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Application of Silicon Strain Gauge Technology-to Aerospace Acceleration and Pressure Measurements

Technical Paper 280

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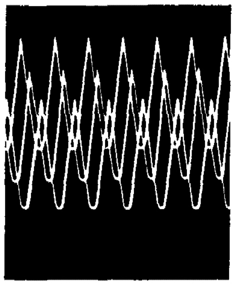

TP280

APPLICATION OF SILICON STRAIN GAUGE TECHNOLOGY TO AEROSPACE ACCELERATION AND PRESSURE MEASUREMENTS

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INTRODUCTION

The world of transducer techology centers around engineering trade-offs. Generally, the compromises are between the performance characteristics of the transducer and its environmental requirements or the constraints imposed by the phenomenon being measured. With aerospace accelerometers and dynamic pressure transducers, typical performance requirements are high sensitivity, wideband frequency response, and wide dynamic range. Common environmental problems are high and low temperature extremes, shock, vibration, moisture, base strain, and thermal transients. Constraints are typically size and weight.

Most of these sensors utilize either piezoelectric or piezoresistive sensing elements. While our firm manufactures both types, the intent of this paper is to describe the design and application of piezoresistive (PR) transducers.

When designing PR sensors for aerospace use, we are generally seeking efficiency, i.e., high output per unit voltage applied, and wideband frequency response starting at dc. The combination of these two factors is expressed as a "figure of merit". As a good start, PR silicon gages provide gage factors about two orders of maganitude greater than metal or foil gages. In both accelerometers and pressure sensors we achieve dramatically greater efficiency through the use of transduction elements which focus the dynamic forces at the tiny area where the gages are located. These considerations represent the main thrust of this paper.

ACCELEROMETER DESIGNS

The strain gage shown in Figure 1 is used in Endevco PR accelerometers. It is fabricated from a single piece of silicon. In use, it becomes one element of a wheatstone bridge circuit.

Two factors are important in gage design, as it pertains to the transduction element. First, the gage's sensitivity with applied force increases as the active gage area is diminished. Therefore the active area of the gage must be as small as possible. Secondly,

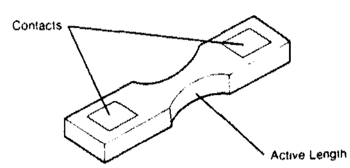

Figure 1. Patented semiconductor strain gage with large mounting pads and narrow active neck

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the gages must be bonded to the force-producing structure. To achieve an inelastic bond, the bonding area must be maximized. Endevco's patented "dumbbell" shaped gage satisfies both of these requirements. Two large mounting pads are connected by a narrow compliant neck which is the active part of the gage.

Endevco's PR accelerometers utilize a cantilevered transduction mechanism. The strain gages are mounted across a slit in a small beam which is rigidly attached to the base of the accelerometer at one end and provides a cantilevered mass on the other end. The structural system provides linear forces to the beam, proportional to the acceleration motion of the transducer.

Miniature designs usually have just two strain gages, one in compression and the other in tension. A schematic drawing of this design is shown in Figure 2. This configuration maximizes the accelerometer's figure-of-merit, in

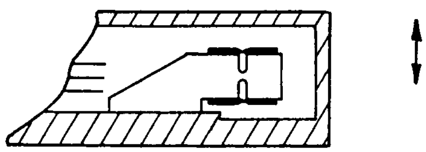
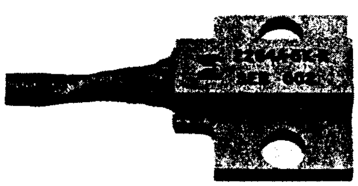


Figure 2. Half-bridge accelerometer design using two gages on a cantilever beam

a small package. Bridge completion resistors are located in an external signal conditioner or, at the expense of size, within the accelerometer. This arrangement permits shunt calibration of the measurement system. Some transducers are fully bridged and, with their high sensitivity, they can be powered very simply and their output fed directly to most voltmeters, oscilloscopes, and recorders.

These devices are undamped and therefore produce no phase shift over their useful frequency range, typically from steady state to 1200 Hz. A miniature accelerometer is shown in Figure 3. Overall dimensions are as small as 10 x 4.6 x 10 mm and weight is as little as one gram.



