

# TECHNICAL NOTES

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## Pressure Sensors and Transducers

### Pressure Measurement

Pressure is a force generated inside a sealed volume by the atoms and molecules either pressing out (positive pressure) or pulling in (negative pressure). A number of different technologies are used to measure pressure. The most common methods of pressure measurement - capacitive, piezoresistive, bonded strain gauge, LVDT (linear variable differential transformer), and quartz oscillator - are discussed and compared in this paper. Important parameters involved in choosing a particular transducer such as range, accuracy, stability, and price are detailed. A discussion of the sensors manufactured by ACI including information on inputs, outputs, and special features is included.

If you were to hold a ruler up to a dollar bill and place the zero of the ruler at one end, you would proclaim the bill to be six inches long. If someone else were to measure the same bill with the same ruler but began measuring at the 1 inch mark, the other individual would notice that the end of the dollar bill fell on the 7 inch mark. Obviously, this is not because the dollar bill grew in length. Rather, the initial starting point or point of reference has changed. In pressure measurement there are typically three reference points from which a measurement can be taken. These three reference points yield three different methods of measurement: absolute, gauge, and differential. In order to accurately compare outputs from separate units, it is necessary to identify which method of measurement is being used.

### Applications

Vacuum (zero pressure) is one of the reference points for measuring pressure. Zero pressure, or no pressure, exists only in an infinite volume or where there is no matter, such as in a vacuum. The only place where there is naturally zero pressure is in the vacuum of outer space. An absolute pressure unit measures pressure using an absolute vacuum that is artificially generated inside the unit as a reference point. An absolute pressure unit is designed to be sensitive and is commonly used for measuring barometric pressure. Barometric pressure changes continuously and is important for weather prediction.

A second method of pressure measurement uses a device known as a gauge unit. Unlike an absolute pressure unit, a gauge unit does not have a zero pressure within the unit to use as the reference point. Rather, a gauge unit uses atmospheric pressure as a reference point. Atmospheric pressure is the pressure that results from the force of the atmosphere upon the surface of the earth. At sea level, the atmospheric pressure is about

15 psi. Since gauge units are typically used to measure much higher pressures (i.e. in the hundreds to thousands of psi) the changes in atmospheric pressure are overshadowed and do not create any measurement error. In the HVAC industry, gauge units are utilized to monitor steam pipes, water lines, and refrigeration lines.

The final method of pressure measurement is called differential. The differential pressure unit is so named because it measures the difference between two input pressures, one of which is the reference. The reference can be a constant pressure, such as vacuum or atmospheric pressure, or a continuously changing input. Differential pressure measurement is very common in the HVAC industry. The reference pressure varies according to the application. For flow detection or controlling pressure in a room or fume hood the reference is usually atmospheric pressure. A pitot tube connected across the input ports of the differential unit and immersed in an airstream can be used for flow measurement. By placing the inputs on either side of a filter or orifice plate a differential unit can be used for blockage monitoring or flow control.

## Sensing Methods

Over the years numerous technologies for measuring pressure have been developed. Our discussion will be limited to bonded strain gauge, piezoresistive (PRT), capacitive, LVDT, and quartz oscillator. Each technology has its own strengths and weaknesses. The key design parameters of accuracy, long term stability, operating temperature range, and price are discussed to give an overview of strengths and weaknesses. This information is used to identify which type of pressure transducer is best suited for a particular task. A table comparing all of the technologies is included at the end of the section.

### Bonded Strain Gauge

The bonded strain gauge is one of the first technologies applied to measure pressure. They are used in higher pressure ranges from 10 psi to 50,000 psi. These sensors have filled a niche in the market measuring the pressure of wet and/or corrosive inputs. Bonded strain gauge transducers differ in three categories, the bonding method, diaphragm material, and the type of strain gauge. The bonding method affects stability and temperature compensation. A weak bond will degenerate over time, creating offsets and nonlinearities. To be compatible with corrosive inputs the strain gauges are bonded to inert diaphragms made of stainless steel or ceramics. Stainless steel is not a perfectly elastic material and if not designed correctly will tend to lose its original shape. Ceramics are more elastic but can not withstand some corrosives and very high pressures. The type of strain gauge affects the magnitude of the output. A higher output provides a better signal to noise ratio.

