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Miniature Accelerometers for Measuring Inertial Motions and Surviving High G Shock Inputs

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MINIATURE ACCELEROMETERS FOR MEASURING INERTIAL MOTIONS AND SURVIVING HIGH G SHOCK INPUTS

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INTRODUCTION

A miniaturized solid state accelerometer is now available on a production basis for use in weapon systems. This accelerometer features a silicon micromachined variable capacitance microsensor packaged with associated microelectronics. Linear measurement ranges are from 2 to 60 g's full scale. Its rugged design provides extremely high overrange protection, from 5,000 to 20,000 g's.

Because it is easily customized, this variable capacitance accelerometer can match many requirements. It is suitable for electronic safe-and-arm and flight control of tactical missiles and projectiles, particularly gun and mortar-fired weapons. Users can easily achieve application-specific solutions and enjoy the flexibility of modular design, because the microsensor is on a separate chip from the electronic circuitry. The accelerometer's packaging utilizes chip and wire hybrid fabrication with various configurations, such as leadless chip carriers, platform cases, or bolt down housings.

This paper will describe the basic sensor, electronic scheme, packaging, and performance results achieved with this accelerometer.

ACCELERATION MICROSENSOR DESIGN

Acceleration sensing is accomplished by using a half-bridge, or three terminal, variable capacitance microsensor. With applied acceleration, the capacitance of one circuit element increases while the other decreases, thus providing a linearized output. This sensor is a second generation design and an extension of development work completed in the mid-1980's. [1, 2]

The total size of each microsensor is 0.08 x 0.11 x 0.036 inch (2.0 x 2.8 x 0.9 mm) as illustrated in Figure 1. Each microsensor is fabricated in an array of three micromachined single crystal silicon wafers "sandwiched" together. The top and bottom wafers of the sandwich contain the fixed capacitor plates which are electrically isolated from the middle wafer. The middle contains the inertial mass, the suspension, and supporting frame. Beams positioned at the top and bottom surfaces of the wafer separate each rectangular mass from its frame along all four sides (See Fig. 2). As a result, the mass remains parallel to the top and bottom plates when deflected with applied acceleration.

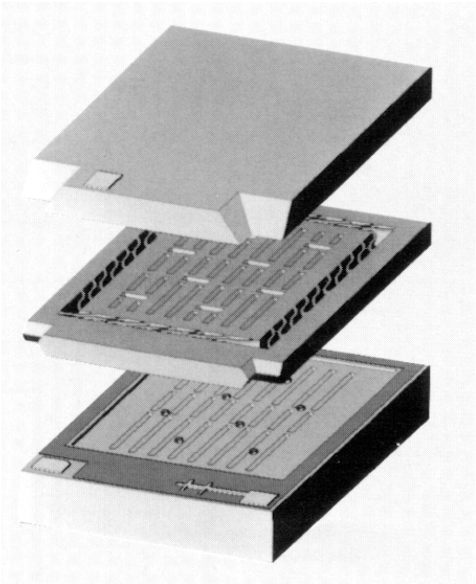

Figure 1. Exploded View of Microsensor.

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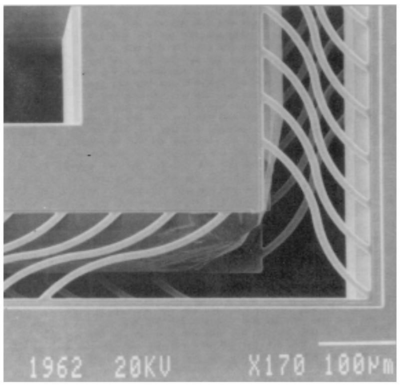

Figure 2. SEM Photo of Microsensor Support Beams

Capacitance is measured from top to middle, and middle to bottom. Element capacitance is 8 pF while typical full scale range is ±0.6 pF. Electrical isolation is achieved by using thin layers of glass. The three wafers are joined together at the wafer level using an anodic bonding process. The bonding temperature is 932°F (500°C). After joining the three wafers together, the devices are sliced into individual microsensors from the wafer array. [3]

The wafers are precisely micromachined to control three additional features:

1. Suspension stiffness: Controlled by varying the shape, cross-sectional dimensions, and number of beams.
2. Damping: Controlled by varying dimensions of grooves and windows on the parallel plates.
3. Overrange: Extended by adding overtravel stops.

