by Dan Handman

Cutting Accelerometers Down to Size

To develop airplanes that fly farther, faster, and more smoothly, or automobiles that are safer, lighter, and more fuel efficient, designers are turning to exotic materials, sophisticated structures, and tighter design margins. This path demands a better understanding of system performance under all loading conditions, and extensive testing to verify the suitability of the new designs and materials.

Fortunately for physicists and engineers working on such advanced systems, new accelerometer technology now allows better measurement of system performance. Fundamental techniques used in microelectromechanical systems (MEMS)—such as microphotolithography, etching, oxidation, diffusion, and thin-film deposition—have been applied to the manufacture of accelerometers to yield smaller, lighter, highly accurate, and robust devices that operate over wide temperature ranges. As a result of these advances, microaccelerometers continue to find new uses in industry.

Accelerometers used for testing complex systems fall into two broad categories: those used in shock-load measurements, such as in car crash testing, and those used in vibration measurements, such as in testing the response of airframes during flight tests.

Car crash testing

In automotive crash tests, microaccelerometers inside the dummies help determine what injuries a passenger would sustain in an accident by measuring acceleration in the head, chest, pelvis, arms, and legs. In addition, integrating measured acceleration with time can pinpoint a dummy's velocity and position at any instant during the crash. Unrestrained dummies can experience head accelerations in the range of several thousand g's if a dummy's head hits the windshield. In contrast, in crash tests run with both seat belts and air bags, dummy acceleration usually reaches less than 100 g. So dummy accelerometers must survive hard impacts, yet give accurate results when subjected to low shock levels.

In crash testing, accelerometers placed throughout the vehicle measure how it crushes during impact—information vital for improving safety. Accelerometers mounted on structural elements in the front of the car tell the test analyst how and when each part moves during the impact event. For example, accelerometers on the engine block measure the movement of the engine toward the rear. Designers use this information to modify engine supports to prevent the engine from penetrating the passenger compartment.

Automotive shock accelerometers must be small enough to fit in tight spaces under the hood and inside dummies. Accurate measurement of the shocks induced by metal-to-metal impacts requires high-frequency response, yet the sensitivity and the zero-acceleration output of the device cannot change as a result of the shock. Also, these accelerometers must operate over the same wide range of temperatures to which vehicles are subjected (-50 to 100° C).

The demanding requirements of effective vehicle crash testing are met by an accelerometer that contains a micromachined piezoresistive sensor made from three layers of silicon (Figure 1). The outer layers (base and lid) protect the sensor's moving parts from external contamination. The inner layer, or core, consists of a frame with an inertial mass suspended from the frame by an elastic hinge and a pair of strain gauges that measure movement around the hinge. Several key design features give this sensor its capabilities:

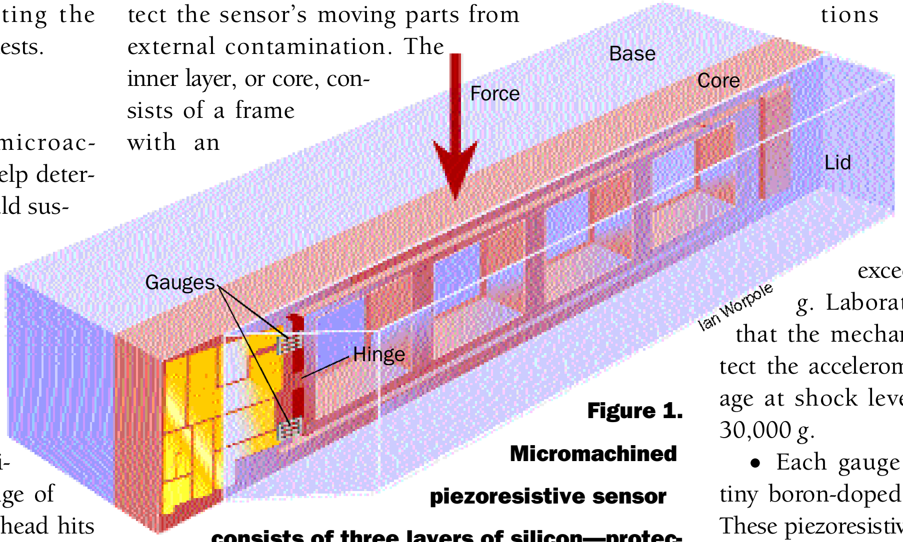

Figure 1. Micromachined piezoresistive sensor consists of three layers of silicon—protective base and lid, and the sensor core. The core consists of an inertial mass, an elastic hinge, and a pair of strain gauges that transmit signals of movement around the hinge.

