White Paper

The Strain Gage Pressure Transducer

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Pressure transducers use a variety of sensing devices to provide an electrical output proportional to applied pressure. The sensing device employed in the transducers under discussion is bonded, metal foil strain gages. The strain gage because of its unique set of operational characteristics has easily dominated the transducer field for the past twenty (20) or so years.

The origin of the strain gage is lost in history. What we do know is that in 1856 William Thomson (Lord Kelvin) delivered before the Royal Society of London a paper describing his investigation of the electrical properties of metals. Among other findings, he reported that the electrical resistance of certain wires varied with the tensile strain to which the wires were subjected. Little use was made of this knowledge until the late 1930's when attempts were made to apply the phenomenon of strain sensitivity in wires to the actual measurement strain in other bodies.

The bonded wire strain gage, which is the ancestor of the present foil strain gage, was perfected independently and almost simultaneously in 1938 by two men working in widely separated laboratories. Arthur C. Ruge at the Massachusetts Institute of Technology and Edward E. Simmons at the California Institute of Technology both developed techniques for bonding a length of very fine wire to a structure such that any and all surface strains were directly transmitted to the wire. From such humble beginnings a multi-million dollar measurements industry grew.

Although Simmons received official credit for priority in inventing the wire resistance strain gage, both men are considered as being co-inventors. Ruge, in particular, was instrumental in introducing many practical forms of the gage and a variety of transducers that incorporate it as the input sensor. It was this early transducer work that laid the foundation for present day foil strain gage pressure transducers.

In the early 1950's, foil strain gages were introduced and began to supplant wire strain gages in most strain gage transducers. The foil gage was a major step forward and brought about major improvements in overall transducer performance.

Foil gages are manufactured using photo-etching technology, which is similar to that used in producing, printed circuit boards. This fabrication technique allows the strain gage manufacturer to produce almost any size and shape of strain gage needed to accommodate the requirements of the transducer design engineer.

Going from wire to foil improved heat dissipation, simplified bonding techniques, reduced creep effects, lowered gage cost and allowed greater freedom in providing gages to adapt to complex transducer geometries.

In order to provide a transducer that meets the needs of the marketplace, you have to start with a basic sensing device that performs the pressure to electrical transfer function as effectively as possible. The bonded foil strain gage has a number of desirable characteristics needed to make a good pressure transducer, as follows:

1. Low and predictable thermal effects allow accurate operation over a wide temperature range. Compensation and correction techniques are straightforward.
2. Strain gages can be creep corrected by the manufacturer to match the requirements of the transducer designer.
3. Small size and low mass allows operation over a wide frequency range and minimum sensitivity to shock effect.
4. Because the strain gage is fully bonded to the transducer's sensing element, there are no mechanical connections to compromise ruggedness and dynamic performance.
5. The strain gage changes resistance with strain; increasing under tensile strains and decreasing when in compression. Since it is essentially insensitive to supply voltage frequency, it can be used with AC or DC systems.
6. The cost of the strain gage is relatively low and readily available in a variety of shapes, sizes and materials.
7. Strain gages are very stable and transducers retain their calibration and performance over extended periods of time.
8. Strain gages have excellent repeatability and linearity over a wide range of strains.

In terms of designing a strain gage pressure transducer, there are two (2) fundamental considerations. One is the mechanical pressure-sensing element and the other is the electrical strain gage Bridge.

The sensing element is typically a diaphragm or tube whose internal volume contains the applied pressure. The fluid pressure causes the element to deflect in a predictable manner causing surface strains as well as an applied force. Depending on design, the strain gages can be bonded to the non-pressurized face of the sensing element and respond to the surface strains. Or the strain gages can be bonded to a separate structure, usually a cantilever beam, driven by the force input of the diaphragm. In this case the strain gages respond to the surface strains of the beam.