This novel design provides unusually high mechanical shock survivability when compared to most other accelerometers, which typically use a cantilever beam or pendulum inertial system. These approaches have fragility problems because mass movement is constrained in the sensitive direction at only one point, usually the end of the beam or pendulum. High shock inputs place these systems into shear stress and suspension may fail.

With this variable capacitance acceleration microsensor, the mass displaces rectilinearly into a group of eight overtravel stops distributed over each surface of the mass. The microsensor moves an extremely small amount, only 24 microinches (0.6 micrometers) before its movement is constrained, compared to its full scale displacement of 12 microinches (0.3 micrometers). An overrange of 90,000 g's has been achieved with a 70 g full scale design. [4]

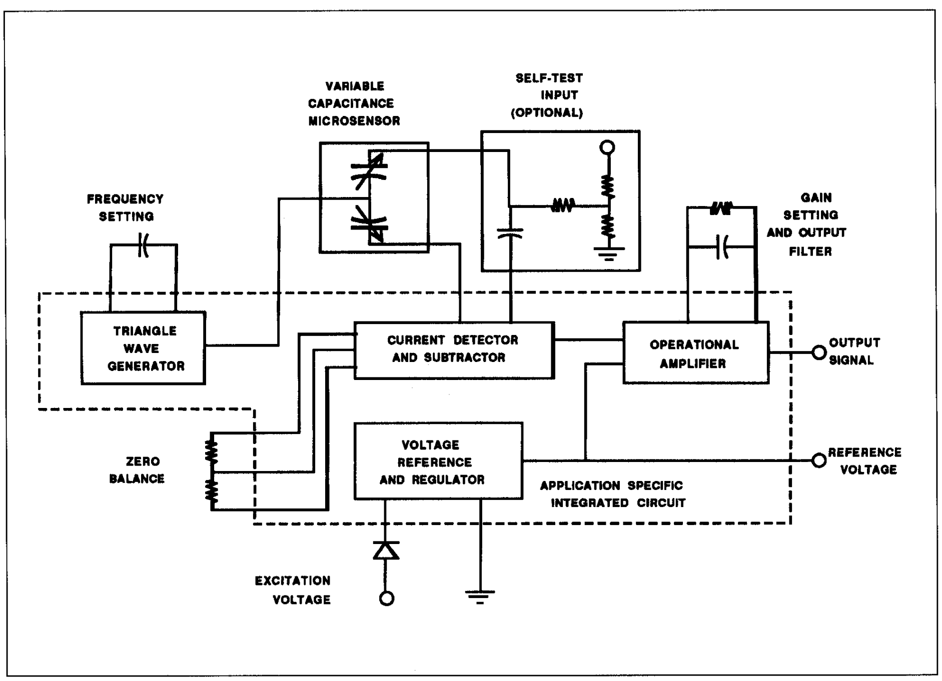

Figure 3. Circuit Block Diagram

Assembly of the three sections of the microsensor is done at the wafer level while still in the wafer fabrication cleanroom. This provides maximum protection for the interior of the sensor since the top and bottom sections also serve to isolate the inertial system from the external environment. Since all three are made of silicon, the temperature coefficients of expansion match. This provides excellent thermal performance.

ACCELEROMETER SYSTEM DESIGN

Several electronic schemes can be used with this microsensor. One approach uses a closely regulated triangle wave voltage which is applied to both capacitive elements of the microsensor. This produces currents through the elements which are proportional to their capacities. A current detector and subtractor full-wave rectifies the currents and outputs their difference. An operational amplifier then converts this current difference to an output voltage signal. A block diagram of the standard circuit is shown in Fig. 3. The active portion of this circuit has been placed on a single application specific integrated circuit chip (ASIC). In the standard circuit, passive components external to the ASIC set gain, zero offset, oscillator frequency, and output filtering.

