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Applications of Piezoresistance to Externally Excited Transducers

Technical Paper 239
By William E. Wall

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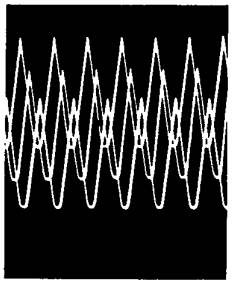

TP 239

APPLICATIONS OF PIEZORESISTANCE TO EXTERNALLY EXCITED TRANSDUCERS

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ABSTRACT

A general presentation, for tutorial purposes, on the use of piezoresistance in the measurement of pressure, acceleration, force and other parameters. The presentation centers on the use of piezoresistive silicon strain gage elements in full-bridge and half-bridge elements in the design of transducers. The use of germanium elements and devices with integral signal conditioning are mentioned briefly but not discussed. For the sake of brevity, the discussion is deliberately general and concerns the sensing element or gage, the electrical configurations, excitation and signal conditioning, and finally the devices themselves including desirable features and some design compromises.

INTRODUCTION

For several years now piezoresistive elements have been utilized in many ways to provide analog signals for a variety of physical phenomena. The majority of these devices utilize silicon elements in partial or complete bridge circuits to measure such parameters as pressure, acceleration, force temperature. The purpose of this presentation is to provide a broad look at the application, general operation and compromises of these devices when used in measurement systems.

The most general use of piezoresistive elements in measurement is as strain gages in half-bridge and full-bridge configurations. Other means of transduction have been utilized and will be mentioned briefly but the bulk of the presentation concerns the use of silicon strain gage elements.

The general characteristics of this useful family of devices are high level signals, good signal to noise ratios, and high resonant frequencies while maintaining steady state response capability.

This presentation examines the basic elements (strain gages), electrical configurations, power sources and signal conditioning of some of these devices and their pertinent operating features.

GENERAL APPLICATIONS

The first major acceptance of a piezoresistive strain gage transducer was probably in pressure measurement. This reached a peak on the instrumentation for the Apollo Program. Some of the acceptance of these devices, in spite of their state-of-the-art status, was due to the familiarity of aerospace test engineers with strain measurement on test aircraft and in part to the high regard for the wire wound strain gage transducers already available.

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After pressure transducers came temperature sensors, accelerometers, specialized devices such as load cells, active force links and the like. The most recent application is a unique device(1)* which utilizes both the pressure and temperature sensitivities of silicon strain gages and essentially computes volume remaining or specific volume from the basic gas laws. The following discussion will not attempt to describe any specific designs but rather general techniques. Also, devices with self-contained signal conditioning and special effect devices are left for other presentations.

THE STRAIN GAGE

The most widely used material for piezoresistive strain gages is ⟨1,1,1⟩ oriented silicon and vacuum deposited or diffused silicon. The use of germanium's similar properties has been investigated in the United States and elsewhere. In Japan it has been used in accelerometer applications.(2) Investigations of directly loading silicon junctions and other similar approaches have been underway for some time but to date have not produced any quantity of commercially available devices. The silicon strain gages in use generally fall into two mechanical categories. The gages are either load bearing members (as in the ENDEVCO® Pixie Beam) or "parasite" devices similar to the Baldwin-Lima-Hamilton SR-4 strain gages, namely a small compliant device measuring the strain present in some active element of the transducer (See Figure 1). Such gages are manufactured by the Electro-Optical Systems Corporation and Kulite Corporation.

Two physical categories also exist, bulk silicon and diffused silicon. Both of the mechanical configurations noted may come in either form. These physical forms are worthy of more detailed examination.

Bulk silicon, oriented in the ⟨1,1,1⟩ plane of the pure silicon crystal offers high resistivity (3.0 ohm-cm), higher gage factors (120 to 180), and are usually mechanically and photochemically formed into their final configuration. These devices usually are used in "bare-bridge" (no integral signal conditioning) configurations. Such transducers are characterized by low impedance (300-600 ohms at ambient temperature) and high signal levels (250 to 500 mV full scale with 10 volts excitation). They also have relatively high resistance versus temperature curves with rather influential higher order terms.

Diffused strain gages are manufactured by vacuum depositing "doped" silicon into prescribed shapes by photo-chemical techniques and then the gage structures are formed much in the manner of bulk gages. In some instances the entire array of strain gages as well as compensation resistors are deposited on a single chip much as is done with micro-circuitry. Pressure transducers have been manufactured in this manner by Electro-Optical Systems and Giannini Control Corporation (now Conrac Corporation).(3) These gage elements are characterized by much lower resistivities (0.1 to .001 ohm-cm) and gage factors of 40% to 60% of those obtained with bulk gages. In spite of this apparent decrease in performance, these devices offer several advantages. First, diffused silicon strain gages have a lower coefficient more linear resistance versus temperature curve allowing better matching of thermal characteristics. In addition they tend to be more stable with temperature and time and offer more rigorous process control than the bulk silicon gages.

While these devices are used in "bare-bridge" applications much as the bulk gages, they find greater application in high accuracy transducers with integral electronics. An added feature of lower resistivity ($\rho = .003$ ohm-cm) is a considerable increase in resistance to nuclear effects compared to bulk silicon. This affords the diffused, piezoresistive strain gage transducer a considerable advantage in tests conducted in areas of nuclear bombardment.

