.

## APPLICATIONS

The Model 7264A-2000 Accelerometer satisfies the performance requirements for a wide range of automotive and aerospace applications, and modifications can be made in the package to suit individual installation requirements.

The device's ruggedness and performance characteristics give it a role in the barrier and sled tests the automotive industry conducts to ascertain how safe a vehicle's occupants can expect to be in the event of a crash. As shown in Photo 4, some of these tests are carried out on an anthropomorphic dummy that incorporates ac-



**Photo 4.** Anthropomorphic dummy response studies are conducted to improve vehicle safety and restraint designs.

celerometers mounted in the head, chest, and pelvic regions. The devices are also suitable for automotive structural studies in which impact tests determine vehicle body strength and the amount of force needed to collapse the auto. The accelerometer can also provide data on various components' response to impact shock.

Shock and vibration testing is performed on automobiles, trucks, and railroad cars to ensure suspension system durability and to make sure that airbags are not triggered by travel over rough roads. This testing is typically performed at proving grounds under extreme environmental conditions. Because the accelerometer is undamped and the gages are well matched, it offers stable thermal performance over a wide temperature range to satisfy these demanding test requirements.

Aerospace vehicles under development are tested extensively to ensure structural integrity and performance. During a missile flight test, for example, parameters such as shock, acceleration, and spin are measured during various stages of launch, stage separation, and impact. The test instrumentation is often required to survive very high g launch environments and then to recover and measure in-flight accelerations. The new Model 7264A-2000 Accelerometer offers high g shock survivability in a low-mass, rugged case that minimizes mass loading of small structures.

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