PRESSURE • STRAIN • FORCE

A TECHNICAL REFERENCE SERIES BROUGHT TO YOU BY **OMEGA** VOL. 3

TRANSACTIONS

IN MEASUREMENT AND CONTROL

VOLUME 3
FORCE-RELATED MEASUREMENTS

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PRESSURE CONVERSION TABLE

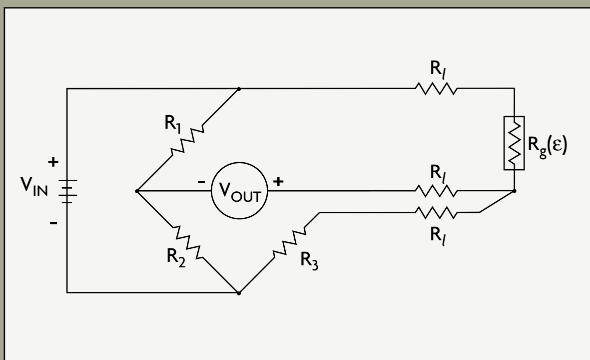
	Atmos	Bars	Dynes/cm^2	In of Hg (0° C)	In of $H_2$0 (4° C)	K grams/ $meter^2$	Lb/in^2 psi	Lb/ft^2	mm of Hg torr	Microns	Pascals
Atmos	1	9.86923 x 10^{-1}	9.86923 x 10^{-7}	3.34207 x 10^{-2}	2.458 x 10^{-3}	9.678 x 10^{-5}	0.068046	4.7254 x 10^{-4}	1.316 x 10^{-3}	1.316 x 10^{-6}	9.869 x 10^{-6}
Bars	1.01325	1	10^{-6}	3.3864 x 10^{-2}	2.491 x 10^{-3}	9.8067 x 10^{-5}	6.8948 x 10^{-2}	4.788 x 10^{-4}	1.333 x 10^{-3}	1.333 x 10^{-6}	10^{-5}
Dynes/cm^2	1.01325 x 10^6	10^6	1	3.386 x 10^{-2}	2.491 x 10^3	98.067	6.8948 x 10^4	4.78.8	1.333 x 10^3	1.333	10
In of Hg (0°C)	29.9213	29.53	29.53 x 10^{-5}	1	7.355 x 10^{-2}	2.896 x 10^{-3}	2.036	0.014139	3.937 x 10^{-2}	3.937 x 10^{-5}	2.953 x 10^{-4}
In of $H_2$0 (4°C)	406.8	4.01.48	4.0148 x 10^{-4}	13.60	1	3.937 x 10^{-2}	27.68	0.1922	0.5354	5.354 x 10^{-4}	4.014 x 10^{-3}
K grams/$meter^2$	1.033227 x 10^4	1.0197 x 10^4	1.0197 x 10^{-2}	345.3	25.40	1	7.0306 x 10^2	4.882	13.59	13.59 x 10^{-3}	1.019 x 10^{-1}
Lb/in^2 psi	14.695595	14.504	1.4504 x 10^{-5}	0.4912	3.6126 x 10^{-3}	1.423 x 10^{-3}	1	6.9444 x 10^{-3}	1.934 x 10^{-2}	1.934 x 10^{-5}	1.450 x 10^{-4}
Lb/ft^2	2116.22	2088.5	2.0885 x 10^{-3}	70.726	5.202	0.2048	144.0	1	2.7844	2.7844 x 10^{-3}	2.089 x 10^{-2}
mm of Hg torr	760	750.06	7.5006 x 10^{-4}	25.400	1.868	7.3558 x 10^{-2}	51.715	0.35913	1	10^{-3}	7.502 x 10^{-3}
Microns	760 x 10^3	750.06 x 10^3	0.75006	2.54 x 10^4	1.868 x 10^3	73.558	51.715 x 10^3	359.1	1 x 10^3	1	7.502
Pascals	1.01325 x 10^5	1 x 10^{-1}	10^{-1}	3.386 x 10^3	2.491 x 10^2	9.8067	6.8948 x 10^3	4.788 x 10^1	1.333 x 10^2	1.333 x 10^{-1}	1

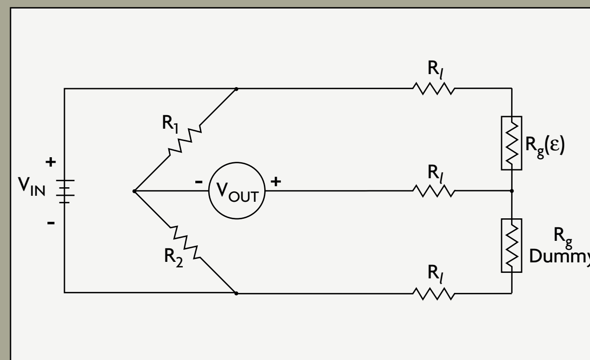
STRAIN GAGE BRIDGE CIRCUITS AND EQUATIONS

Equations compute strain from unbalanced bridge voltages:

- Sign is correct for V_{IN} and V_{OUT} as shown
- GF = Gage Factor ν = Poisson's Ratio
- $V_r = [(V_{OUT}/V_{IN})\text{strained} - (V_{OUT}/V_{IN})\text{unstrained}]$
- ε = Strain; multiply by 10^6 for micro-strain
- Tensile is (+) and compressive is (-)

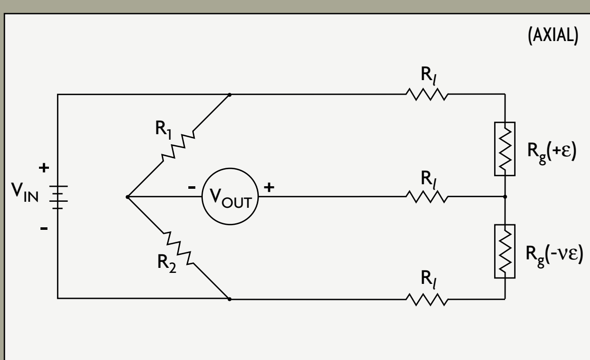
QUARTER BRIDGE CONFIGURATIONS

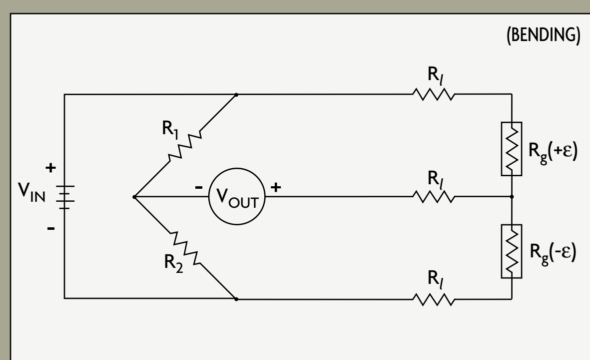




$$\varepsilon = \frac{-4V_r}{GF(1 + 2V_r)} \cdot \left(1 + \frac{R_l}{R_g}\right)$$