ELECTRICAL CONFIGURATIONS

Piezoresistive strain gage elements are seldom used singly. This is due to the extreme difficulty of separating the resistance change due to temperature from the resistance change due to the straining of the element itself. When the gages are arranged in either half-bridge or full-bridge (Wheatstone) array these effects can be handled as follows (See Figure 2a and 2b). First, the device is now a voltage divider and if the paired elements of a half-bridge are properly matched (thermally) then no unbalance is encountered due to resistance changes due to temperature. Zero drift due to differences in thermal expansion and gage factor is now minimized and may be further compensated by judicious use of small values of Evanohm and nickel resistors. Then only the shift in sensitivity with temperature need be compensated to provide a useful transducer. This will be covered in detail under the section discussing external power supplies.

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*Superior numbers refer to similarly numbered references at the end of this paper.

Many instrumentation systems require remote calibration capability. The high temperature coefficient of resistance of the active strain gage elements makes the use of a shunt resistor difficult. If the transducer utilizes a full bridge but configures one-half of the bridge active elements (strain gages) and the other half emphasize passive resistors, then shunt calibration can be accomplished by shunting these stable reference resistors. This eliminates the effect of temperature as well as any non-linearity due to the presence of any non-zero measurand at the transducer. The most important effect of this configuration on instrument performance is that the devices' output sensitivity is reduced by one-half for the same excitation voltage. Referring to Figure 2c, note that additional leads (paralleled) are provided across the reference resistor. This is to ensure that any load imbalance created by shunting is carried through the instrument leads and not from one terminal of the power supply to one terminal of the signal conditioner.

One specialized configuration worthy of some note here is one using a half-bridge arrangement but driving the device with equal but opposed constant current sources (See Figure 2d). The two current sources each excite one active arm and return to ground through the center lead. Output voltage is generated as a potential difference between the outer leads and occurs only when the impedances of the arms of device are unbalanced. The signal is equal to $2 \times i\Delta R$ when equal resistance changes occur in each arm. As can be seen, no R term exists in the equation, thus the device is excellent for long lead line applications with remote sensing. Another feature should be noted. During underground nuclear tests such transducers were used to measure both pressure and acceleration (long pulse duration) shocks. During such testing two phenomena occur. First the blast is preceded by an expanding magnetic wave. This wave generates a voltage in all leads, but as the leads are equal, so essentially are the voltages generated. The output is insensitive to voltage, just voltage differences; therefore this effect is minimized. (This voltage typically may reach as high as 100 volts.) The second effect, due to neutron and gamma radiation bombardment, is the presence of many free electrons. Within limits these effects are minimized as well. When their primary transients have passed, the system is stable and operable when the pressure and seismic waves, traveling at much slower rates, reach the transducers.

EXTERNAL POWER

Three basic power sources are used to excite piezoresistive transducers; constant current, constant voltage and opposed constant current. The last has already been discussed and no further detail is offered. Some confusion exists as to why some manufacturers stipulate that their devices must operate with constant current excitation and others specify constant voltage. This is further complicated by historical preferences for exciting strain gages with constant current.

The reason behind these two requirements is quite straightforward. The sensitivity of piezoresistive transducers with temperature is a function of the thermal effect on gage factor, the change in stiffness (Modulus of Elasticity) of the structure and the influence of the structure on the gages. Two examples are presented. Referring to Figure 3A, the plot shows typical uncompensated response of sensitivity with temperature for a pressure transducer using a stainless high chrome diaphragm (e.g., Ni-Span C or 17-4 ph steel). Ideal performance is most closely approximated by constant current excitation; therefore a large value shunt resistor (low power loss) will change the current source impedance so that temperature effects on sensitivity are minimized. In Figure 3B the effect of constant current and constant voltage excitation are again presented but for an accelerometer using load bearing gages and a structure of tungsten alloy. In this case, a small series resistor (low power loss) will modify the voltage source impedance to optimize performance.

It should be pointed out that either device can be made to operate satisfactorily with either power source but the relatively small size of the devices and their sensitivity to self-heating make the more efficient method desirable. Another point, after a unit has been compensated for operation in one mode (e.g., constant voltage), then operating in the other mode (e.g., constant current) reverses the effect of compensation and results in performance far worse than would be found in an uncompensated transducer.

SIGNAL CONDITIONING

In many instances the piezoresistive transducer may be used without signal conditioning. They are low impedance (typically 300 to 500 ohms output) voltage sources. When the recording device is of sufficiently low impedance, or requires a current source, then some form of signal conditioning is recommended. This usually consists of a voltage amplifier. In one instance, where for preliminary tests the probable level of the measurand could not be readily estimated, a logarithmic gain amplifier was used.(4)

Most piezoresistive transducers are characterized by high natural frequencies and undamped response. This poses two problems to the user. First, if he is interested in the high frequency components of his data, the signal conditioning and recording devices must equal or exceed the transducer's characteristics. Secondly, if only the lower frequency content is of interest, then, although the electrical output is properly filtered, the transducer must respond to and withstand the rejected components. Two examples are given to illustrate this effect. In one case an accelerometer was destroyed by an explosive shock while recordings indicated that failure occurred well below rated full scale, whereas in another case where only low frequency data was of interest(5) a mechanical filter was placed between the test specimen and the transducer, thus exposing the transducer only to frequencies of interest. Many high frequency pressure transducers having natural frequencies between 5 kHz and 100 kHz have much of their capability decreased because they are mounted by means of long leads, distorting their response characteristics.