The strain gages change resistance in response to the surface strains they sense. The relationship between strain and resistance is expressed by the gage factor (G.F.) of the strain gage foil, which can range from 2.0 to 4.0. The most common foil in constantan, a 55% copper, 45% nickel alloy with a gage factor of 2.0.

In the following example, a constantan strain gage with a gage factor of 2.0 and an initial resistance of 350 ohms is bonded to a 17-4 PH stainless steel sensing element. The element has both tensile and compressure strains of 1500 microinches/inch at rated pressure. The resistance change **(Δ**R) is:

Where: G.F. = 2.0

R = 350 ohms, Strain Gage Resistance

Є = 0.0015 inches/inch (1500 microinches/inch)

ΔR = G.F. X R X **Є** = Resistance Change
= 2.0 x 350 x 0.0015
= 1.05 ohms

As a result of the given strain level, the strain gage resistance can change by + 1.05 ohms. The resistance will increase (+) if the strain is tensile and decrease (-) if the strain is compressive.

The element stress can be calculated as follows:

E = S/**Є** = Stress/Strain

Where: E = Modulus of Elasticity

= 28,500,000 PSI for 17-4 PH

S = Stress, PSI

Є = 0.0015 inches/inch

= 1500 microinches/inch

S = E x **Є**

= 28,500,000 x 0.0015

= 42,750 PSI

In order to make use of the strain gage, it must be electrically connected in some manner for measuring small changes in resistance. The circuit used in all transducers is in the form of a four-arm Bridge widely used for precision measurement of resistance.

The Bridge is composed of four resistors (strain gages) connected in a definite pattern, schematically shown in a series connected diamond configuration. Two (2) opposite corners of the Bridge are for connecting excitation voltage and the other corners are used for the read-out instrumentation.

This system, devised by S.H. Christie in 1833, is one of the most convenient and accurate methods of resistance measurement ever conceived. It was named the Wheatstone Bridge in honor of Sir Charles Wheatstone who first made significant use of the principle.

In most transducers all four arms of the Bridge are strain gages and fully active in measuring sensing element strains. There are also transducers in which two (2) of the arms are active strain gages and the other arms are fixed resistors. However, regardless of the number of strain gages actually involved in sensing strain, the final circuit is always in the form of a Wheatstone Bridge.

When the Wheatstone Bridge network is used, it is initially balanced so that the electrical output at zero balance will be zero millivolts when the input voltage is applied. For a 350-ohm strain gage Bridge, the input voltage is typically 10 volts. When the pressure-sensing element is stressed under pressure, the resulting strains change the resistance of the gages and the Bridge will no longer be in balance. The amount of unbalance is represented by the electrical output, which can be read on appropriate instrumentation.

The Wheatstone Bridge has many advantages. In most cases complete temperature compensation can be achieved over an extremely wide temperature range. By using the computational characteristics of the Bridge, electrical output can be increased by as much as four times the output from a single gage. Also, by gage location and grid geometry the Wheatstone Bridge can cancel unwanted components involved in a measurement.

The electrical output signal from the Bridge will be:

1. A millivolt signal directly proportional to the applied voltage. Typically it will be 30 millivolts at a 10-volt excitation when rated pressure is applied to the transducer.
2. Directly proportional to the sums and differences of the unit changes in resistances of the four arms of the Bridge.
3. A linear signal with respect to the input pressure
4. Directly proportional to the product of the applied voltage and the net unit change in the resistance of all four arms.

To achieve optimum transducer performance, a strain gage Bridge having four (4) active arms with pair subjected to equal and opposite tensile and compressure strains is a requirement.

The electrical output using this configuration will be as follows:

$E_o = E \times G.F. \times \epsilon$

Where: E = Output Voltage
E = Input Voltage
$G.F.$ = Gage Factor
ϵ = Strain, Inches/Inch

The above requirement is always a design goal and achieved to a greater or lesser degree depending on the sensing element configuration.