The basic manufacturing method involves building a diaphragm, attaching it to a substrate or fitting, and bonding strain gauges to one side. A pressure input causes the diaphragm to bend, stressing the strain gauges, creating an electrical output. Adjusting the diaphragm thickness changes the measurable pressure range. The strain gauges are made of many different materials, metals and semiconductors being the most common. Different

strain gauges are characterized by a number called the gauge factor. The gauge factor is the proportion of resistance change over applied stress. The gauge factor for metals can be anywhere from 2 to 4.5. A semiconductors gauge factor will vary from 100 to 175. Semiconductors provide much larger electrical outputs when used as the strain gauge. Four strain gauges are bonded to each diaphragm in the areas of greatest stress, two of the strain gauges in an area of compression, the other two in an area of tension. Electrically, the strain gauges are connected in a Wheatstone bridge configuration. As the diaphragm bends the arms of the bridge are unbalanced causing the output voltage to increase. The temperature coefficients of the strain gauges, diaphragm, and bonding material must be matched. If the temperature coefficients differ the strain gauges will be affected by temperature expansion of the bond or diaphragm. Temperature compensation of the unit is achieved by placing highly accurate resistors in parallel or series with the arms of the bridge.

Bonded strain gauge sensors can be found in numerous configurations. Some are highly temperature compensated to withstand extreme heat. Some use high quality strain gauges and achieve excellent linearity, high repeatability, and little to no hysteresis. Typically non-linearity, repeatability, and hysteresis are less than 0.5% of full scale. Thermal shifts of bonded strain gauge sensors can be as low as 0.1% of full scale over a 200°F compensated temperature range. Bonded strain gauge units are commonly in the middle of the price range but transducers with excellent specifications can be found priced in the thousands of dollars.

### Piezoresistive (PRT)

Piezoresistive technology is evolving rapidly. These sensors are easy to mass produce and possess many desirable performance qualities. The sensing element is made of silicon with much of the manufacturing technology being borrowed from IC makers. Piezoresistive sensors have large outputs requiring less amplification electronics than some other types of sensors. The sensing element is small and is able to be packaged in a variety of different ways.

The physical structure of piezoresistive sensors is much the same as a strain gauge sensor, but because they are made entirely of silicon, micromachining processing techniques can be used to build them. First, a cavity is etched in a piece of silicon. A silicon diaphragm is diffused with four silicon strain gauges connected in a Wheatstone bridge. The diaphragm thickness is adjusted to measure different ranges. The diaphragm is placed over the etched cavity and the two pieces of silicon are bonded using a silicon fusion bonding technique. Temperature compensation is generally done directly on the chip. Resistors are diffused in parallel with arms of the bridge and are laser trimmed to meet specifications after testing of the raw sensor.

Piezoresistive technology functions very well at intermediate pressure ranges from 1 psi to 1000 psi. Although some sensors are currently for sale that measure as little as 4 inches of w.c., resolution is low because temperature effects create a high noise floor. A typical output is 100mV at full scale. Zero offsets are caused by an unbalanced bridge. The bridge becomes unbalanced because the strain gauges are not exactly equal or changing temperatures affect the strain gauges resistance. Zero offsets are usually one to

two millivolts. Temperature compensation is difficult over large spans because the temperature coefficient is large and the curve changes slope as the temperature drops. Typical sensors are compensated from 0 to 70°C with +/-1% full scale drift in this temperature span. Silicon is a very elastic material, a property that ensures these sensors have low hysteresis (+/- 0.005% FS) and repeatability (+/- 0.1% FS). Stability is affected by silicon degradation and the high amplification required for a useable output. Improvements in manufacturing technology has made the stability of piezoresistive sensors quite good.