THE TRANSDUCERS

Several simple configurations are illustrated here to show typical applications to transducer designs for measuring pressure, force or displacement and acceleration. No attempt is made to cover all designs but several unique devices are noted for their interesting features.

Pressure transducers offer one of the most straightforward approaches, the flat diaphragm. Figure 4 illustrates a typical design. The fixed edge diaphragm can be gaged as noted with a pair of parallel gages at the center (in tension) and another pair near the edge (in compression). If the gages are arranged electrically as noted then an increase in pressure will cause the resistance of the center (T) gages to increase and the edge gages (C) to decrease. This results in a highly stable, linear pressure transducer. One feature of this design, which can be noted in the stress diagram, is that the compression stresses at the edge are considerably greater than the tension stresses at the center. This results in a reduced sensitivity for the device as while the compression gages are operating at some predetermined safe level, the tension gages are at a considerably lower stress. Figure 5 shows a rather unique solution to this. By discretely increasing the diaphragm thickness at the edges the stress levels are made equal and the stress gradient through the edge is reduced making a more efficient transducer.(6)

A second type of pressure transducer allows the diaphragm to drive a load cell. Figure 6 illustrates a device with the diaphragm attached to a cantilever beam by means of a drive rod. This device affords overpressure capability by means of a backing plate which is particularly useful in providing safe high overranging in low pressure transducers.

Force and displacement transducers can be devised in the following manner. The high spring rate transducer provides reasonable stress levels with small displacements and the displacement transducer affords large displacements also at reasonable stress levels.

An example of the first is the short stiff column (See Figure 7). The arrangement of the gages in the manner indicated makes the device sensitive to end load and insensitive to bending moments. The use of the effect of Poisson's Law on the transverse gages increases the signal level at any given stress level by approximately 30% over a two active element device. A cantilever beam is an extremely convenient device as well. Figure 8 indicates a typical configuration. The use of pairs of gages above and below the beam allows maximum efficiency in gage utilization. Changes in beam length and cross-section allows simple adjustment of sensor compliance.

Several special applications (not illustrated) of these techniques have resulted in six component (three forces, three moments) stings for wind tunnel and thrust stand testing.

Acceleration transducers have also been devised using piezoresistive strain gages. Here two examples are shown to illustrate the difference between the two mechanical categories of gages, load bearing elements and "parasitic" elements. Figure 8 shows an accelerometer where the active gage elements represent as much as 80% to 90% of the stiffness (section modulus) of the flexure. These members, because of the stress-strain properties of bulk silicon, provide the transducer with a linear output better than 1% when operating over a plus and minus 250 millivolt output range.

In the second case, where extremely high range and resonant frequency are desirable, the short stiff column is again used as it was in the load cell. Here the extremely small size of the "parasitic" strain gage allows for a very short proof mass resulting in high resonant frequency. The use of Poisson's Ratio in the bridge decreases a normal plus and minus 250 millivolt full scale output to about plus and minus 190 millivolts full scale.

SUMMARY

The previous presentation has discussed briefly the construction and operation of piezoresistive strain gage transducers. In considering the advantages of these devices to the user, some of the major benefits are as follows:

1. Large, unamplified full scale outputs, typically 250 millivolts to 500 millivolts with 10 volts excitation
2. Higher resonant frequencies than similar devices utilizing other pick-off schemes, resulting in better dynamic performance
3. These high resonant frequencies also result in extremely low acceleration sensitivities for the non-inertial devices
4. Excellent static error band (linearity, hysteresis and repeatibility) performance, typically better than 1% of full scale
5. The ability to withstand three to five times overload without any degradation of performance
6. Good to excellent thermal performance depending upon choice of sensor and base material

It can be seen that with so many performance tradeoffs the transducer designer has considerable flexibility when approaching a new measurement problem.

CONCLUSION

Piezoresistive transducers are in use today and occupy a place in the spectrum of measurement techniques available to the user. Piezoresistive transducers by no means fill all measurement requirements but do offer many advantages and should be seriously considered when selecting transducers for any new measurement requirement.

ILLUSTRATIONS

REFERENCES

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(5) Judd, E.; "Instrumentation of Shipboard Equipment and Machinery for Shock Studies (Development of Shock Measuring Instrumentation-Accelerometer Mountings)", p. 30 Report of NRL Progress, February 1965.

