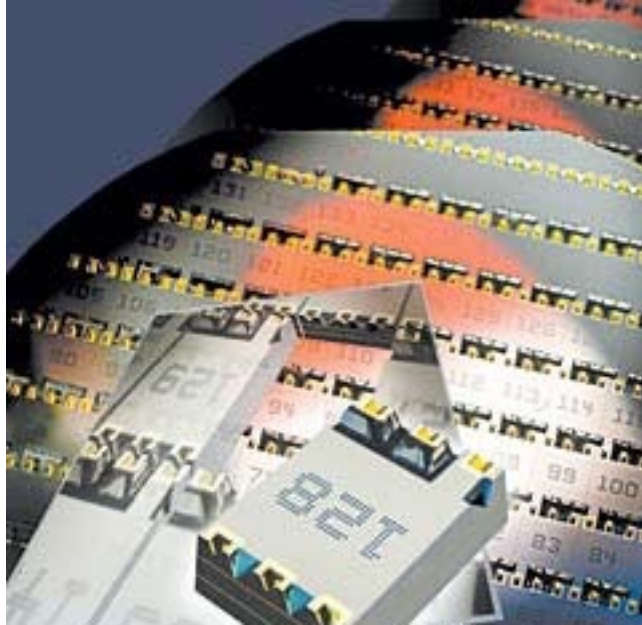


Variable Capacitance Accelerometers: Design and Applications

Micromachined silicon variable-capacitance accelerometers are designed for easy manufacture and demanding applications.

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All variable capacitance accelerometers have certain basic design elements in common. They incorporate a seismic mass whose motion in response to shock or vibration lags behind that of the accelerometer housing. The capacitor consists of two plates, one attached to the outer frame and therefore stationary and the other attached to the seismic, or inertial, mass. The value of this capacitor is a function of the distance between the plates, which varies with the motion of the seismic mass.



Sensor Element Design

In the silicon differential variable capacitance sensor element shown in Photo 1, an inertial mass, suspended from either outer layer of the sensor element by a system of multiple flexible beams, undergoes rectilinear movement with applied acceleration. The mass is electrically connected as part of a variable-capacitance half-bridge circuit. Fixed capacitive plates in the lid and base of the sensor element complete the circuit. The capacitance on one side of the circuit increases with acceleration, while the other side proportionally decreases, providing a linearized output. Capacitor gaps of 3.6 microns provide sensitivity to 0.003 pF/g. Stops protect against overtravel protection, and gas damping achieves a frequency response to 11,000 Hz.



Photo1. The variable capacitance sensor element weighs 15 mg and measures 0.14 by 0.11 by 0.03 in high

The sensor element is fabricated by eutectically bonding together three micromachined single-crystal silicon wafers and then dicing the sandwich. Eutectic bonding minimizes the charge migration in the capacitive gaps and the thermal coefficient of expansion mismatch problems that can occur with the more conventional approach of anodic bonding of silicon to Pyrex glass. Both charge migration and relaxation of stress over time due to thermal mismatches can result in zero-bias instability.

The middle layer contains the inertial mass and suspension system. The suspension system (see Photo 2) is an array of up to 188 sinuous beams at the levels of the two principal surfaces of the inertial mass around its rectangular periphery within a supporting frame. Modifications in the shape, cross-sectional area, and number of beams control the suspension stiffness which, in turn, directly affects the device's sensitivity to acceleration. After the beams are laid out on the wafer by high-level boron implantation at particular locations, and with specific geometries, the beams, inertial mass, and ringframe are formed by anisotropic bulk micromachining that etches the wafer from both sides.



Photo 2.
The beams in the suspension system supporting the inertial mass are typically 9 microns wide and 1.5 microns thick.

Varying the dimensions of channels and windows etched into the faces of the inertial mass permits squeeze-film gas damping within the capacitive gaps. The advantage of gas damping over the more common method of viscous fluid damping is dramatically smaller thermally induced changes of frequency response over temperature. The reason is that temperature changes have less effect on gas viscosity than they do on liquids.

Internal travel stops distributed over each surface of the seismic mass enable the sensor element to survive high acceleration loads and shock events up to 30,000 g's. The linear full-scale displacement of the mass is 0.3 microns; at 0.6 microns its movement is constrained by the travel stops.

Table 1 summarizes the typical performance characteristics of the variable-capacitance sensor elements.