By and large there are two (2) fundamental sensing element designs which cover the majority of bonded strain gage pressure transducers. One configuration is a closed end circular, rectangular or flattened tube and the other a flat or convoluted diaphragm.

The diaphragm unit has two (2) major variations depending on the pressure range of the transducer. In the lower ranges, generally below 1000 PSI, the diaphragm is coupled to a cantilever beam, which has the strain gages bonded to its upper and lower surfaces. In the higher-pressure ranges, usually up to 30,000 PSI, the strain gages are bonded to the non-pressurized side of the diaphragm. In both cases, there are four (4) strain gages wired into a Wheatstone Bridge with two (2) gages sensing tensile strains and two (2) compressive strains.

The tube design has two (2) major variations; the flattened thin walled tube and the thick walled tube, which can have a rectangular or circular cross section. The flattened tube can accommodate pressure ranges from 100 through 20,000 PSI. The thick walled tube is used mostly in the pressure range from 5,000 through 100,000 PSI. These are rules of thumb and such factors as transducer size; electrical output, performance requirements and safety factors can expand or restrict the operational ranges.

The tube transducer-sensing element is in effect a closed pressure vessel. The pressure is on the inside and the strain gages are bonded to the outside surface. However, the strain pattern is quite different between the flattened and the thick walled designs.

In the flattened tube, both tensile and compressive strains exist on the gaged surfaces. By proper dimensioning of the tube plus strain gage selection and location, a close approximation of equal tensile and compressive strains can be achieved.

On the other hand, the surface strains on the thick walled design are only tensile. Because compressive strains are not available, this type of sensing element has only two (2) active strain gages whose resistance increased with pressure. The Wheatstone Bridge circuit is completed by bonding another pair of gages in an area of relatively low tensile strains. The result is a four-arm configuration with two (2) active and two (2) inactive strain gages. The consequence is a somewhat greater than 50% reduction in electrical output based on a fully active Bridge.

Regarding performance specifications, manufacturers have generally standardized on a 350-ohm Bridge resistance, a full-scale sensitivity of 3 mV/V and an excitation level of 10 VDC. Other parameters such as zero output, temperature effects on zero output, temperature effects on sensitivity and full-scale output are usually a function of the accuracy class of the device. The higher the accuracy class, the tighter the individual specifications will be.

Some parameters can be compensated to meet their particular specification. Others cannot and are inherent in the design of the transducer. The compensation consists of adding resistance elements to the Wheatstone Bridge circuit; some within the Bridge itself and others located external to the Bridge.

Those characteristics that can be compensated or adjusted during the manufacturing cycle are the following:

1. Full scale output
2. Temperature effect on zero output
3. Temperature effect on full scale output
4. Input resistance
5. Zero output
6. Shunt calibration

Because of manufacturing tolerances, each transducer parameter must be adjusted and trimmed into tolerance on an individual basis.

Other key parameters such as linearity, hysteresis, repeatability, pressure range and overload capability are designed into the product. After the sensing element has been machined, heat-treated and the strain gages bonded to the element, the above parameters are established. They cannot be adjusted or trimmed by means of electrical compensation. In this case the adjustments would be mechanical and are difficult, if not impossible, to adjust or trim into specification.

All transducers basically measure differential pressure. That is, all measurements are made with respect to a reference pressure. Thus pressure transducers are either PSIG, PSIS, PSIA or PSID.
The gage pressure transducer, PSIG, measures pressure referenced to local atmospheric pressure and is vented to the atmosphere.

The sealed pressure transducer, PSIS, measures pressure referenced to the prevailing atmospheric pressure sealed within the transducer. The sealed pressure is a constant and does not vary.

The absolute pressure transducer, PSIA, measures pressure referenced to an absolute vacuum sealed within the transducer.

The differential pressure transducer, PSID, measures the difference of two (2) pressures applied simultaneously to the transducer.

The foil strain gage pressure transducer has an established reputation and an outstanding record in satisfying a great many applications requiring an accurate measurement of fluid pressure.

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