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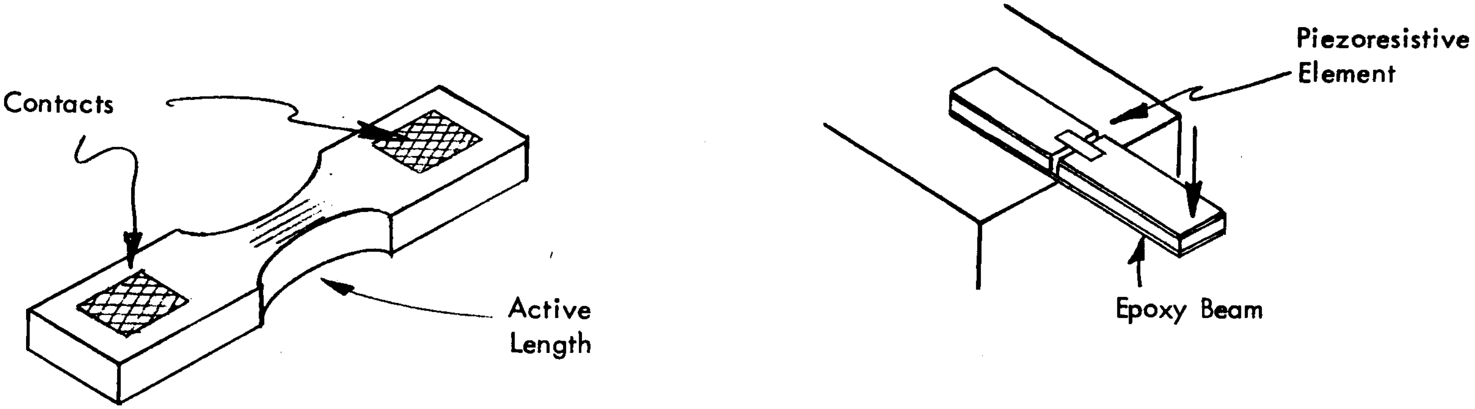
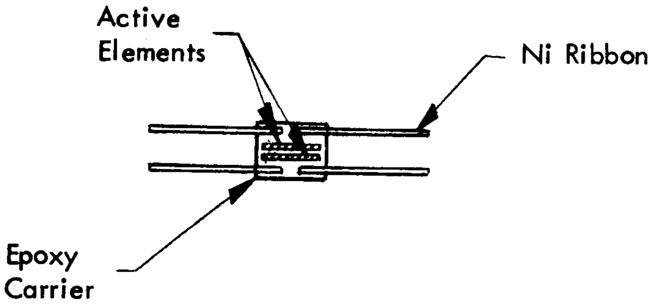