HALF BRIDGE CONFIGURATIONS

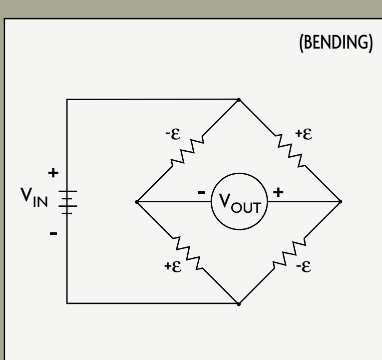


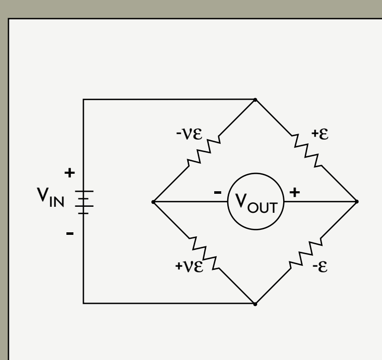


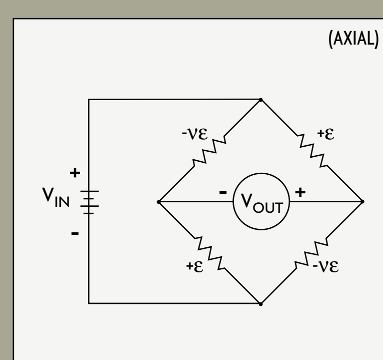
$$\varepsilon = \frac{-4V_r}{GF[(1 + \nu)-2V_r(\nu - 1)]} \cdot \left(1 + \frac{R_l}{R_g}\right)$$

$$\varepsilon = \frac{-2V_r}{GF} \cdot \left(1 + \frac{R_l}{R_g}\right)$$

FULL BRIDGE CONFIGURATIONS



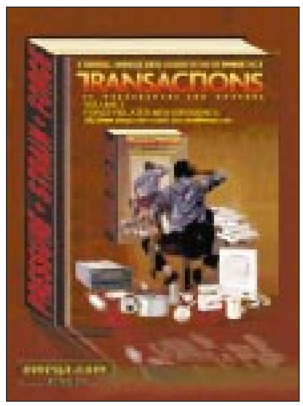




$$\varepsilon = \frac{-V_r}{GF}$$

$$\varepsilon = \frac{-2V_r}{GF(\nu + 1)}$$

$$\varepsilon = \frac{-2V_r}{GF[(\nu + 1)-V_r(\nu - 1)]}$$



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VOLUME
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TABLE OF CONTENTS

TRANSACTIONS

IN MEASUREMENT AND CONTROL

VOLUME 3—FORCE-RELATED MEASUREMENTS

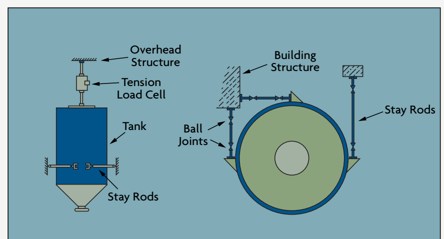

Figure 1-6: Tank "Staying" Designs

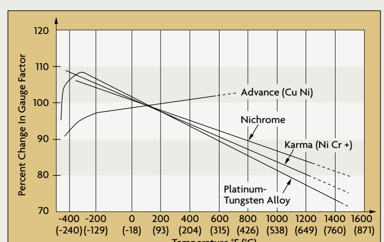

Figure 2-11: Gage Factor Temperature Dependence

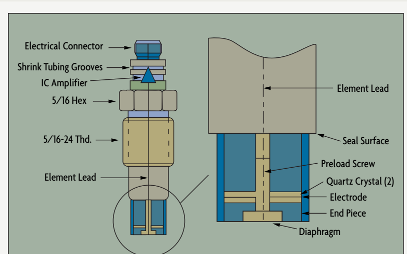

Figure 3-8: Typical Piezoelectric Pressure Sensor

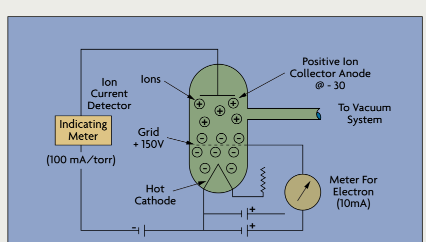

Figure 4-7: Hot-Cathode Vacuum Gauge

REFERENCE SECTIONS

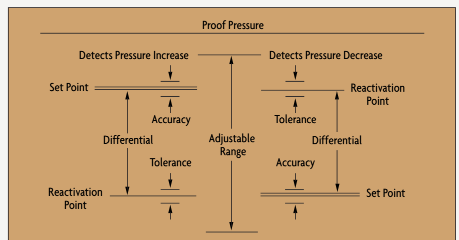

Figure 5-3: Pressure Switch Terminology

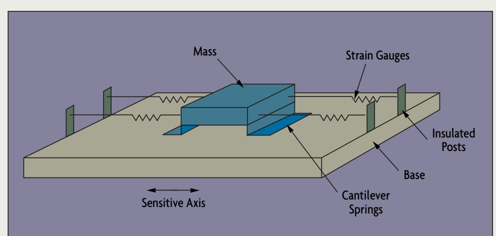

Figure 6-3: Piezoelectric Sensor Element Designs

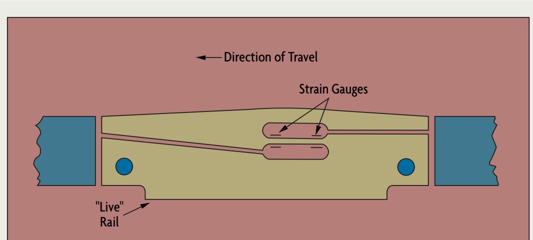

Figure 8-6: Monorail Weighing Transducer

Solutions—More Than Just Sensors

This third volume in OMEGA's Transactions in Measurement & Control series explores the full gamut of force-related instrumentation technologies—devices for measuring a range of kindred variables from acceleration to pressure to torque to weight.