## Capacitive

Capacitive technology has many of the strengths of bonded strain gauge and piezoresistive sensors together in one package. Capacitance sensing has a higher gauge factor than any strain gauge. The amplification needed for a useable signal is contained to a minimum providing excellent stability. Capacitive sensors can measure pressures as low as 0.5 inches of w.c. and as high as 10000 psi. Temperature drift is held to changes in the physical dimensions of materials. The silicon and ceramics used for the sensing element are very elastic and hold their shape well. Capacitive sensors are generally larger than the PRTs and strain gauges and somewhat more expensive. They are very versatile sensors which are able to reach both very low and very high pressures and are also able to sense in corrosive environments.

Capacitive sensors use a deflecting diaphragm to sense pressure. The diaphragm is one plate of a capacitor. The substrate forms the other plate. The capacitance changes as the diaphragm deflects under the pressure load. The thickness of the diaphragm is carefully controlled, the thickness determines the pressure range of the sensor. When the sensor is made of silicon the plates of the capacitor are heavily doped regions within the substrate. The use of one material keeps temperature coefficients equal and drift to a minimum. A ceramic sensor usually has gold plates screen printed on the substrate. The temperature coefficients are tailored such that they match. The electronics for signal conditioning a capacitive sensor are more complicated than the other technologies.

The temperature effects on capacitive sensors are small and can be compensated from -30 to 125°F. Typical temperature effects on zero and span are +/-0.5% of full scale or better. Combined hysteresis and repeatability errors are less than +/-0.03% of full scale. Non linearity is 0.1% of full scale. One drawback of a capacitive sensor is it will have a slower response time than other technologies.

## LVDT and Quartz Oscillator

Both of these technologies are very accurate and sensitive, and tend to be expensive as a result. Many instruments built using these technologies are laboratory grade quality.

An LVDT sensor has a diaphragm or another structure that deflects under a pressure load. The LVDT then measures this deflection. A LVDT can measure tiny deflections very accurately. LVDT's have a much higher sensitivity than strain gauges

leading to higher outputs. An LVDT consists of a high magnetic permeability core moving through a set of coils. When one coil is driven the mutual inductance creates a voltage in another coil. The signal processing required to decode an LVDT output is more complex compared to the other technologies. An LVDT is also a large instrument. LVDT's are produced that function over nearly any pressure range. Inputs can be corrosive. The stability is good and linearity and repeatability are excellent. Compensated temperature ranges can be -40 to 200°F with temperature drifts as low as +/- 0.015%FS/°F. This type of sensor works well under adverse conditions.

A quartz oscillator functions using the piezoelectric property of a crystal. When the quartz is strained by a pressure a charge separation takes place creating a voltage on the surface of the crystal. The frequency response of the crystal is excellent but does not extend down to DC. A quartz oscillator unit can measure dynamic pressures and short term static pressure. The output will eventually decay to zero under an unchanging load. A quartz oscillator, like the LVDT, has a large measuring range from vacuum to 10,000 psi. Measurements can be taken using corrosive inputs, and in extreme environmental conditions with excellent accuracy. No moving parts ensure a high stability. A quartz crystal has high sensitivity and resolution is excellent with low noise electronics. The temperature coefficients are typically +/- 0.03%/°F, compensated temperature ranges from -100 to 210°F. Overall an excellent sensor to use when measuring conditions are uninhabitable.

All the specifications used are typical numbers. The specifications were taken from data sheets for that type of sensor. Generalizations do not always tell the whole story. There are some companies that have taken each of these technologies to the next level. By using ingenious electronics or some other method some companies have squeaked out better specifications. The table below gives a general idea of the important parameters used to choose a pressure transducer.