- The precision of the mass and hinge dimensions is achieved by crafting the sensitive axis in the plane of the silicon wafer, which takes advantage of the vertical-wall-etching capability of (110)-oriented silicon. This allows the mass to be etched free from the frame along the silicon crystal planes. Only the resolution of the photolithography limits the dimensional precision of the mass and hinge.

This micromachining technique results in a lightweight and stiff inertial system with a high resonant frequency, capable of yielding a wide frequency response. The monolithic mass, hinge, and sensor design provides a stable acceleration signal with low variability among the individual accelerometers.

- A gap of less than 3.5 μm exists between the beam and the frame. As a result, the frame acts as a mechanical, or over-travel stop for the mass. This limits the motion of the mass and the stresses on the hinge and strain gauges during accelerations beyond the accelerometer's maximum useful range of 2,000 g. The beam contacts the stops when the acceleration exceeds about 5,000 g. Laboratory tests show that the mechanical stops protect the accelerometer from damage at shock levels in excess of 30,000 g.

- Each gauge consists of six tiny boron-doped silicon bridges. These piezoresistive bridges have a rectangular cross section of 0.6 μm × 0.4 μm—so small that 1,000 of them could be packed within the diameter of a human hair. The gauges are connected between the sensor frame and the beam. Very

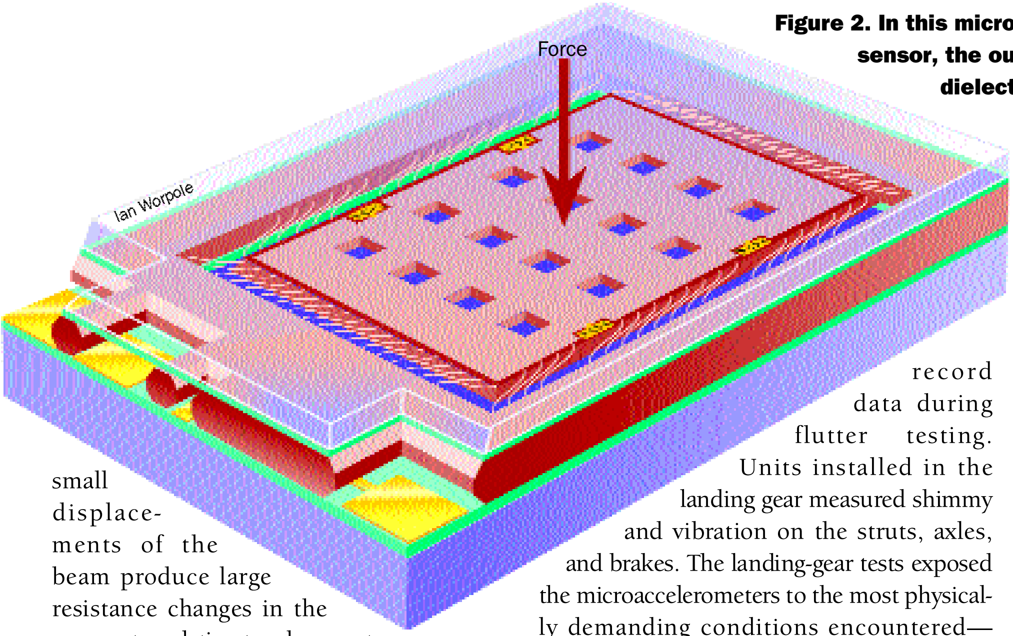

Figure 2. In this micromachined silicon variable-capacitance sensor, the outside elements are electrodes of an air dielectric, parallel-plate capacitor. The middle element is etched to form a rigid central mass suspended by thin, flexible fingers. Changes in capacitance are proportional to acceleration.

small displacements of the beam produce large resistance changes in the gauges, translating to a large output signal.