ENDEVCO® P-9 Strain Gage

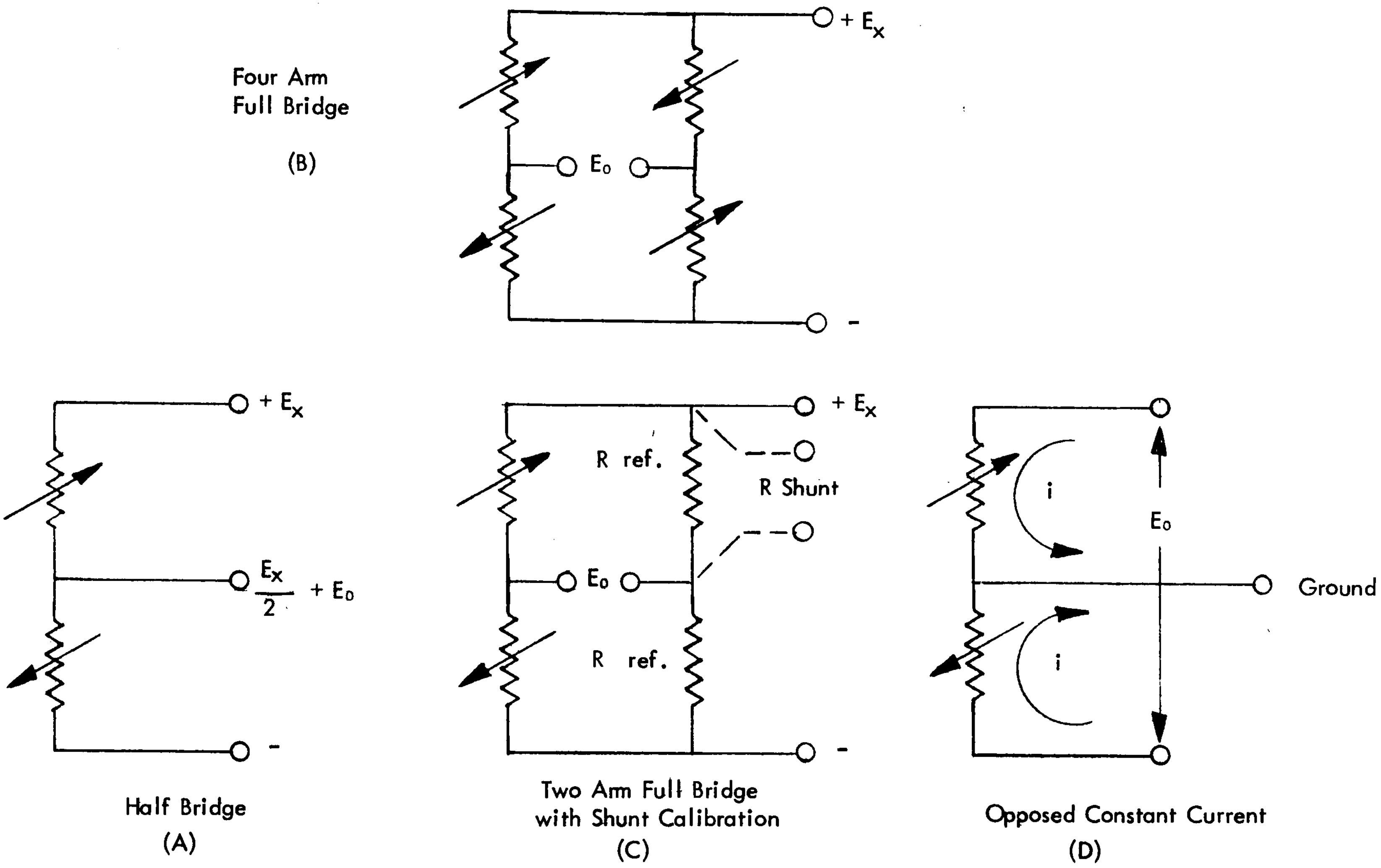
ENDEVCO® Pixie Beam



Kulite MP Series Strain Gage

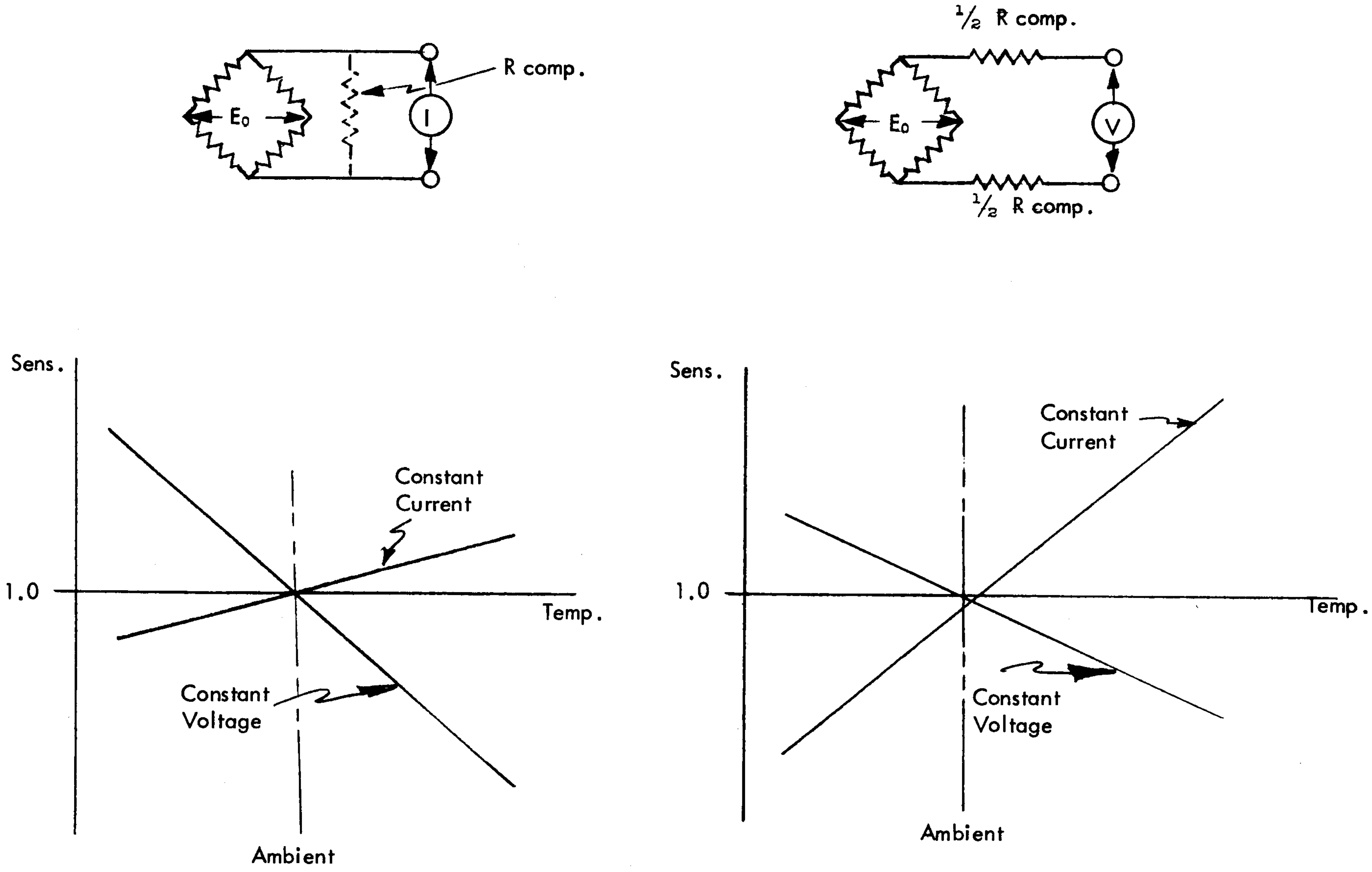
THREE TYPICAL PIEZORESISTIVE STRAIN GAGES

FIGURE 1