This ASIC is designed to operate from 8.5 to 40 VDC excitation and provide a low impedance voltage output. The triangle wave input to the sensor is approximately 2 MHz and is controlled by an off-chip capacitor. Zero output and sensitivity (gain) can be adjusted by either adding laser trimmable resistors or placing the coefficients in the memory of a digital correction circuit. The standard circuit output is ±2 peak and includes a single pole filter to reduce extraneous output noise. Additionally, external filters and other circuit functions can be added depending on the application requirements.

The mechanical packaging approach is based on standard hybrid chip and wire fabrication technology. The microsensor and associated electronics are generally bonded to a thick film alumina substrate, which is placed into a hermetic hybrid enclosure. Physical layout can be easily varied to accommodate different circuit packages and circuit features. Several examples of accelerometer designs are described below:

Structure Mounted Housing (10 to 16 grams)

Packaging the hybrid into an external housing offers exceptional application flexibility and ruggedness. Fig. 4 depicts a standard accelerometer that is currently available off-the-shelf.

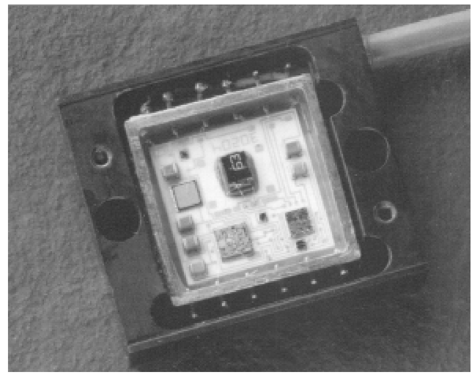

Figure 4. Standard Accelerometer
Size: 0.85 x 1.00 x 0.30 inches (21.6 x 25.4 x 7.6mm)

The device in Fig. 5 features a housing that adds EMI line filtering and shielding, electrical isolation from structure, bolt hole mounting, and terminals for external wiring. For this design, special circuitry is included to add two-pole Butterworth filtering and increase the output voltage.

Figure 5. Custom Accelerometer
Size: 1.00 x 1.00 x 0.38 inches (25.4 x 25.4 x 9.7mm)

Accelerometers such as these typically include laser trimmed zero and gain to provide interchangeability without system adjustments.

In-Circuit, Platform Package (6 grams)

When packaged as an electronic component, the accelerometer can be placed directly on a circuit board within an electronic assembly. An example of this approach is shown in Fig. 6 where the accelerometer is contained in a dual in-line platform package. This particular design includes additional components to provide a self-test feature.

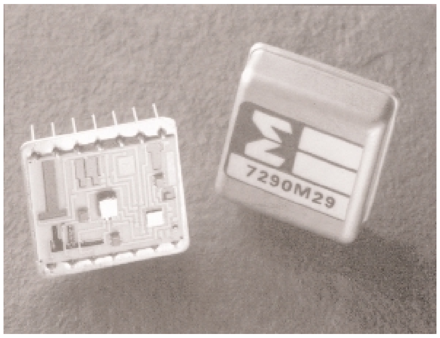

Figure 6. Accelerometer in Platform Package
Size: 0.75 x 0.75 x 0.25 inches (19.0 x 19.0 x 6.3 mm)

Minimum Case with Electronic Circuit (1 gram)

When space is limited, accelerometers can be provided which include only the microsensor, system IC (ASIC), and minimal passive components. The design shown in Fig. 7 includes two capacitors, and one trimmable resistor. This configuration requires only three electrical terminals. This design approach can be effective if external digital correction can be implemented elsewhere as in "SMART" systems. Mounting space is minimized because the accelerometer footprint is only three-eighths inch square.