Two times actual size

Figure 3. Model 2264A Miniature Piezoresistive Accelerometer

Miniature designs are guaranteed to withstand environmental shock of more than twice their rated measurement range. They must be handled rather carefully, however, because they will be damaged if they are dropped and their natural resonance is excited. And in some applications, there can be environmental shocks much greater in amplitude than the vibration being measured. To satisfy these situations, designs are available which have a longer cantilever mass protected by overload stops. See Figure 4. Additionally, some models are also

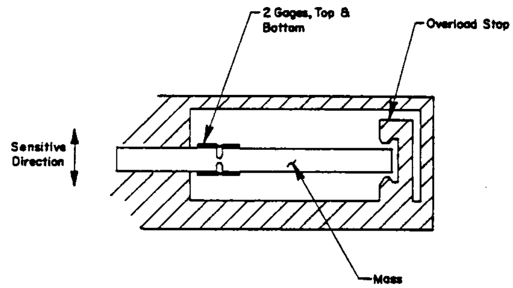


Figure 4. Accelerometer design using cantilever beam with overload stops

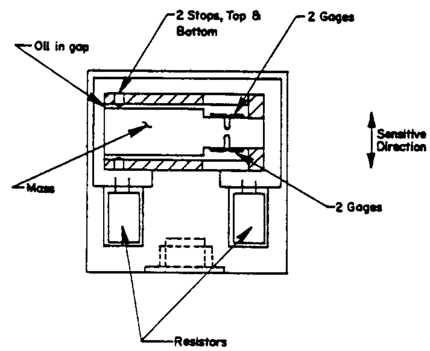


Figure 5. Accelerometer with compensation resistors and overload stops

oil-damped to provide a critically damped frequency response. See Figure 5. A typical transducer with overload stops and oil damping is shown in Figure 6. These units have a 5/8-inch hex mounting base and a height of 25 mm.

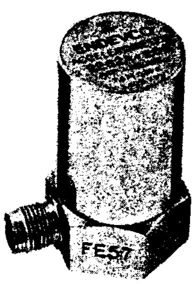


Figure 6. Model 2262A Piezoresistive Accelerometer with overload stops and damping

ACCELEROMETER APPLICATIONS

It is well to discuss the trade-offs between piezoresistive and the more widely used piezoelectric accelerometers. Table I shows that PR accelerometers feature primarily a low output impedance which simplifies interconnection with signal conditioners, simple turnover calibration, and alternative shunt calibration. Their most significant application advantage is steady state response.

	Piezo-electric	Piezo-resistive
Self-generating	Yes	No
DC response	No	Yes
Sensitivity to non-vibration environments	Low*	Very low
Low impedance output	No	Yes
High temperature	Yes	No
Cryogenic temperature	Yes	No
Turn-over or shunt calibration	No	Yes
Subminiature designs	Yes	No
Zero shift at high shock	*	No
Rugged, high sensitivity designs	Yes	No
Availability of damped resonance designs	No	Yes

* Depends on design

Table 1. Trade-offs between piezoelectric and piezoresistive accelerometers

PR accelerometers are widely used for transportation shock measurements, blast studies, and automotive crash studies where low frequency vibrations or long duration shocks require near-dc response. Reliable data can often be obtained from 0.1 Hz to 5000 Hz with no phase shift, thereby replicating the transient condition. Their low mass and wideband frequency response also bring wide usage for modal testing, flutter testing, weapons effects testing and biomechanical studies.

Ranges are available from 10 g to 50 000 g. Case configurations include miniature designs, integral electronics models, and triaxial units. One triaxial model used in the heads of anthropomorphic dummies for automotive crash tests has user-replaceable sensing elements.

PRESSURE TRANSDUCER DESIGNS

Pressure transducer designs have also been made more efficient by achieving stress concentrations at the gage locations. The use of PR gages diffused into a flat circular diaphragm of silicon is an old techology. But the anisotropic etched, transverse gage design has made several state-of-the-art contributions to pressure transducer technology.

Stresses need not be spread over a large area as with a flat circular diaphragm. Because the diaphragm undergoes bending stresses during measurement, stress concentrations can be achieved by varying the thickness of the bending element. This is one of the basic conceptual differences which gives this transducer superior performance.

A typical sculptured diaphragm is shown in Figure 7. Note the two thicknesses. It is considerably thicker at the outer edge, and it has two islands in the middle section. Notice how closely the islands come to each other and to the edge. This is shown much better in the micrograph photograph in Figure 8. It can be easily seen that a distributed load, or

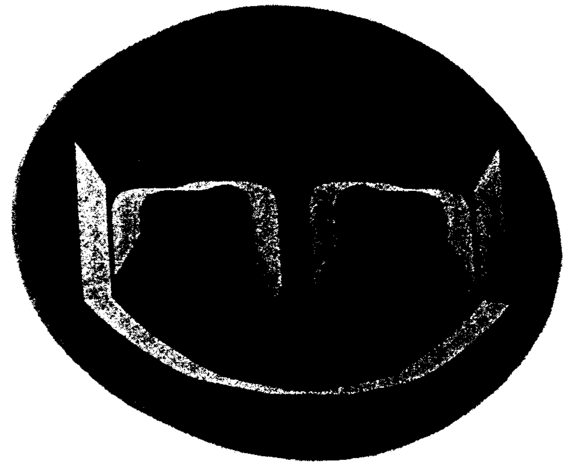


Figure 7. Photograph of diaphragm taken with scanning electron microscope, 0.05 in. (1.25 mm) O.D.