FOUR TYPICAL BRIDGE CONFIGURATIONS

FIGURE 2

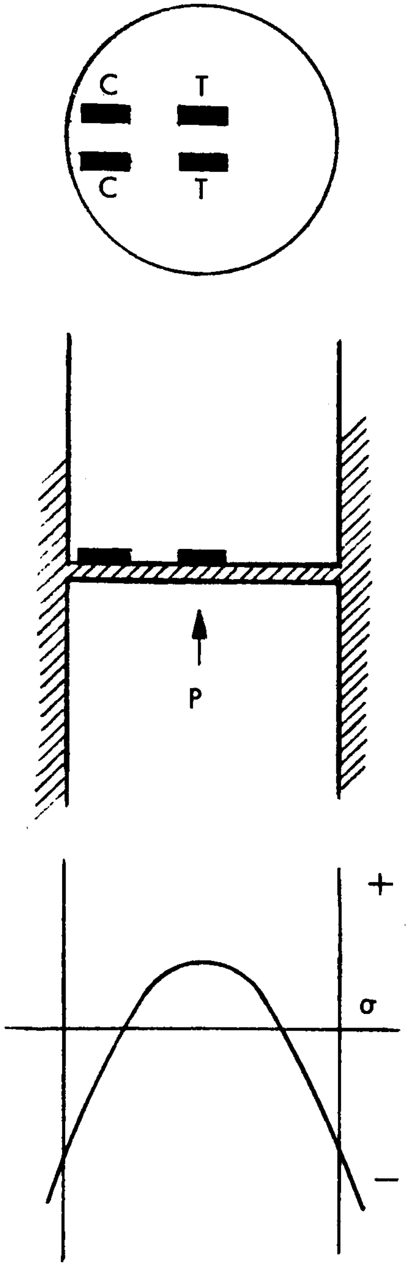


(A)

(B)

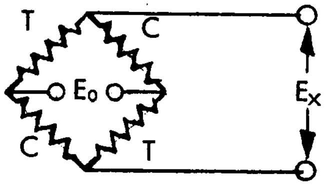
UNCOMPENSATED SENSITIVITY RESPONSE TO TEMPERATURE
TWO TYPICAL PIEZORESISTIVE TRANSDUCERS