The sensor and transducer technologies that underlie these superficially different variables have quite a lot in common. Pressure, for example, is simply a force applied over an area, acceleration is a force with the mass divided out, and weight is a force resisting the pull of the earth's gravity. Indeed, the primary differences among the technologies discussed in the chapters that follow is in the painstaking engineering that has optimized the physical phenomena behind devices such as the strain gage into instruments precisely tailored to your specific application requirements.

But sensors and transducers are only the first element of what it takes to perform a meaningful measurement. Once a particular sensor has been chosen, many other decisions often must still be made. Power supply, signal conditioning, panel display or other host system—even the electrical connectors, tubing, and fittings—must be properly specified to fully satisfy your complete measurement needs. Nobody comes to OMEGA simply needing a strain gage or load cell; they need a solution to a measurement and control problem. And nobody can fill that bill like OMEGA.

At OMEGA, we believe it's this ability to provide you with a complete solution, teamed with exceptional service, that keeps thousands of satisfied customers coming back. Sure, it helps that we've got more than 40,000 products at our beck and call, but whether your solution demands a custom-engineered product in OEM quantities or simply application engineering assistance for a single installation, rest assured we've got you covered.

We hope you find this issue of Transactions useful and that it finds a permanent home on your reference shelf. And if the first two issues on "Non-Contact Temperature Measurement" and "Data Acquisition" somehow missed you, visit us on the web at www.omega.com for your complementary copies.

Mrs. Betty Ruth Hollander
Chairman-CEO
OMEGA Technologies

P.S. If you wish to submit an article of relevance for future issues of *Transactions*, please submit to my attention via mail (P.O. Box 4047, Stamford, CT 06907), FAX (203-359-7700), or e-mail (info@omega.com).

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OMEGA's *Transactions in Measurement & Control* series, as well as our legendary set of handbooks and encyclopedias, are designed to provide at-your-fingertips access to the technical information you need to help meet your measurement and control requirements. But when your needs exceed the printed word—when technical assistance is required to select among alternative products, or when no "off-the-shelf" product seems to fill the bill—we hope you'll turn to OMEGA. There is no advertising or promotional material in the *Transactions* series. There will be none.

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A Historical Perspective

The existence of life itself has been attributed over the ages to an underlying "force." Life is manifested by change and movement—it involves actions and interactions of a variety of forces. Therefore, no measurement is more fundamental to human activity than the measurement of force in its many manifestations, including weight, pressure, acceleration, torque, work, and energy.

The purpose of this first chapter is to trace the historical evolution of the understanding of force and of the theories which evolved at various stages of human development. While the ancient civilizations of 8,000 to 6,000 B.C., in the river valleys of Southwest Asia, Mesopotamia or Egypt and others in China, India, and South America, all used lever and roller systems to amplify the muscle power of men, the first attempts to formalize a theoretical understanding of force were in ancient Greece.

From Aristotle to Hawking

The ancient Greek philosophers considered themselves qualified to make pronouncements in the field of science, but their views had little to do with the real world. Aristotle (384-322 B.C.), for example, believed that "form" caused matter to move. He defined motion as the process by which the "potentiality" of matter became the "actuality" of form. With that view of reality, it is no wonder that the Greeks of Aristotle's time created much more art than technology.

Yet, a hundred years later, the Greek physicist Archimedes (287-212 B.C.) became a pioneer of real engineering experimentation. He not only discovered the force-amplifying capability of the pulley, but also noted that the same weight of gold will displace less water than does an equal weight of silver.

Some 400 years later, the astronomer Clausius Ptolemaeus (second century A.D.) developed the first model of planetary movements. He assumed the Earth as being stationary in the center of the universe, with the Sun, Moon and stars revolving around it in circular orbits. The first revision of the Ptolemaic system came a millennium later; Nicholas Copernicus (1473-1543) replaced the Earth with the Sun as the center of the universe (a heliocentric system). Because he still did not understand the role of the force of gravity, however, he, too, assumed that the planets traveled in perfect circles.

Another century passed before Galileo Galilei (1564-1642) discovered, by dropping various items from the Leaning Tower of Pisa, that the velocity of a falling object is independent of its weight. His attitude was that of a good engineer: "I don't know why, but it works, so don't forget it!"

Johannes Kepler (1571-1630), who correctly established that the orbits of the planets about the Sun are elliptical, did not realize the cause of all this: the force of gravity. He noted that the Sun had some "mysterious power or virtue" which compelled the planets to hold to their orbits. The role of gravity escaped even Blaise Pascal (1623-1662), although he did correctly explain some related phenomena such as pressure and barometric pressure. It was also Pascal who first noted that, when pressure is applied to a confined fluid, the pressure is transmitted undiminished in all directions. It is for these discoveries that we honor him by using his name (in the SI system) as the unit of pressure.