TABLE 1

VC Sensor Element Performance Characteristics				
Full Scale Range	±1 g	±10 g	±30 g	±150 g
Sensitivity	0.8 pF/g	0.05 pF/g	0.016 pF/g	0.003 pF/g
Resonant Frequency	600 Hz	3,000 Hz	5,000 Hz	11,000 Hz
Damping Ratio	2.3	0.7	0.7	0.7
Temperature Change (-55°C to 125°C)	+0.08%/°C	+0.08%/°C	+0.08%/°C	+0.08%/°C
Nonlinearity BFSL	±0.2% F.S.O.	±0.2% F.S.O.	±0.2% F.S.O.	±0.2% F.S.O.
Overrange Stops	2 g min.	20 g min.	50 g min.	300 g min.

Packaging

The package design is optimized for low-cost, high-volume production (see Photo 3). The sensor element is loaded onto a ceramic substrate along with the chip components for its self-contained conditioning circuit. Gold-plated contact pads on the base of the sensor element permit the user to make electrical connections on the circuit board by means of surface-mount technology. The combination of surface-mount technology with chip-and-wire construction facilitates miniaturization of the accelerometer. Long-term stability is ensured by the attachment of a metal lid to the substrate, creating a hermetic environment. The lid is connected to circuit ground for EMI protection.



Photo 3. The Model 7594 OEM accelerometer is 5/8 by 5/8 in. with a height of 0.15 in. The weight is 1.6 g. The cover has been removed to display the sensor element and conditioning circuitry.

Signal conditioning is accomplished by the use of an ultralow-noise CMOS IC with an onchip EEPROM provided to store trim settings. The IC is capable of measurement resolution down to 4.0 aF/Hz. The IC applies a 100 kHz oscillator frequency to the sensor element and detects the change in capacitance between the two capacitive elements within the sensor. This differential signal is then converted to a high-level, low-impedance analog voltage output proportional to acceleration.

For unit substitutability, the performance of each device is normalized at the factory by electronically trimming gain and output offset.

The accelerometer in Photo 3 operates off 5 VDC excitation with a 5 mA current draw and has a ± 1.75 V differential output swing. An onboard temperature sensor allows users to further improve accuracy by thermal modeling in their system.

Applications

Gun-Launched Projectile Guidance. Accelerometers are being mounted in projectiles that must survive 15,000 g cannon and 8000 g mortar launch shocks. Bias shifts after firing are 1% F.S. or better. Quick recovery is required after the pyroshock event with a specification of 5 ms max. Accelerated aging tests of 3000 hr. duration were conducted under power at 100°C to simulate a 16-year storage life. Performance shifts due to aging averaged <0.5%.

Missile Guidance and Flight Control. Accelerometers are used for flight control in shoulder-launched antitank missiles. Qualification testing demonstrated 10 mg bias stability for environmental effects including aging. The accelerometers have a low noise floor of 5 mg/Hz up to 10 kHz. Vibration rectification levels are <5 mg when subjected to a 5 grms random vibration level over a bandwidth of 20–3000 Hz.

Missile Safe-and-Arm. For this application, mechanical integrity was rigorously tested during qualification by subjecting the accelerometers to 100 thermal cycles from –55°C to 125°C and 8 hr. of 20 g peak sine vibration. Radiation hardness was tested to typical military survivability levels as part of qualification.

Aircraft Flight Test. The accelerometers are used to measure commercial and military engine loading, control surfaces (flutter), and landing gear. Custom designs incorporate special features that allow the sensors to survive water and mud splash, particle impingement, temperature extremes, and icing. Repeatabilities of 0.5% or better were reported when the accelerometers were recalibrated after repeated flight test cycles with 200 hr. of operation per installation. The accelerometers have a compensated temperature range of –55°C to 125°C. The specification for maximum thermal zero slope is 0.02%/°C of full-scale output, and the thermal sensitivity slope is 0.04%/°C.

Launch Vehicle Load. When monitoring structural loads on booster rockets, as well as performing ground test measurements for the main engine of the space shuttle, accelerometers must provide accurate results while being subjected to random vibration that can exceed 78 grms on some installations. The environmental challenges posed by the shuttle are particularly severe due to the accelerometers' proximity to surfaces in contact with cryogenic propellants. Even when the accelerometer was operating outside its temperature range, testing demonstrated that its output was nearly constant to –100°C and didn't drop out until below –165°C. After an excursion to –185°C, the sensor recovered at –165°C.

Summary

Batch processing and automated testing and assembly have produced a variable capacitance sensor element and packaged accelerometer that accommodates the performance and cost demands of severe OEM applications. The devices are capable of withstanding high shock levels, severe vibrations, and multiple thermal excursions.

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