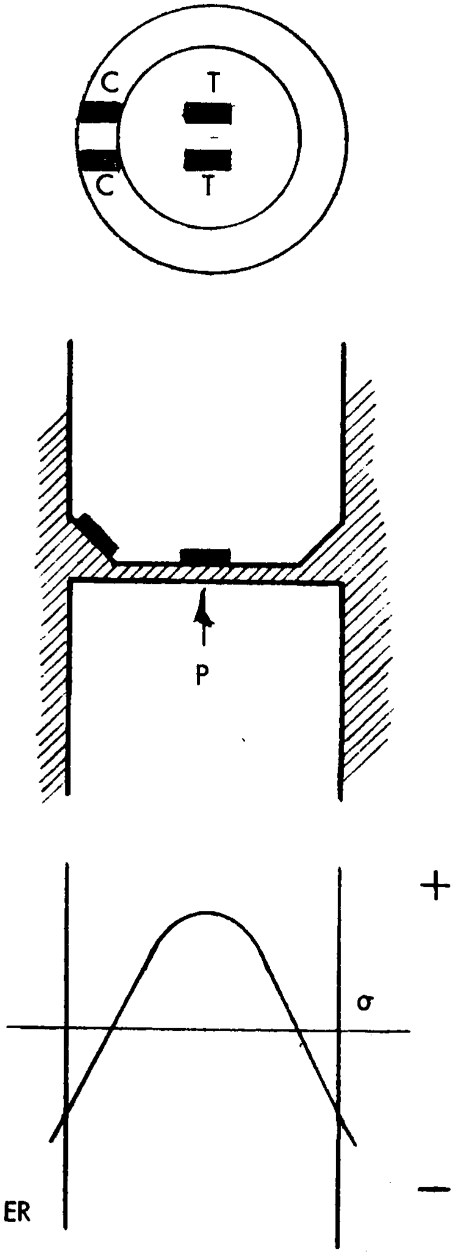
FIGURE 3



TYPICAL FLAT DIAPHRAGM
PRESSURE TRANSDUCER

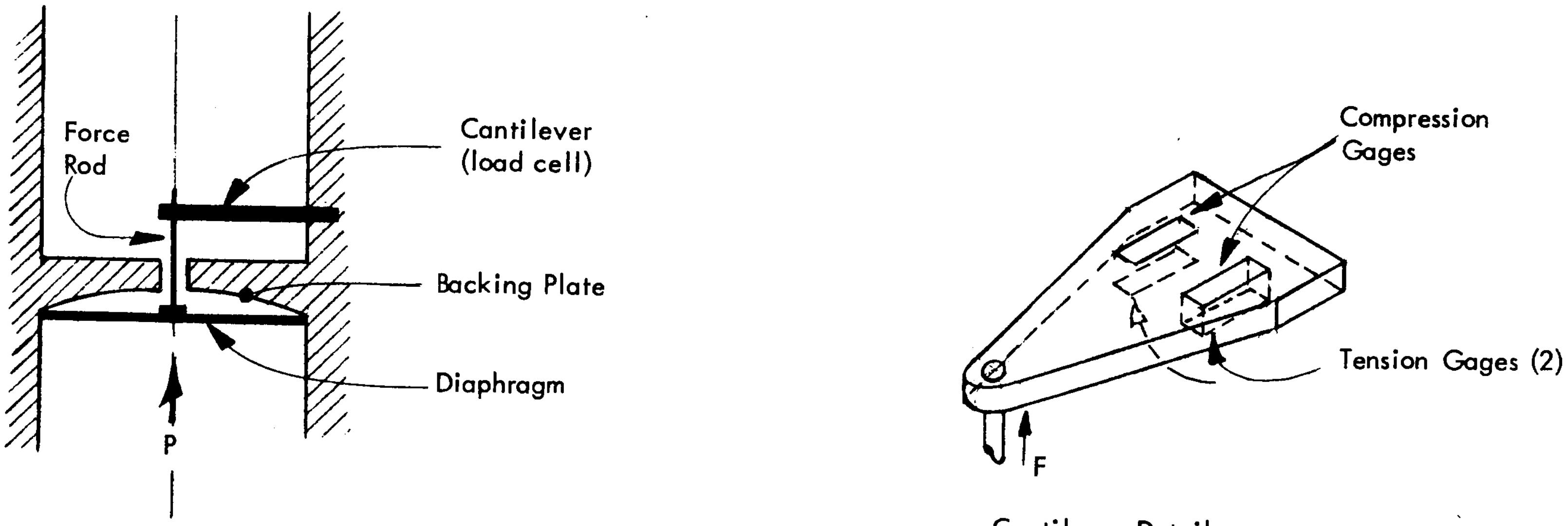
FIGURE 4





OPTIMIZED FLAT
DIAPHRAGM
PRESSURE TRANSDUCER

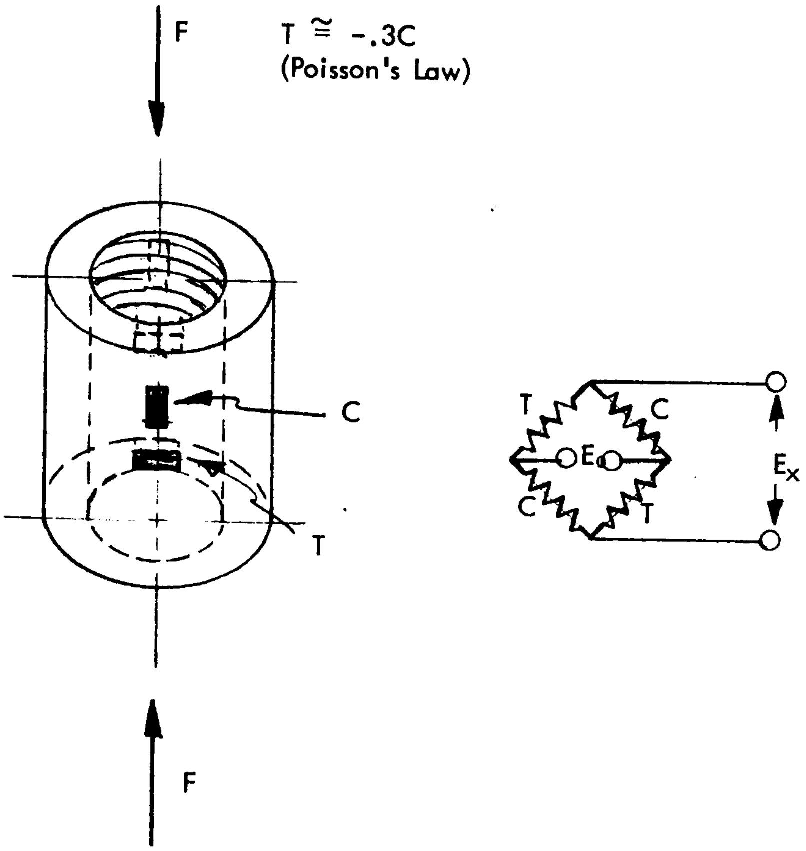
FIGURE 5



Cantilever Detail

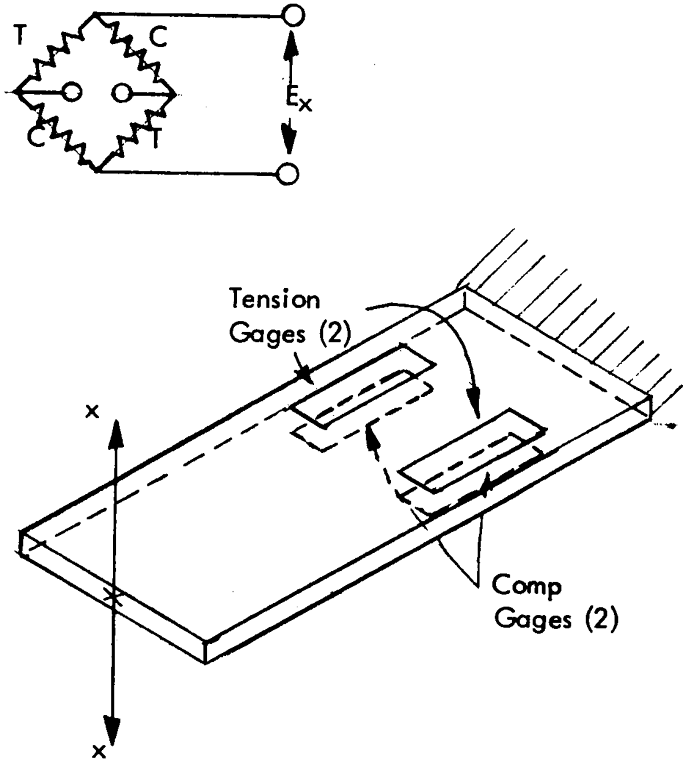
AUXILIARY SENSOR PRESSURE TRANSDUCER