The role of the force of gravity

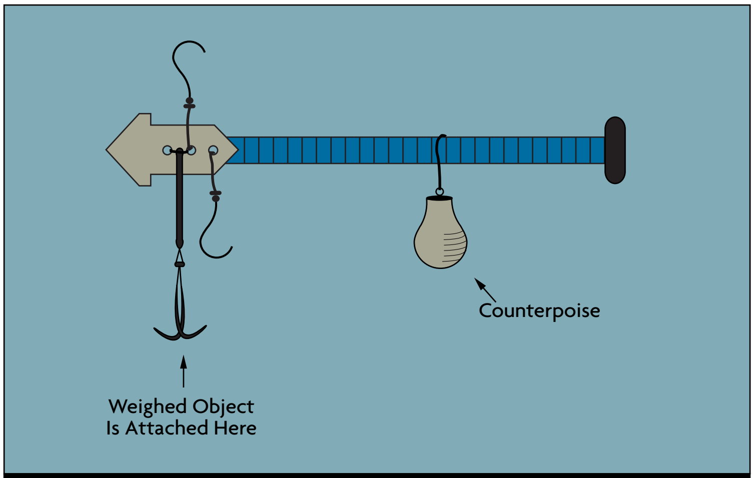

Figure 1-1: Steelyard for Weight Comparison

was first fully understood by Sir Isaac Newton (1642-1727). His law of universal gravitation explained both the fall of bodies on Earth and the motion of heavenly bodies. He proved that gravitational attraction exists between any two material objects. He also noted that this force is directly proportional to the product of the masses of the objects and inversely proportional to the square of the

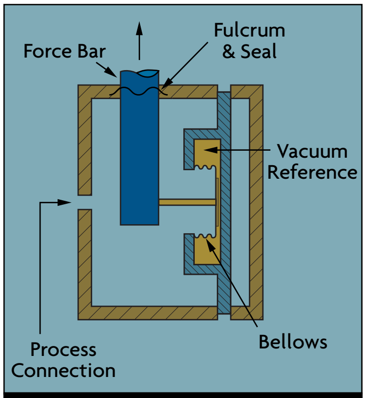

Figure 1-2: Vacuum Reference Gauge

distance between them. On the Earth's surface, the measure of the force of gravity on a given body is its weight. The strength of the Earth's gravitational field (g) varies from 9.832 m/sec^2 at sea level at the poles to 9.78 m/sec^2 at sea level at the Equator.

Newton summed up his understanding of motion in three laws:

1) The law of inertia: A body displays an inherent resistance to changing its speed or direction. Both a body at rest and a body in motion tend to remain so.

2) The law of acceleration: Mass (m) is a numerical measure of inertia. The acceleration (a) resulting from a force (F) acting on a mass can be expressed in the equation $a = F/m$; therefore, it can be seen that the greater the mass (inertia) of a body, the less acceleration will result from the application of the same amount of force upon it.

3) For every action, there is an equal and opposite reaction.

After Newton, progress in understanding force-related phenomena slowed. James Prescott Joule (1818-1889) determined the relationship between heat and the various mechanical forms of energy. He also established that energy cannot be lost, only transformed (the principle of conservation of energy), defined potential energy (the capacity for doing work), and established that work performed (energy expended) is the product of the amount of force applied and the distance traveled. In recognition of his contributions, the unit of work and energy in the SI system is called the joule.

Albert Einstein (1879-1955) contributed another quantum jump in our understanding of force-related phenomena. He established the speed of light (c = 186,000 miles/sec) as the maximum theoretical speed that any object with mass can travel, and that mass (m) and energy (e) are equivalent and interchangeable: $e = mc^2$.

Einstein's theory of relativity corrected the discrepancies in Newton's theory and explained them geometrically: concentrations of matter cause a curvature in the space-time continuum, resulting in "gravity waves." While making enormous contributions to the advancement of science, the goal of developing a unified field theory (a single set of laws that explain gravitation, electromagnetism, and subatomic phenomena) eluded Einstein.

Edwin Powell Hubble (1889-1953) improved our understanding of the universe, noting that it looks the same from all positions, and in all directions, and that distances between galaxies are continuously increasing. According to Hubble, this expansion of the universe started 10 to 20 billion years ago with a "big bang," and the space-time fabric which our universe occupies continues to expand.

Carlo Rubbia (1934-) and Simon van der Meer (1925-) further advanced our understanding of force by discovering the subatomic W and Z particles which convey the "weak force" of atomic decay. Stephen Hawking (1952-) advanced our understanding even further with his theory of strings. Strings can be thought of as tiny vibrating loops from which both matter and energy derive. His theory holds the promise of unifying Einstein's theory of relativity, which explains gravity and the forces acting in the macro world, with quantum theory, which describes the forces acting on the atomic and subatomic levels.

Force & Its Effects

Force is a quantity capable of changing the size, shape, or motion of an object. It is a vector quantity and, as such, it has both direction and magnitude. In the SI system, the

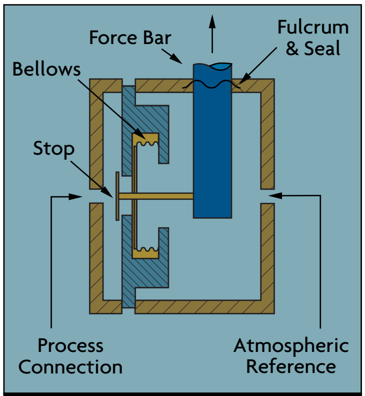

Figure 1-3: Atmospheric Reference Gauge

magnitude of a force is measured in units called newtons, and in pounds in the British/American system. If a body is in motion, the energy of that motion can be quantified as the momentum of the object, the product of its mass and its velocity. If a body is free to move, the action of a force will change the velocity of the body.

There are four basic forces in nature: gravitational, magnetic, strong nuclear, and weak nuclear forces. The weakest of the four is the gravitational force. It is also the easiest to observe, because it acts on all matter and it is always attractive, while having an infinite range. Its attraction decreases with distance, but is always measurable. Therefore, positional "equilibrium" of a body can only be achieved when gravitational pull is balanced by another force, such as the upward force exerted on our feet by the earth's surface.

Pressure is the ratio between a force acting on a surface and the area of that surface. Pressure is measured in units of force divided by area: pounds per square inch (psi) or, in the SI system, newtons per square meter, or pascals. When an external stress (pressure) is applied to an object with the intent to cause a reduction in its volume, this process is called compression. Most liquids and solids are practically incompressible, while gases are not.

