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Shock and Vibration Measurement Using Variable Capacitance

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By Davis Olney and Brian Link

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Low-frequency, low-g acceleration measurements are now possible using a very rugged and reliable new technology.

Historically, transducers designed for measurement of shock and vibration have successfully employed one of two basic technologies: piezoelectricity (PE) and piezoresistivity (PR). Both types are used for measurement in high-frequency, highly dynamic environments. However, piezoelectric accelerometers, while extremely rugged, have limited low-frequency response capabilities. Piezoresistive accelerometers, on the other hand, are very useful for measuring the DC or steady-state accelerations, a characteristic essential for making accurate long-duration, shock-motion measurements. The latter are particularly temperature sensitive and often fragile to shock overranging or resonant amplification.

A new sensing technology employed by Endevco in the Model 7290 Microtron® accelerometer (Figure 1) is based on the variable capacitance principle. Performance improvements such as increased accuracy, output stability over temperature, and extreme ruggedness have distinguished this design from its PE and PR counterparts. Microtron, developed by Endevco's R & D center in Sunnyvale, California, is a solid-state device incorporat-

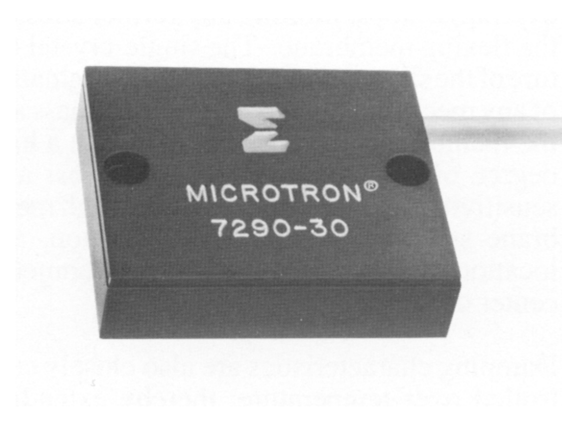

Figure 1. Endevco's Model 7290 MICROTRON® variable capacitance accelerometer is designed to measure low level accelerations while surviving high g shocks.

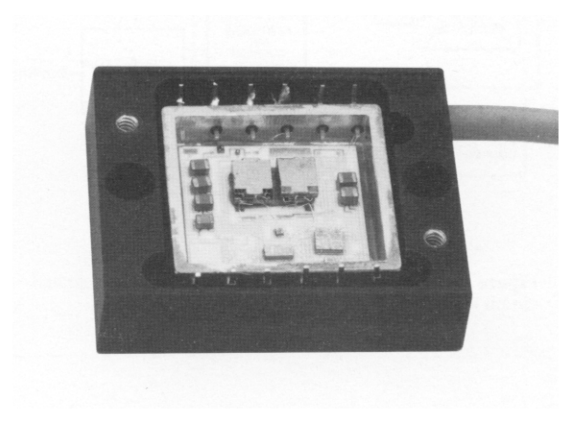

Figure 2. Shown is a variable capacitance accelerometer substrate board assembly in a hermetic chip carrier.

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ing state-of-the-art micromechanical silicon sensors and integral microelectronics (Figure 2). It has been designed to meet customer needs in those applications requiring the measurement of low-g accelerations (0 to 50 g) in the frequency bandwidth from DC to 1000 Hz.

THEORY OF OPERATION

Acceleration sensing is accomplished using a pair of uniquely designed micromechanical silicon sensors. These sensing elements experience a change in capacitance due to minute deflections induced by varying acceleration levels. Because of a differential configuration, an applied acceleration increases the capacitance of one sensor while decreasing the other, resulting in an unequal current flow through the sensors. This differential current is then measured, conditioned, and converted to a voltage, providing an output that is proportional to the applied input acceleration.

A simplified operational block diagram is shown in Figure 3. The variable capacitance sensing elements are mounted on a substrate along with various discrete components and an integrated circuit, which is then mounted in a hermetic chip carrier.

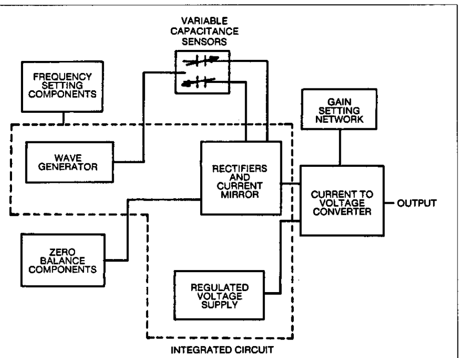


Figure 3. MICROTRON incorporates a hybrid integrated circuit resulting in a high-level voltage output signal.