FIGURE 6



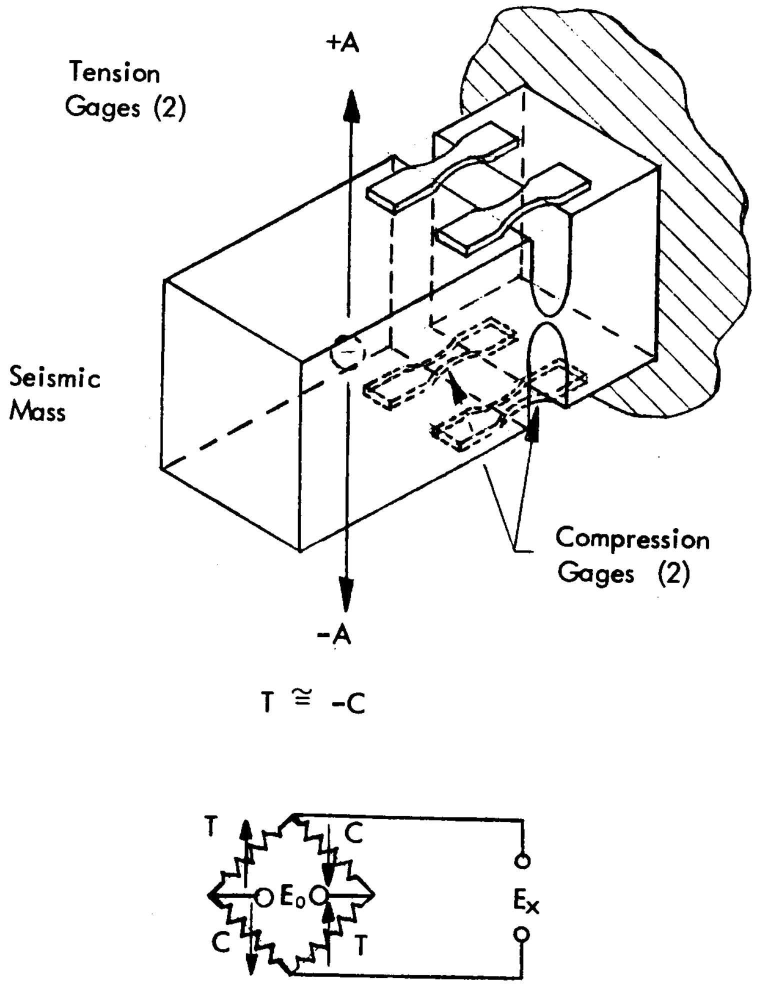
HIGH Fn LOAD CELL

FIGURE 7



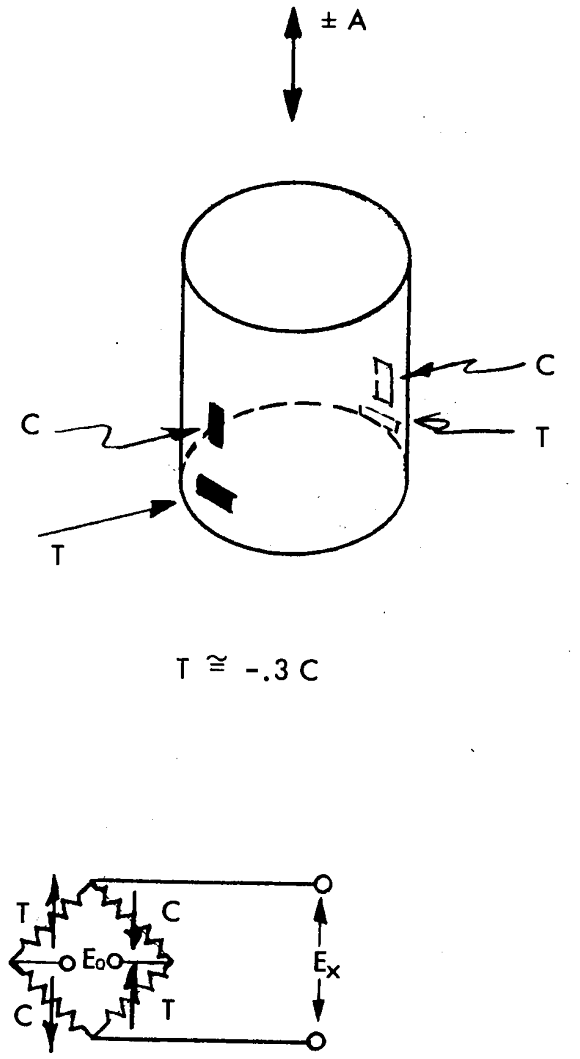
LOW Fn DISPLACEMENT SENSOR

FIGURE 8



TYPICAL PIEZORESISTIVE ACCELEROMETER

FIGURE 9



HIGH Fn PIEZORESISTIVE ACCELEROMETER

FIGURE 10

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