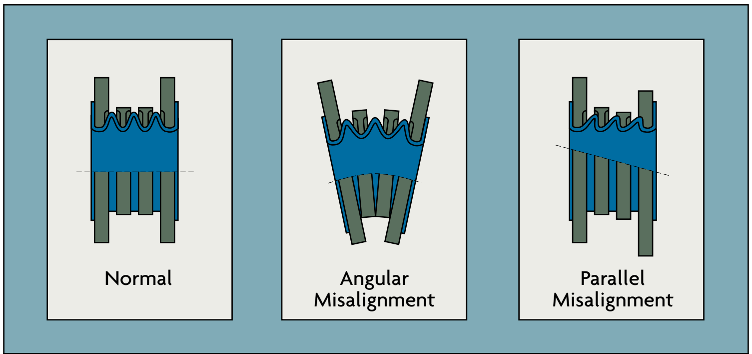

Figure 1-4: Flexible Load-Cell Connections

The First Gas Law, called Boyle's law, states that the pressure and volume of a gas are inversely proportional to one another: PV = k, where P is pressure, V is volume and k is a constant of proportionality. The Second Gas Law, Charles' Law, states that the volume of an enclosed gas is directly proportional to its temperature: V = kT, where T is its absolute temperature. And, according to the Third Gas Law, the pressure of a gas is directly proportional to its absolute temperature: P = kT.

Combining these three relationships yields the ideal gas law: PV = kT. This approximate relationship holds true for many gases at relatively low pressures (not too close to the point where liquification occurs) and high temperatures (not too close to the point where condensation is imminent).

Measurement Limitations

One of the basic limitations of all measurement science, or metrology, is that all measurements are relative. Therefore, all sensors contain a reference point against which the quantity to be measured must be compared. The steelyard was one of mankind's first relative sensors, invented to measure the weight of an object (Figure 1-1). It is a beam supported from hooks (A or B), while the object to be weighed is attached to the shorter arm of the lever and a counterpoise is moved along the longer arm until balance is established. The precision of such weight scales depends on the precision of the reference weight (the counterpoise) and the accuracy with which it is positioned.

Similarly, errors in pressure measurement are as often caused by inaccurate reference pressures as they are by sensor inaccuracies. If absolute pressure is to be detected, the reference pressure (theoretically) should be zero—a complete vacuum. In reality, a reference chamber cannot be evacuated to absolute zero (Figure 1-2), but only to a few thousandths of a millimeter of mercury (torr). This means that a nonzero quantity is used as a zero reference. Therefore, the higher that reference pressure, the greater the resulting error. Another source of error in absolute pressure measurement is the loss of the vacuum reference due to the intrusion of air.

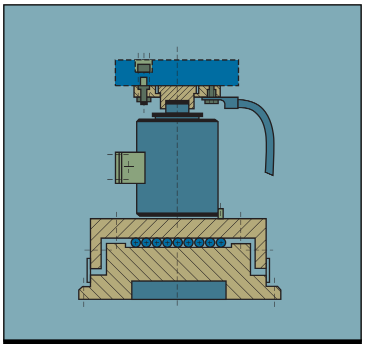
Figure 1-5: Typical Load Cell Installation

In the case of "gauge" pressure measurement, the reference is atmospheric pressure, which is itself variable (Figure 1-3). Thus, sensor output can change not because there is a change in the process pressure, but because the reference pressure is changing. The barometric pressure can change by as much as an inch of mercury (13.6 inches of water), which in some compound measurements can result in excessive and intolerable errors. By definition, a compound pressure detector measures near atmospheric pressures, both above and below atmospheric.

Consider, for example, a blanketed chemical reactor. A typical case is a reactor which (when empty) needs to be evacuated to an absolute pressure of 10 torr. After evacuation, it must be purged with an inert gas, while the pressure in the reactor is maintained at 1 in. of water above atmospheric. No pressure sensor provided with a single reference is capable of detecting both of these pressures. If a vacuum reference is used, the purge setting of 1 in. water cannot be maintained, because the instrument does not know what the barometric pressure is. On the other hand, if a barometric reference is used, the 10-torr vacuum cannot be measured because the reference can change by more than the total value of the measurement—as much as 25 torr.

Today, with microprocessors, it would be possible to provide the same pressure sensor with two references and allow the intelligence of the unit to decide which reference should be used for a particular measurement.

Another important consideration in force-related measurements is the elimination of all force components which are unrelated to the measurement. For example, if the goal is to measure the weight of the contents of a tank or reactor, it is essential to install the vessel in such a way that the tank will behave as a free body in the vertical but will be rigidly held and protected from horizontal or rotary movement. This is much more easily said than done.

Freedom for the vessel to move in the vertical direction is achieved if the tank is supported by nothing but the load cells. (The amount of vertical deflection in modern load cells is less than 0.01 in.) This means that all pipes, electrical conduits, and stay rods connected to the vessel must be designed to offer no resistance to vertical movement. In pressurized reactors, this usually requires the use of flexible piping connections installed in the horizontal plane (Figure 1-4) and ball joints in the stay rods. For best results in larger pipes, two horizontal flexible couplings are typically installed in series.

It is equally important to protect and isolate the load cells from horizontal forces. These forces can be caused by thermal expansion or by the acceleration and deceleration of vehicles on active weighing platforms. Therefore, it is essential that load cells be either free to move in the horizontal (Figure 1-5) or be provided with an adaptor that transmits virtually no side load. In addition, tanks—particularly agitated reactors—should be stayed, that is, protected from rotary motion. This is achieved by installing three stay rods, each with two ball joints (Figure 1-6).

The art of weighing requires a lot of common sense. A successful weighing system requires that tank supports be rigid and be located above the vessel's center of gravity for stability. This is particularly important outdoors, where outside forces such as the wind need to be considered. It is also important that the load be evenly distributed among the load cells. This consideration necessitates that all load buttons be positioned in the same plane. Since three points define a plane, equal load distribution is easiest to achieve by using three load cells.

Common sense also tells us that the accuracy of an installation will not match the precision of the load cells (which is usually 0.02% or better) if the full load is not being measured or if the load cells are not properly calibrated. The precision of high quality load cells does little good if they are calibrated against flowmeters with errors of 1% or more. The only way to take full advantage of the remarkable capabilities of accurate modern load

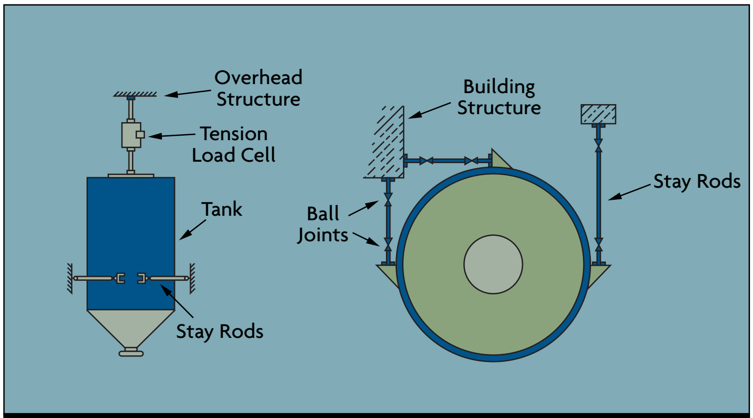

Figure 1-6: Tank "Staying" Designs

cells is to zero and calibrate the system using precision dead weights. It is also important to remember that dead weights can only be attached to a reactor if hooks or platforms are provided for them.