This micromachined accelerometer, which replaces designs using conventionally machined cantilevered steel beams with bonded-on strain gauges, offers industrial users expanded capabilities. Until now, the accuracy limits inherent in conventional machining prevented the use of over-travel stops. Without such stops, a test that would “kill” the dummy could also destroy the accelerometers.

The older design required manual placement and bonding of the gauges as well as manual connection of wires to the gauges. These manual operations resulted in less reliability from one unit to the next and a higher scrap rate. With the manufacturing process automated by micromachining and semiconductor-manufacturing techniques, reliability has increased.

Aircraft flight testing

Accelerometers designed for aerospace applications are used to verify the response of airframes to vibration. Boeing Corp. selected micromachined accelerometers—both for their performance and for their durability over a wide dynamic range—to perform critical low-frequency vibration measurements during flight testing of its 777 aircraft. Sensors were mounted in various locations throughout the aircraft, including the wings and around the engines. Accelerometers encircling the engine inlet-fan case provided “six degrees of freedom coverage,” which gave a picture of the engine’s complete rigid-body motion during flight loading cycles.

Other microaccelerometers were mounted on control surfaces, such as wing tips, to record data during flutter testing. Units installed in the landing gear measured shimmy and vibration on the struts, axles, and brakes. The landing-gear tests exposed the microaccelerometers to the most physically demanding conditions encountered—extremely low temperatures at high altitude, high temperatures created by the brakes during landing, and rain, ice, and splashing mud.

To obtain reliable, consistent results under such challenging conditions, the accelerometers incorporate a unique, variable-capacitance sensor element. This component is particularly well suited for measuring low-level accelerations in the presence of severe vibration. During the 777 tests, Boeing obtained accurate results with vibration levels of 30 to 50 g-rms at frequencies of 200 to 1,200 Hz.

The accelerometer package is only 0.85 × 1.00 in., with a height of 0.3 in. Inside, an inertial mass, suspended within the sensor element, moves within the sensor as acceleration is applied. The mass is electrically connected as part of a variable-capacitance, half-bridge (three-terminal) circuit. Fixed-capacitive plates in the lid and base complete the circuit. As the mass moves closer to one of the plates, the capacitance between the mass and plate increases, while the capacitance between the mass and the other plate decreases. Electronics measure these increases and decreases in capacitance and generate a linear output voltage versus acceleration.

The sensor element itself measures just 0.08 × 0.11 × 0.036 in. It is fabricated by bonding and then dicing three micromachined, single-crystal silicon wafers. Unlike the cantilevered beam used in the crash-test accelerometer, the mass here is suspended with small support beams around its periphery (Figure 2). These beams deflect symmetrically, keeping the mass parallel to the lid and base plates through its full range of motion under acceleration.

The mass, beams, and support frame start out as a single bonded part. Material is then micromachined (etched) away, leaving the mass suspended from the frame via the beams. The stiffness of the beams directly affects the sensitivity of the device. Differences in stiffness, which yield different accelerometer ranges, are controlled by varying the shape, the cross-sectional dimensions, and the number of beams.

As with the automotive accelerometer, micromachining allows building accurately spaced mechanical stops into the design, which prevents over-travel of the mass and damage to its suspension system. Over-travel stops allow the accelerometer to withstand shocks up to 10,000 *g* without damage. The flat mass moving between two fixed plates provides damping, which improves the frequency response and increases the ability to withstand high-g shocks.

To date, this family of accelerometers has been used successfully in more than 200 test flights of Boeing’s 777 aircraft. As an indication of their performance, ruggedness, and reliability, Boeing intends to use these accelerometers in other flight-test programs, including the stretch 777B, 767A, AWACS, and the new-generation 737.

Today and tomorrow

Micromachining can be used to make many different types of sensors. Although this article describes only two types of microaccelerometers, similar techniques enable the crafting of miniature pressure and force sensors.

Micromachining has provided smaller accelerometers that save weight, space, and power, and allow optimized designs to satisfy demanding requirements, while becoming increasingly sophisticated.

BIOGRAPHY

Dan Handman is marketing manager for the silicon business unit at Endevco Corp., in San Juan Capistrano, California (dan@endevco.com).