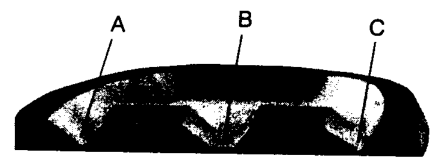


Figure 8. Photomicrograph of diaphragm section through notches and islands

pressure, on one side results in stress concentrations at points A, B, and C where all the bending occurs. If a stress sensitive material is placed at these points, a sensor with improved efficiency results, in comparisoon to the flat diaphragm. The gage elements in our design are diffused into the diaphragm over the entire grooves at points A, B, and C.

The sculpturing of the diaphragm has explained a significant part of the benefits of this design, but not all. Optimizing the piezoresistive characteristics is also important. The piezoresistive coefficients of silicon semiconductor materials vary with the direction of stress in the crystal and with the dopant material and its amount. Most devices have been designed to stress the gage material so that the gage increases its length. This is the manner in which larger wire and foil gages are used. Another approach is to use a transverse gage laid lengthwise in the groove. As the groove bends, this gage is strained so that it effectively changes width.

A fundamental benefit from using the transverse gage is that pressure transducer amplitude linearity can be excellent, typically better than 0.1% BSL to full scale. The transverse gage has decreasing sensitivity in tension and increasing sensitivity in compression. With gages mounted in tension and compression, their average nonlinearity is close to zero. Parallel gages have decreasing sensitivity with increasing stress in both tension and compression, so that bridge nonlinearity is the average nonlinearity of both.

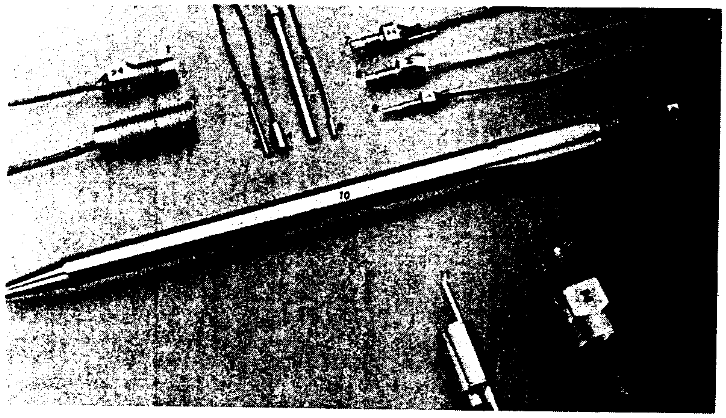


Figure 9. Examples of special and standard transducer by Endevco: 1) Model 8511; 2) side-on probe, 2000 psig; 3) Model 8507; 4) Model 8550M1; 5) probe for jet engine tests; 6) Model 8507 without temperature compensation; 7) Model 8510; 8) Model 8530; 9) Model 8506; 10) Pitot Static Probe, 5000 psig for artillery shell burst test; 11) Model 8508-5M2 differential equal volumes; 12) Integral electronics transducer

The combination of using stress concentration and transverse gages provides about three times better linearity than alternative flat-diaphragm approaches. This advantage can be even greater for pressures above full scale. Many of these transducers provide one volt of output with less than 1% nonlinearity. For a more complete description of sculptured-diaphragm pressure transducers, request copies of Endevco TP277.

PRESSURE TRANSDUCER APPLICATIONS

Dynamic pressure transducers are widely used in the aerospace industry. Turbulence is a major application. Transducers are flush mounted in wind tunnel models, in turbine blades, and on aerodynamic surfaces during actual flight. Pressures lower than 0.001 psi can be measured at frequencies up to 10 kHz. Transducers are available in diameters down to 1.5 mm for use on curved panels or in restricted locations. Similar applications are found for high temperature units in jet engine testing. Figure 9 shows the variety of configurations that are available using the technology.

Our pressure transducers have also played a major role in developing protection for nuclear power reactors. They have been used to study the structural integrity of ducts employed to inject excess steam into a pool of water in event of loss-of-coolant accidents. They were selected for this application because severe transient conditions produced an insignificant extraneous output from the transducer. They were able to measure post-impact pressure as low as 0.1% of rated full scale range despite the transient temperature environment. Moreover, they endured 20 months of such rugged testing on one reported project.

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