Range considerations also are important because load cells are percent-of-full-scale devices. This means that the absolute error corresponding to, say, 0.02% is a function of the total weight being measured. If the total weight is 100,000 pounds, the absolute error is 20 pounds. But if one needs to charge a batch of 100 pounds of catalyst into that same reactor, the error will be 20%, not 0.02%.

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The Strain Gage

When external forces are applied to a stationary object, stress and strain are the result. Stress is defined as the object's internal resisting forces, and strain is defined as the displacement and deformation that occur. For a uniform distribution of internal resisting forces, stress can be calculated (Figure 2-1) by dividing the force (F) applied by the unit area (A):

Stress (σ) = F/A

Strain is defined as the amount of deformation per unit length of an object when a load is applied. Strain is calculated by dividing the total deformation of the original length by the original length (L):

Strain (ε) = (Δ L)/L

Typical values for strain are less than 0.005 inch/inch and are often expressed in micro-strain units:

Micro-strain = Strain x 10^6

Strain may be compressive or tensile and is typically measured by strain gages. It was Lord Kelvin who first reported in 1856 that metallic conductors subjected to mechanical strain exhibit a change in their electrical resistance. This phenomenon was first put to practical use in the 1930s.

Fundamentally, all strain gages are designed to convert mechanical motion into an electronic signal. A change in capacitance, inductance, or resistance is proportional to the strain experienced by the sensor. If a wire is held under tension, it gets slightly longer and its cross-sectional area is reduced. This changes its resistance (R) in proportion to the strain sensitivity (S) of the wire's resistance. When a strain is introduced, the strain sensitivity, which is also called the gage factor (GF), is given by:

GF = (Δ R/R)/(Δ L/L) = (Δ R/R)/ Strain

The ideal strain gage would change resistance only due to the deformations of the surface to which the sensor is attached. However, in real applications, temperature, material properties, the adhesive that bonds the gage to the surface, and the stability of the metal all affect the detected resistance. Because most materials do not have the same properties in all directions, a knowledge of the axial strain alone is insufficient for a complete analysis. Poisson, bending, and torsional strains also need to be measured. Each requires a different strain gage arrangement.

Shearing strain considers the angular distortion of an object under stress. Imagine that a horizontal force is acting on the top right corner of a thick book on a table, forcing the book to become somewhat trapezoidal (Figure 2-2). The shearing strain in this case can be expressed as the angular change in radians between the vertical y-axis and the new position. The shearing strain is the tangent of this angle.

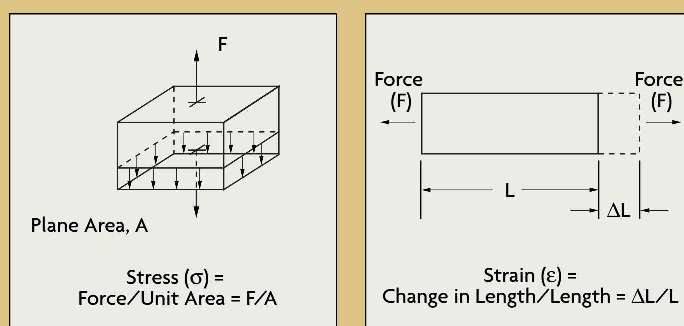


Figure 2-1: Definitions of Stress & Strain

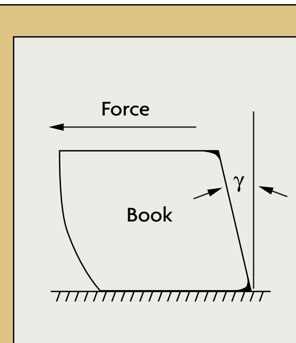


Figure 2-2: Shearing Strain

Poisson strain expresses both the thinning and elongation that occurs in a strained bar (Figure 2-3). Poisson strain is defined as the negative ratio of the strain in the traverse direction (caused by the contraction of the bar's diameter) to the strain in the longitudinal direction. As the length increases and the cross sectional area decreases, the electrical resistance of the wire also rises.

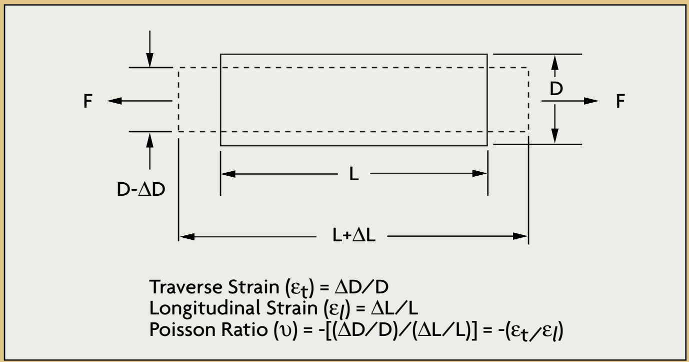


Figure 2-3: Poisson Strain

Bending strain, or moment strain, is calculated by determining the relationship between the force and the amount of bending which results from it. Although not as commonly detected as the other types of strain, torsional strain is measured when the strain produced by twisting is of interest. Torsional strain is calculated by dividing the torsional stress by the torsional modulus of elasticity.

Sensor Designs

The deformation of an object can be measured by mechanical, optical, acoustical, pneumatic, and electrical means. The earliest strain gages were mechanical devices that measured strain by measuring the change in length and comparing it to the original length of the object. For example, the extension meter (extensiometer) uses a series of levers to amplify strain to a readable value. In general, however, mechanical devices tend to provide low resolutions, and are bulky and difficult to use.

