Mechanical Pressure Measurement

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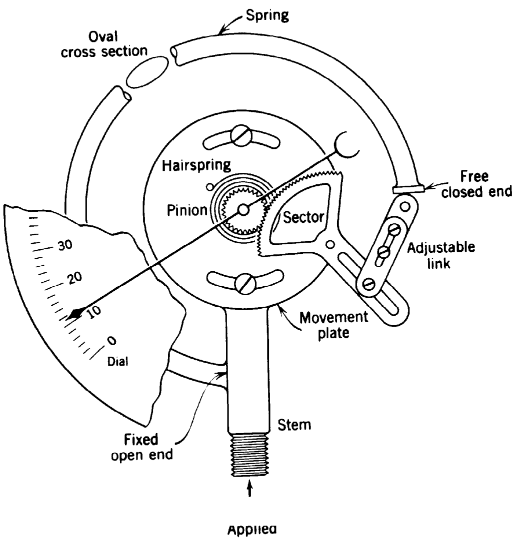


Figure 1
Bourdon tube pressure gauge

Bourdon tube-type pressure sensors are the most common for industrial use in the family of elastic pressure elements. They have been in use for over a century. Their accuracy substantially improved around 1930 when friction effects, drift and elastic hysteresis were reduced and ±0.1% accuracy's became possible.

These elements are not ideally suited for low pressure, vacuum or compound measurements because the spring gradient in the Bourdon tube is too low for precision measurements at spans 10 PSI or below.

Bourdon tube materials include bronze, monel, alloy and various grades of stainless steel.

In the following paragraphs some of the basic types of elastic Bourdon elements will be discussed, including the C type Bourdon tube, the spiral and helical elements.

C-Bourdon Pressure Sensors

Figure 1 illustrates the classic C-Bourdon tube used in a direct indicating gauge, which usually has an arc of 250°. The process pressure is connected to the fixed socket end of the tube, while the tip end is sealed. Because of the difference between inside and outside radii, the Bourdon tube presents different areas to pressure, which causes the tube to tend to straighten when pressure is applied.

The resulting tip motion is non-linear because less motion results from each increment of additional pressure. This non-linear motion has to be converted to linear rotational pointer response. This is done mechanically by means of a geared sector and pinion movement. The tip motion is transferred to the tail of the movement sector by the connector link. The angle between the connecting link and the sector tail is called the "traveling angle". This angle changes with tip movement in a non-linear fashion, compensating for the non-linearity of the tip movement itself.

It is desired to minimize backlash and provide smooth roll-on and roll-off characteristics in the geared sector and pinion movement. Fine pitch gears minimize backlash or a cam sector that rides on a roller surface eliminates the gears altogether. On gear and pinion designs, the operation has been improved by the use of nylon and Teflon bearing materials.

Bourdon tube materials are listed in the table below, noting some of the important characteristics by the letters P (poor), F (fair), G (good), and indicating the maximum pressure range which the Bourdon tube can detect.

Tube Material	*Corrosion*	*Spring Rate*	*Temp. Coefficient*	*Hysteresis*	*Maximum Pressure*
Phosphorus Bronze	P	F	P	F	800 PSIG
Beryllium Copper	P	G	P	G	5,000 PSIG
316 Stainless	G	P	P	P	10,000 PSIG
403 Stainless	G	P	P	P	20,000 PSIG
Ni-Span C	G	G	G	G	12,000 PSIG
K-Monel	G	P	P	P	20,000 PSIG

Direct indicators or motion balance transmitters using C-Bourdon elements are available with spans from 0-15 PSI to 0-20,000 PSI and can be used for positive, negative or compound pressure ranges, but the indication on the vacuum side will not be especially accurate or sensitive. The accuracy of these devices is a function of the Bourdon tube diameter, design quality, and calibration procedures. As such, it can vary from ±0.1% to ±5% with the majority of these units falling in the area of ±1% accuracy.