•Variable Capacitance Sensing Elements. The micromechanical silicon sensors used in Microtron® are variable capacitance (VC) devices designed to sense low levels of acceleration. Each individual sensor is fabricated from single-crystal silicon measuring 0.11 by 0.12 by 0.35 in. The sensor is constructed of three silicon elements bonded together to form a hermetically sealed assembly (Figure 4). Two of the elements are the

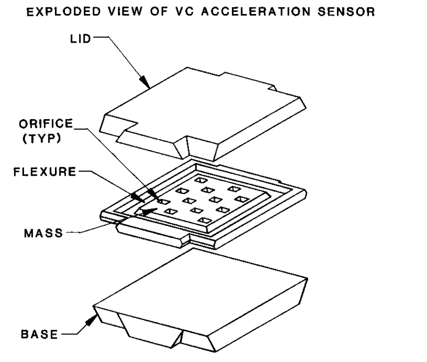


Figure 4. An exploded view of a variable capacitance acceleration sensor shows the primary elements in this assembly.

electrodes of an air dielectric, parallel-plate capacitor. The middle element is chemically etched to form a rigid central mass suspended by a thin, flexible membrane whose thickness is varied depending on the full scale acceleration range of the unit. With acceleration, the mass deflects, changing the capacitance between the mass and the plates. The elimination of adhesive bonding and moving components results in a design with extremely high reliability and MTBF.

The sensor has been designed such that the inertial mass deflects parallel to the top and bottom plates with minimal flexing or distortion. Under larger acceleration levels, the inertial mass deflection increases, eventually moving into an evenly distributed contact with overrange stops, limiting any further stress to the flexing membrane. The single-crystal nature of the silicon, coupled with the elimination of any mechanical joints between the mass and the membrane results in a sensor with a high degree of overrange capability. Cross-axis sensitivity is also minimized due to high membrane stiffness in the lateral direction, and location of the inertial mass at the geometric center of the element.

Damping characteristics are also closely controlled over temperature, thereby extending the frequency response of the accelerometer. This is achieved with a series of grooves that communicates with a series of holes in the "fenestrated" central mass. As the mass displaces, gas is forced or "squeezed" through the grooves and holes. The damping characteristic is dependent upon and, thus, altered by the number and location of the holes in the central mass, as well as the spacing between the plates. Since the thermal viscosity of gas is small when compared to that of a liquid, this technique has proven effective in providing a stable damping coefficient over a wide temperature range.

•**Advantages**. The variable capacitance accelerometer meets the needs of varied existing market sectors requiring measurement of DC or low-frequency, low-level accelerations. Currently, two types of transducers address this market: servo and piezoresistive accelerometers.
Servo accelerometers, being closed-loop devices, are capable of extremely high-accuracy/high-stability measurement. Unfortunately, they are often costly, undesirably large, and the intended measurements do not dictate the accuracy that servo devices offer. Also, the majority of seismic systems incorporated in servo accelerometers are susceptible to severe performance degradation or failure when subjected to high levels of shock, random vibration, or overrange acceleration.

Similarly, piezoresistive transducers designed for low-g measurements are also limited in overrange capability. While able to withstand higher overrange acceleration levels than servos, piezoresistive transducers still cannot offer the ruggedness dictated by many applications. In addition, piezoresistive transducers do not exhibit the accuracy or output stability over temperature which is required for many low-g applications.

Piezoresistive transducers designed for low-g measurement often require oil damping which experiences large changes in viscosity over temperature, resulting in wide variations in damping ratio and frequency response. The damping ratio over temperature of a variable capacitance accelerometer, however, remains stable near 0.7 of critical damping. Table 1 compares the performance characteristics of piezoresistive accelerometers and the Microtron® variable capacitance accelerometer.

APPLICATIONS

The variable capacitance accelerometer provides performance commensurate with the requirements of a wide range of applications within both the commercial and aerospace industries. The Microtron design lends itself to packaging and circuitry modifications, making it highly adaptable.