Optical sensors are sensitive and accurate, but are delicate and not very popular in industrial applications. They use interference fringes produced by optical flats to measure strain. Optical sensors operate best under laboratory conditions.

The most widely used characteristic that varies in proportion to strain is electrical resistance. Although capacitance and inductance-based strain gages have been constructed, these devices' sensitivity to vibration, their mounting requirements, and circuit complexity have limited their application. The photoelectric gage uses a light beam, two fine gratings, and a photocell detector to generate an electrical current that is proportional to strain. The gage length of these devices can be as short as 1/16 inch, but they are costly and delicate.

The first bonded, metallic wire-type strain gage was developed in 1938. The metallic foil-type strain gage consists of a grid of wire filament

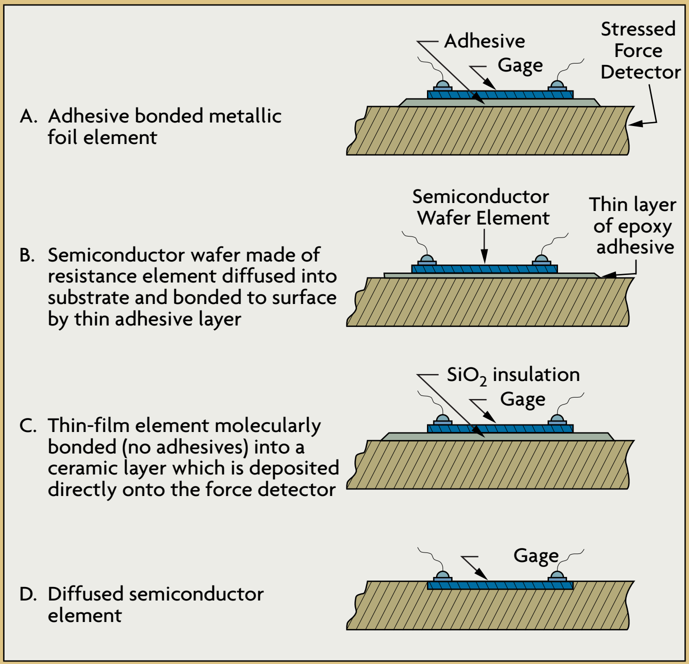


Figure 2-4: Strain Gage Designs

(a resistor) of approximately 0.001 in. (0.025 mm) thickness, bonded directly to the strained surface by a thin layer of epoxy resin (Figure 2-4A). When a load is applied to the surface, the resulting change in surface length is communicated to the resistor and the corresponding strain is measured in terms of the electrical resistance of the foil wire, which varies linearly with strain. The foil diaphragm and the adhesive bonding agent must work together in transmitting the strain, while the adhesive must also serve as an electrical insulator between the foil grid and the surface.

When selecting a strain gage, one must consider not only the strain characteristics of the sensor, but also its stability and temperature sensitivity. Unfortunately, the most desirable strain gage materials are also sensitive to temperature variations and tend to change resistance as they age. For tests of short duration, this may not be a serious concern, but for continuous industrial measurement, one must include temperature and drift compensation.

Each strain gage wire material has its characteristic gage factor, resistance, temperature coefficient of gage factor, thermal coefficient of resistivity, and stability. Typical materials include Constantan (copper-nickel alloy), Nichrome V (nickel-chrome alloy), platinum alloys (usually tungsten), Isoelastic (nickel-iron alloy), or Karma-type alloy wires (nickel-chrome alloy), foils, or semiconductor materials. The most popular alloys used for strain gages are copper-nickel alloys and nickel-chromium alloys.

In the mid-1950s, scientists at Bell Laboratories discovered the piezoresistive characteristics of germanium and silicon. Although the materials exhibited substantial nonlinearity and temperature sensitivity, they had gage factors more than fifty times, and sensitivity more than a 100 times, that of metallic wire or foil strain gages. Silicon wafers are also more elastic than metallic ones. After being strained, they return more readily to their original shapes.

Around 1970, the first semiconductor (silicon) strain gages were developed for the automotive industry. As opposed to other types of strain gages, semiconductor strain gages depend on the piezoresistive effects of silicon or germanium and measure the change in resistance with stress as opposed to strain. The semiconductor bonded strain gage is a wafer with the resistance element diffused into a substrate of silicon. The wafer element usually is not provided with a backing, and bonding it to the strained surface requires great care as only a thin layer of epoxy is used to attach it (Figure 2-4B). The size is much smaller and the cost much lower than for a metallic foil sensor. The same epoxies that are used to attach foil gages also are used to bond semiconductor gages.

While the higher unit resistance and sensitivity of semiconductor wafer sensors are definite advantages, their greater sensitivity to temperature variations and tendency to drift are disadvantages in comparison to metallic foil sensors. Another disadvantage of semiconductor strain gages is that the resistance-to-strain relationship is nonlinear, varying 10-20% from a straight-line equation. With computer-controlled instrumentation, these limitations can be overcome through software compensation.