Spiral and Helical Bourdon Pressure Detectors

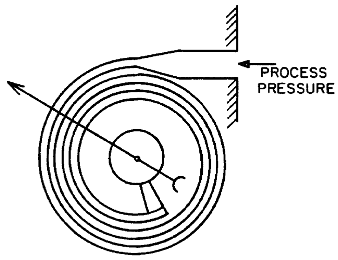


Figure #2
Spiral Bourdon Tube

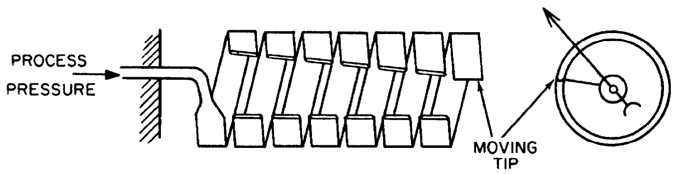


Figure #3
Helical Bourdon Tube

Figure 2 shows a ***spiral*** Bourdon element.

When pressure is applied the flat spiral tends to uncoil producing a greater movement of the free end eliminating the need for mechanical amplification. This increases the sensitivity and accuracy of the instrument because no lost motion or friction is introduced through links and levers.

Standard spiral materials include bronze, steel, stainless steel, beryllium copper, monel and Ni-Span C. Spans as low as 10 PSI are available for positive, negative or compound ranges.

Heavy-wall, spiral tube springs to detect pressures up to 100,000 PSIG are also available in direct indicators.

Figure 3 shows a helical Bourdon tube element. This sensor produces an even greater motion of the free end than the C-Bourdon or spiral elements, eliminating the need for mechanical amplification. Other advantages of this design include the high over-range protection available; for example, a 0-1000 PSIG element may be safely exposed to 10,000 PSIG pressure, and it is suitable for pressure measurement on continuously fluctuating services.

The diameter, wall thickness, number of coils, and construction materials affect the range of the helical coil. High-pressure elements might have as many as twenty coils while low span sensors can have only two or three coils. Available materials include bronze, beryllium copper, Ni-Span C, and stainless steel.

Diaphragm Pressure Capsule

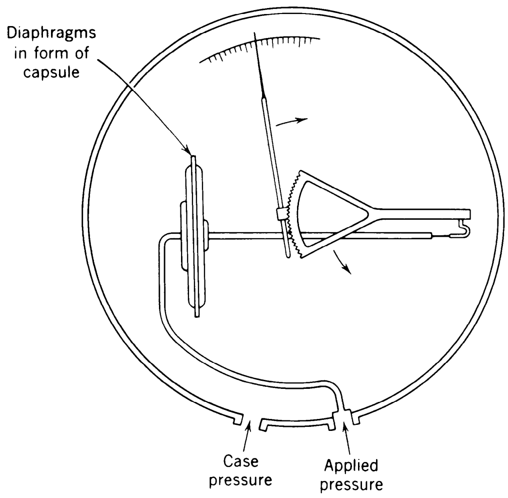


Figure 4
Diaphragm Pressure Capsule

Pressure sensors depending on the deflection of a diaphragm have been in use for over a century. In the last few decades, the elastic hysteresis, friction and drift effects have been reduced to approximately ±0.1% of span in high quality designs. New materials have been introduced with improved elastic qualities such as beryllium copper and with very low temperature coefficients of elasticity such as Ni-Span C.

Inconel and stainless steel are used where extreme operating temperatures or the corrosive nature of the process demand them.