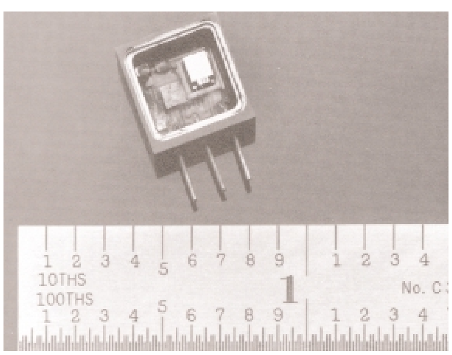

Figure 7. Accelerometer in Minimum Case w/Electronics
Size: 0.38 x 0.38 x 0.13 inches (9.7 x 9.7 x 3.3mm)

SMT Sensor Package (less than 1 gram)

For some applications the variable capacitance microsensor can be provided without electronic circuitry. For ease of use, the sensor can be packaged into a leadless ceramic chip carrier having a size of 0.24 x 0.24 x 0.08 inch (6.1 x 6.1 x 2.0mm), and then handled as an SMT component.

PERFORMANCE CHARACTERISTICS

The variable capacitance sensing approach provides a performance capability which generally exceeds that of other open loop systems. Specifically, errors due to temperature can be quite low, particularly since the sensor is fabricated from a homogeneous material.

Table 1 describes the basic performance capabilities of these accelerometers. Detail specifications and circuit features vary depending on application requirements. Performance features such as filtering, self-test, EMI protection, and special input and output circuits can be provided.

TABLE 1
TYPICAL PERFORMANCE CHARACTERISTICS

Characteristic	Performance
Ranges	±2 g to ±60 g full scale
Noise level (0.5 to 100 Hz BW)	0.0001 g rms for 2 g FS 0.001 g rms for 60 g FS
Linearity	0.25% from BFSL
Frequency Response	Damped, natural frequency of 1300 Hz for 2 g FS 5500 Hz for 60 g FS
Transverse Sensitivity	1%
Temperature Errors	1% to 2% over a 180°F span -65°F to +250°F (100°C span from -55°C to +121°C)
Maximum Shock	5,000 g to more than 20,000 g
Warm-Up Time	1ms to within 1% of final output
Overrange Recovery	less than 10 µs
Full Scale Output	±2 peak differential
Excitation Voltage	8.5 to 40.0 VDC (designed for unregulated 28 VDC and 12 VDC battery operation)

SELF-TEST CAPABILITY

Unlike piezoresistive approaches, variable capacitance sensing can easily incorporate true self-test. When an external voltage is applied to the sensor, it physically moves the inertial mass through electrostatic attraction, therefore the integrity of both the mechanical and electrical systems are checked. The circuit block diagram for this configuration is shown in Fig. 3 as an optional feature.

The force required to move a sensor mass is proportional to the square of the applied self-test voltage. In cases where the stiffness of the microsensor is increased to achieve the higher g-ranges, the applied self-test voltage must be increased to achieve an equivalent proportion of full scale output. Because of the miniaturization of the microsensor, the required input voltages are of a practical level. Fig. 8 shows the input voltages required to provide self-test for the accelerometers with linear full scale ranges of 2 to 60 g's. These self-test voltage levels provide outputs equivalent to 60% of the linear range of the microsensor.

As an example, when 10 VDC was applied to the 10 g microsensor element of one of the custom accelerometers, the device output increased by 2.27 volts. Based on the calibrated sensitivity of the device of 0.38 volts/g, 6 g's of self-test output were provided.

LONG TERM STABILITY AND SHOCK ENDURANCE

One of the accelerometers currently in production is used in a terminally guided fire and forget anti-armor mortar. The accelerometer must perform after withstanding15 years of storage and a mortar launch.

In order to substantiate the long term stability and shock endurance of the design in the qualification test program, three accelerometers were exposed to a 3,000 hour bake at 100°C while fully powered. This simulates more than 15 years at 45°C according to the Arrhenius relationship. This was followed by a rail gun test at 8,000 g's with a pulse duration of 10 milliseconds. The small zero offset and sensitivity shift results contained in Table 2 illustrate the ruggedness and stability of this device, which is used to measure projectile motions of up to ±4.6 g's.