	Range	Temperature Drift	Media	Stability	Price
Bonded Strain Gauge	0 to 50 psi 0 to 50000 psi	0.1% of full scale from -40 to 250°F	Wet inputs Corrosive	Fair	Range from Intermediate to Expensive
PRT	0 to 0.5 psi (10" H <sub>2</sub> O) 0 to 200 psi	1% of full scale from 32 to 150°F	Dry inputs Noncorrosive	Good	Inexpensive
Capacitive	0 to 0.015 psi (0.5" H <sub>2</sub> O) 0 to 5000 psi	0.5% of full scale from -30 to 125°F	Wet inputs Corrosive	Excellent	Intermediate
LVDT	Vacuum to 10000 psi	0.015% of full scale from -40 to 200°F	Wet inputs Corrosive	Excellent	Expensive
Quartz Oscillator	Vacuum to 10000 psi	0.03% of full scale from -100 to 210°F	Wet inputs Corrosive	Excellent	Expensive

## Product Specifications

ACI provides two types of pressure sensors to its customers, the low differential unit, ACI/DP, and the gauge pressure sensor, ACI/GP. True to our creed, when developing our products ACI spends a lot of time choosing the correct technology to achieve our design parameters. The design parameters reflect the need of our customers. In each case the chosen technology reflects customers needs first and cost second.

### ACI/DP

The ACI/DP is designed to measure low differential pressure. To meet this specification ACI chose a capacitive sensor with a ceramic substrate and sensing diaphragm. Capacitive technology provides a high output and signal to noise ratio. The ceramic substrate is nearly elastic and has no degradation over time improving the overall stability of the sensor. A capacitive sensor also avoids the temperature drift problems associated with PRT's while still being competitive in price. The DP units are offered for sensing ranges from 0 to 0.25 inches of w.c. (+/- 0.25") up to 0 to 10 inches of w.c.. Two separate diaphragms are milled to exacting specifications to cover the pressure ranges. ACI also designed electronics able to produce jumper selectable spans. With each unidirectional DP unit there are four possible spans, the bi-directional units handle two spans. By moving the jumpers the user can select full span, 80%, 60%, and 50% of the full span. The bi-directional units have 100% and 50% of full span selectability.

The low pressures measured by these units can cause problems for other technologies. At such a low pressure the diaphragm displacements are also small, leading to problems with signal to noise ratio. Our capacitive sensor has been designed exclusively to function in the low pressure realm and works very well. The transducer is temperature compensated from 50 to 104°F. In this temperature band the temperature error is less than +/- 1% of full scale for 2 inches of w.c. and higher, and less than +/- 2% of full scale for less than 2 inches of w.c.. Non-linearity of the transducer is +/-0.3 % F.S. based on a best fit algorithm. Because of the excellent elasticity of ceramics hysteresis and repeatability are +/-0.03% of full scale. The ACI/DP is mounted securely into a plastic housing. Brass fittings are used for pressure inputs. The long term stability is excellent.

### ACI/GP

The ACI/GP is a gauge pressure transmitter designed to measure medium to high pressure ranges with wet inputs. In the HVAC industry a gauge pressure unit must be able to measure corrosive and wet inputs. ACI chose a bonded silicon strain gauge unit to accommodate corrosive inputs. Measurable pressure ranges vary from 0 to 25 psi up to 0 to 5000 psi and the output is a linear two wire 4-20mA current. The sensing element is a silicon strain gauge bonded to a stainless steel diaphragm. The diaphragm and fitting are all milled from one piece of stainless steel. There are no welds, seals, or o-rings that could fail. Any input compatible with stainless steel can be used. The silicon strain gauges are bonded to the stainless steel permanently using a proprietary sputtering technology. The

electronics are protected by an aluminum housing attached to the back of the sensing element. Aluminum is used to facilitate heat removal and minimize corrosion created by a harsh environment. The ACI/GP is temperature compensated from -30 to 130°F. The thermal sensitivity throughout the compensated temperature range is less than +/-0.035% of full scale. The accuracy of the unit includes non-linearity, hysteresis, and repeatability combined using a RMS algorithm. The accuracy of all ACI/GP units is better than +/-1% of full scale.