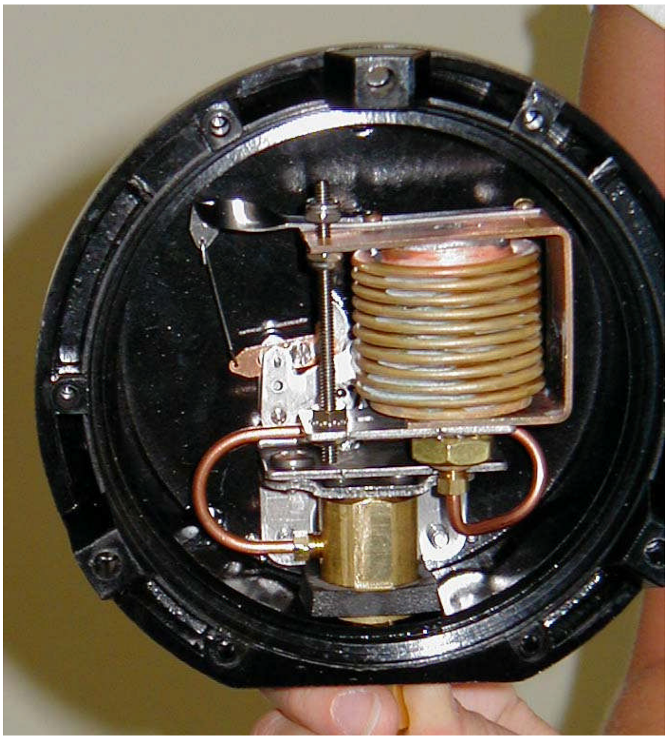
The diaphragm is a flexible disc, either flat or with concentric corrugations, made of sheet metal with precise dimensions. The pressure deflection characteristics of both flat and corrugated diaphragms have been well investigated.

Figure 4 shows a single capsule design. The capsule consists of two diaphragms welded together at their periphery. Evacuated capsules are used for absolute pressure detection and single diaphragms for highly sensitive measurements. The sensitivity of a capsule increases in proportion to its diameter, which in the conventional designs varies from one to six inches. Multiple capsule elements can be built from either convex or nested capsules. These elements are useful in increasing the output motion resulting from a pressure change.

These sensors can be referenced to full vacuum for absolute pressure indication, or they can be referenced to atmospheric pressure for gauge or differential pressure indication. Force balance designs are transmitting devices with high accuracy, but without local indication capability.

Typical performance:

Capsule Material	*Minimum Span*	*Maximum Span*
2" Diameter Cu-Ni-Mn	20" H_2O	5 PSI
3" Diameter Cu-Ni-Mn	8" H_2O	40" H_2O
Ni-Span C-large diameter	3" H_2O	5 PSI
Ni-Span C-small diameter	5 PSI	15 PSI
Ni-Span C-nested capsule	12 PSI	180 PSI



← Bellows Type Sensing element

Electronic Pressure Measurement

Capacitance Type Pressure Detectors

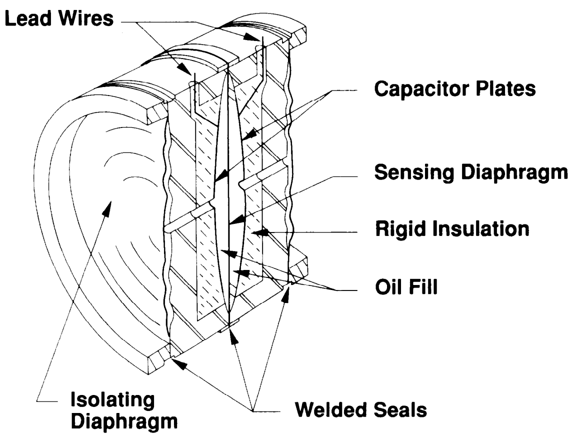


Figure 5
Capacitance Cell

The basic operating principle involved in all capacitive pressure sensors is the measurement of change in capacitance resulting from the movement of an elastic element.

The elastic element in most designs is a Ni-Span C or stainless steel diaphragm exposed to the process pressure on one side and to the reference pressure on the other. Depending on the reference pressure used, the unit can detect absolute, gauge or differential pressures.

The unit shown in Figure 5 incorporates two capacitor plates; other designs have only one capacitor plate.