•**Aerospace Tests**. Primary applications are missile and aircraft flutter testing, vehicle launch and flight testing and engine monitoring involving long-duration, low-g shock measurements. To date, this market has been satisfied by both piezoresistive and low-accuracy servo accelerometers, primarily because of their DC response capability. Both, however, suffer from their own limitations. Piezoresistive accelerometers are subject to temperature effects and instability, while servo accelerometers, by and large, provide more performance than required at a higher cost to

TABLE 1

Variable Capacitance vs. Piezoresistive Performance Comparison

Characteristic	Units	Low-g Piezoresistive Accelerometer	Microtron® Variable Capactitance Accelerometer
Full Scale Range	g	± 10	± 10
Sensitivity, Nominal	mV/g	8 to 10, typical	200 ± 10
Nonlinearity, 0 to Full Scale (F.S.)	% F.S.	± 1.0	± 0.25
Frequency Response	Hz	0-250	0-600
Resonant Frequency, typical	Hz	600	3000
Damping Ratio (over rated operating temp.)	---	0.3 to 1.0	0.7 ± 0.2
Transverse Sensitivity, maximum	% F.S.	3.0	2.0
Input Voltage	VDC	10 or 15, typical	13 to 18
Input Current, maximum	mA	NA	15
Zero Measurand Output, maximum	mV	± 25 to ± 50, typical	± 50
Acceleration Overrange	g	2000, typical 10,000 special	> 10,000
Recovery Time after Overrange, typical	ms	10	< 1

the customer. Limitations in ruggedness further hinder the effectiveness of a servo in these applications. The variable capacitance accelerometer does very well in addressing the needs of this market sector due to its ruggedness, stability and repeatability over temperature, and lower cost.

•**Transportation Shock**. The testing and monitoring of transportation vehicles such as automobiles, trucks, railroad cars and high speed magnetically elevated trains requires highly durable, yet sensitive accelerometers. Installation and in-test shocks are common, with the subsequent requirement to measure milli-g's of data. The variable capacitance accelerometer's high-g overshock capability and quick recovery time after overrange allows acceleration measurements not possible with piezoresistive devices. Typical applications for the automotive industry are ride comfort, structural response and vehicle crash testing.

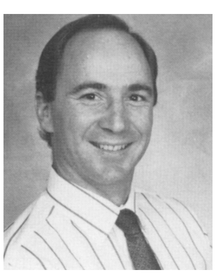
•**Trajectory Monitoring**. As with long-duration, low-g shock measurements, the trajectory monitoring sector has traditionally been addressed by piezoresistive and low-performance servo accelerometers. However, the same basic limitations apply. Sensor ruggedness becomes increasingly important for trajectory monitoring, since many projectiles and missiles experience very high-g launch environments which make it difficult or impossible for many sensor designs to survive. The variable capacitance accelerometer has incorporated unique features enabling the unit to withstand tens of thousands of g's of acceleration. As the need for lower cost military projectiles, torpedoes, and missiles becomes increasingly evident, rugged and accurate accelerometer technology must be positioned to meet market requirements.

•**Safe and Arming**. Missiles, torpedoes, targets, and other flight vehicles all require safe and arming mechanisms. Most devices used today are mechanical switches that are costly and less reliable than solid-state sensing devices. A growing trend to incorporate "smart" electronics in development weapons makes the variable capacitance accelerometer appropriate for this market.

SUMMARY

The variable capacitance approach to acceleration measurement has been proven to outperform its piezoresistive counterpart in applications requiring measurement of low-frequency, low-g accelerations. The combined advantages of ruggedness, high overall accuracy, size, and weight, provide the customer with more choices in an effort to maximize the performance/cost ratio. This technology promises to replace piezoelectric and piezoresistive transducers for applications requiring moderate to high-accuracy acceleration measurements with DC to quasi-steady-state response.

Continued advances in micromechanical technology, combined with those in microelectronic circuitry, will pace the performance capabilities of tomorrow's sensors. Through these technologies, sensors with extremely high accuracy, high reliability, low power consumption, and miniature size will be realized. Such sensors will provide users with an expanded application base for more precise, economical measurement of physical phenomena.



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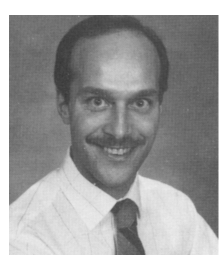

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