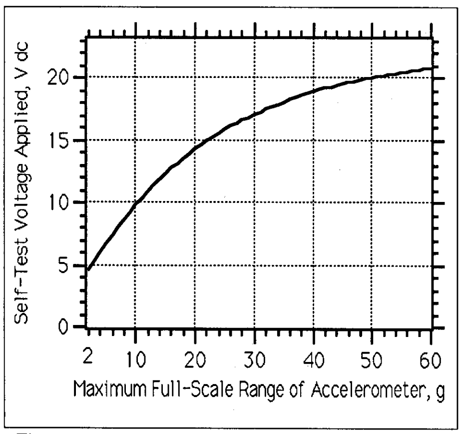

Figure 8. Applied Self-Test Voltage to Provide 60% Full Scale Output

TABLE 2
PERFORMANCE ERRORS AFTER THERMAL AGING AND LAUNCH SHOCK

Serial Number	Zero Offset Shift (g's)	Sensitivity Shift (%)
AA17	0.003	0.79
AA21	0.027	0.74
AA25	0.039	0.99

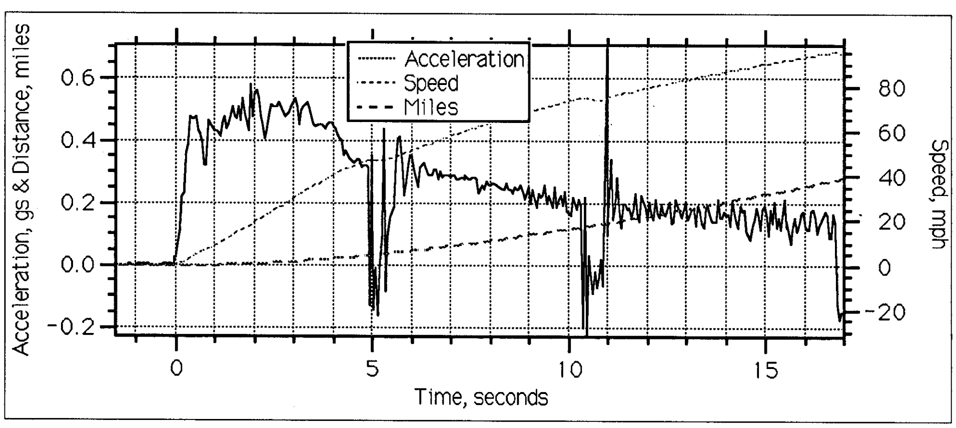

Figure 9. Dragstrip Run Results

In another accelerometer design, seven devices using a 70 g sensor were tested and survived up to 90,000 g's with only small shifts in performance. The average zero bias shift was less than 0.3 percent of full scale, and sensitivity shift was less than 0.7 percent. In addition, the shock was applied in the transverse axis, which is most sensitive to damage. The sensors have also survived 125,000 g centrifuge tests.

APPLICATIONS

As an example of the capabilities of this type of device for low-g level acceleration measurements, Endevco engineers instrumented a stock automobile with a standard 2 g full scale accelerometer. The device was aligned with the sensitive axis in the direction of travel. A run was then conducted on a quarter-mile dragstrip, while the output of the accelerometer was recorded on a data logger. The device was calibrated for one volt per g output. Fig. 9 depicts the output of the accelerometer with the zero nulled. Note that the low level fluctuations are due to suspension vibration.

The data was integrated once to produce the velocity curve. Note that the two points at which the driver shifted gears can be identified. Another integration was done to produce the distance curve. From that, the quarter-mile race distance was derived from the accelerometer output. In this case the stock car took 15.9 seconds to travel the quarter mile (1320 feet).

This example illustrates the suitability of the accelerometer design for safe-and-arm and other applications requiring double integration of the signal over moderately long time periods.

CONCLUSIONS

The variable capacitance approach using silicon microsensors for acceleration measurement has demonstrated excellent performance. This microsensor design has proven tolerant of extremely high overrange inputs. By combining this microsensor with analog ASIC technology, highly rugged, low-power-consuming, miniature accelerometers can be provided.

This variable capacitance accelerometer can meet the increasing demands in the military market for higher reliability, more rigorous quality control, and advanced technology weaponry. Furthermore, the building block approach of this design allows optimal customization for each application.

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4.) Sill, R.D., "A ±70 g Full Scale Accelerometer Designed to Survive 100,000 g Overrange," Sixteenth Transducer Workshop, Range Commanders Council, White Sands New Mexico; June 18-20, 1991.

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