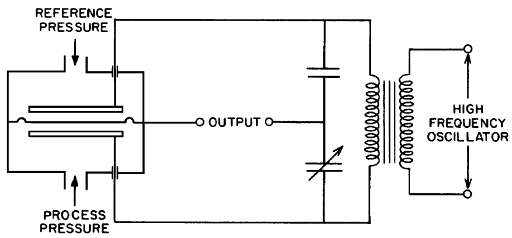


Figure 6
Schematic of Capacitance Cell

A high voltage, high frequency oscillator is used to energize the sensing element.

Changes in process pressure deflect the diaphragm and a bridge circuit detects the resultant change in capacitance. The two-plate design can be operated in balanced or unbalanced modes.

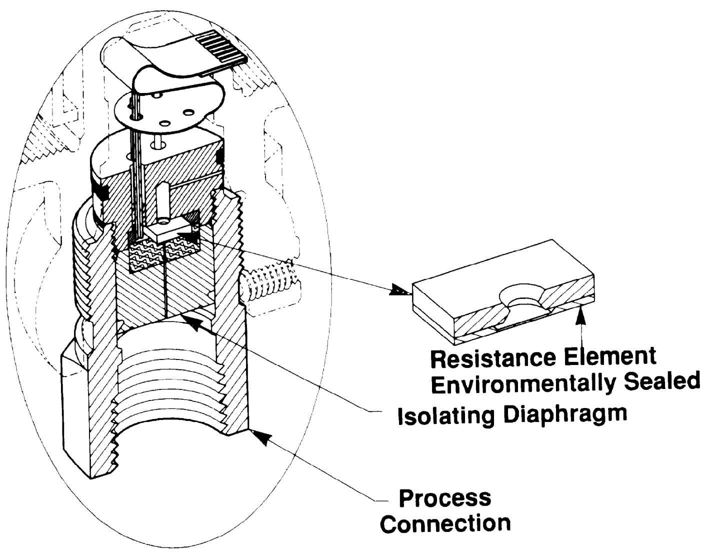
If the circuit is operated in the balanced mode, then the output voltage is fed to a null detector and the capacitor arms are varied to maintain the bridge at null. In this mode, the null setting itself is a measure of process pressure.

If the circuit operates in the unbalanced mode, then the ratio between output voltage and excitation voltage is the indication of process pressure.

In the single capacitor design the plate is positioned on one side of the sensing diaphragm. The capacitance of the element, being a function of diaphragm deflection, is a measure of process pressure. The element's capacitance is converted and amplified into a DC milliamp current signal.

Capacitive pressure sensors are accurate to ±0.1 to ±0.2% of span and with the proper selection of diaphragms can handle pressure ranges from 3" H_2O up to 5000 PSIG. Both their temperature sensitivity and hysteresis is low while their speed of response is high. Their output is linear and can be temperature compensated for optimum results.

Strain Gauge Type Pressure Transducers



Thin-Film Polysilicon Sensor.

Figure 7
Strain gauge Pressure Transmitter

The word strain refers to changes in dimensions of solid bodies due to the actions of forces exerted upon them. These instruments simply determine the change in length of bodies, and the change in length divided by the original length is a measure of the average strain. The true strain gauge does not measure extension, but changes its physical characteristics such that its electrical resistance changes as a function of the strain to which it is subjected.

The bonded strain gauge represented a major advance in strain gauge technology. This design eliminates the mechanical frame by attaching the sensing wire directly to the strained surface. Strain gauge wires with less than 0.001-inch diameter have a surface area that is several thousand times more than the cross-sectional area. Therefore, the bond between the strained surface and the wires mounted on paper or plastic carriers is sufficiently strong. Foil gauges have also been used where the foil thickness can be as low as 0.0001 inches.

One of the bonded designs is shown in Figure 7. Here the process pressure is applied to a flat diaphragm. The strains resulting from the diaphragm deflection are sensed by four strain elements bonded directly to the underside of the diaphragm. Changes in resistance of these elements are measured as an indication of process pressure.

Recently, another breakthrough occurred in strain gauge technology. This involved the use of semi-conductors such as silicon and germanium as the gauge elements. The most attractive characteristic of semi-conductors is their sensitivity, which is close to a hundred times greater than metal wires. When metal wires are used, they are likely to be chrome-nickel alloys although pure metals such as platinum are also used as temperature compensators. The desirability of a certain alloy used as a wire element is partially a function of its strain sensitivity. Strain sensitivity (S) is defined as the ratio between unit extension ($\Delta L/L$) and corresponding change in specific receptivity ($\Delta r/r$).

$$S = \frac{\Delta r / r}{\Delta L / L}$$

where L is the initial length of the wire and r is the specific receptivity in the unstrained condition. If the strain occurs within a certain portion of the elastic range, the strain sensitivity is constant, meaning that by detecting resistance, we are sensing a value linearly related to strain.

When using strain gauge type sensing elements, process temperature variations must be compensated for. Temperature changes cause both the base material to which the element is bonded and the element itself to expand or contract. In addition, the coefficient of receptivity of the clement varies with temperature. There are several methods of temperature compensation.

The most frequently employed method is the use of dummy elements. The dummy gauge is mounted on the same surface as the active clement, and is exposed to the same temperature, but is not subject to the forces applied. If a dummy is connected in a Wheatstone bridge arm adjacent to the active element, it will automatically compensate for temperature effects.

The resistance change of strain gauges being small, precise instrumentation is required to detect it with good accuracy.

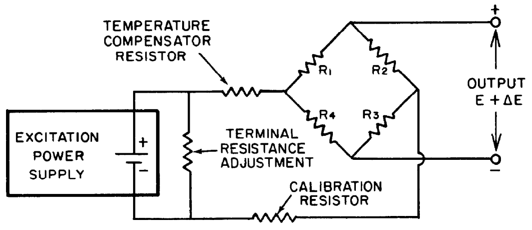


Figure 8
Wheatstone Bridge Circuit

The Wheatstone Bridge is one of the common configurations used for strain gauge measurement. Usually each arm of the bridge contains a strain sensitive element. Some of the elements can be active or dummies.

The bridge is balanced when:

R1+ R3 = R2 +R4.

After an initial condition of balance, the change in output voltage is:

$$\Delta E = \frac{V}{4R_0}\left(\Delta R_1 + \Delta R_3 - \Delta R_2 - \Delta R_4\right)$$

Where Ro is the initial, equal resistance of each clement. From this equation it can be seen that if two elements form adjacent arms of the bridge (R1 & R2 or R3 & R4), the temperature effects will be minimized because their influence on the output is subtractive. If the active gauges are on opposite arms of the bridge, their effect is additive and, therefore, dummy elements are needed to achieve compensation. The Wheatstone circuit can detect both static and dynamic strains and is well suited for temperature compensation.

The Ballast or Potentiometric circuit is arrived at by making R2 = Infinity and R3 = 0 in the above figure. This circuit is simpler than the Wheatstone bridge and has the added advantage of possibility for common ground for the measuring instrument, amplifier and measuring circuitry. The drawbacks include the difficulty of temperature compensation, and that it is suited only to dynamic but not to static strain sensing.

Strain gauge transducers normally have a bridge resistance from 100 to 500 Ohms. They can be excited by either AC or DC voltage from a power supply providing an output voltage in the range of 8 to 40 volts. The output generated by the bridge can be anywhere from 1 to 4 millivolts per volt excitation. Calibrated accuracy is 0.25% or better.

The output millivolt signal from the circuit can be converted to DC milliamperes or sensed directly by analog or digital readout devices. Where fluctuating pressures are to be detected, the frequency of vibration has to be taken into account. For frequencies up to 50 cycles per second, conventional recorders are acceptable, at higher frequencies the cathode ray oscilloscope is used.

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