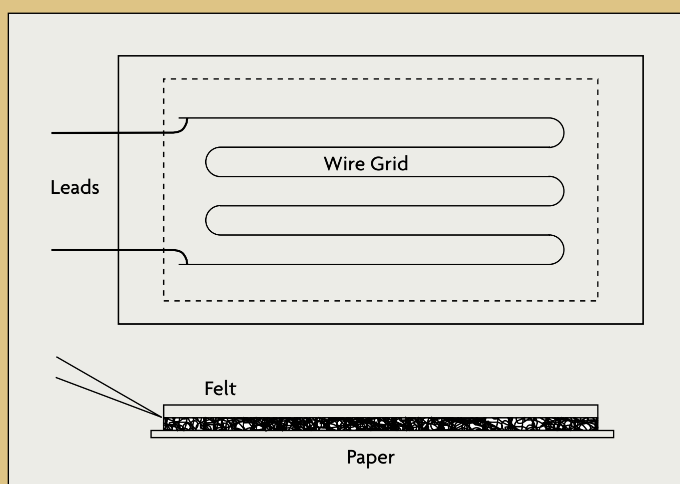


Figure 2-5: Bonded Resistance Strain Gage Construction

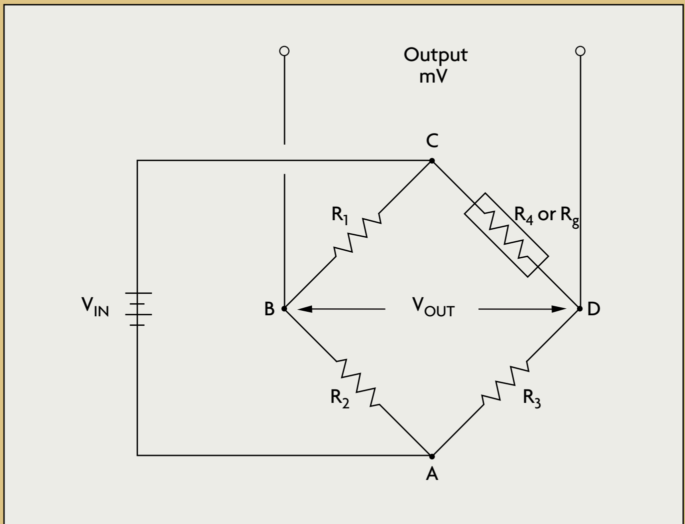
A further improvement is the thin-film strain gage that eliminates the need for adhesive bonding (Figure 2-4C). The gage is produced by first depositing an electrical insulation (typically a ceramic) onto the stressed metal surface, and then depositing the strain gage onto this insulation layer. Vacuum deposition or sputtering techniques are used to bond the materials molecularly.

Because the thin-film gage is molecularly bonded to the specimen, the installation is much more stable and the resistance values experience less drift. Another advantage is that the stressed force detector can be a metallic diaphragm or beam with a deposited layer of ceramic insulation.

Diffused semiconductor strain gages represent a further improvement in strain gage technology because they eliminate the need for bonding agents. By eliminating bonding agents, errors due to creep and hysteresis also are eliminated. The diffused semiconductor strain gage uses photolithography masking techniques and solid-state diffusion of boron to molecularly bond the resistance elements. Electrical leads are directly attached to the pattern (Figure 2-4D).

The diffused gage is limited to moderate-temperature applications and requires temperature compensation. Diffused semiconductors often are used as sensing elements in pressure transducers. They are small, inexpensive, accurate and repeatable, provide a wide pressure range, and generate a strong output signal. Their limitations include sensitivity to ambient temperature variations, which can be compensated for in intelligent transmitter designs.

In summary, the ideal strain gage is small in size and mass, low in cost, easily attached, and highly sensitive to strain but insensitive to ambient or process temperature variations.



$$V_{OUT} = V_{IN}\left[\frac{R_3}{R_3 + R_g} - \frac{R_2}{R_1 + R_2}\right]$$

Figure 2-6: Wheatstone Bridge Circuit Schematic

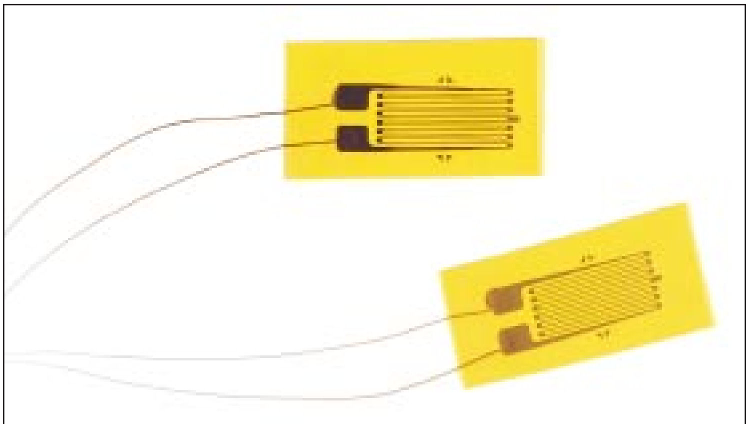
Bonded Resistance Gages

The bonded semiconductor strain gage was schematically described in Figures 2-4A and 2-4B. These devices represent a popular method of measuring strain. The gage consists of a grid of very fine metallic wire, foil, or semiconductor material bonded to the strained surface or carrier matrix by a thin insulated layer of epoxy (Figure 2-5). When the carrier matrix is strained, the strain is transmitted to the grid material through the adhesive. The variations in the electrical resistance of the grid are measured as an indication of strain. The grid shape is designed to provide maximum gage resistance while keeping both the length and width of the gage to a minimum.

Bonded resistance strain gages have a good reputation. They are relatively inexpensive, can achieve overall accuracy of better than ±0.10%, are available in a short gage length, are only moderately affected by temperature changes, have small physical size and low mass, and are highly sensitive. Bonded resistance strain gages can be used to measure both static and dynamic strain.

In bonding strain gage elements to a strained surface, it is important that the gage experience the same strain as the object. With an adhesive material inserted between the sensors and the strained surface, the installation is sensitive to creep due to degradation of the bond, temperature influences, and hysteresis caused by thermoelastic strain. Because many glues and epoxy resins are prone to creep, it is important to use resins designed specifically for strain gages.

The bonded resistance strain gage is suitable for a wide variety of environmental conditions. It can measure strain in jet engine turbines operating at very high temperatures and in cryogenic fluid applications at temperatures as low as -452°F (-269°C). It has low mass and size, high sensitivity, and is suitable for static and dynamic



Typical metal-foil strain gages.

applications. Foil elements are available with unit resistances from 120 to 5,000 ohms. Gage lengths from 0.008 in. to 4 in. are available commercially. The three primary considerations in gage selection are: operating temperature, the nature of the strain to be detected, and stability requirements. In addition, selecting the right carrier material, grid alloy, adhesive, and protective coating will guarantee the success of the application.

Measuring Circuits

In order to measure strain with a bonded resistance strain gage, it must be connected to an electric circuit that is capable of measuring the minute changes in resistance corresponding to strain. Strain gage transducers usually employ four strain gage elements electrically connected to form a Wheatstone bridge circuit (Figure 2-6).

A Wheatstone bridge is a divided bridge circuit used for the measurement of static or dynamic electrical resistance. The output voltage of the Wheatstone bridge is expressed in millivolts output per volt input. The Wheatstone circuit is also well suited for temperature compensation.

In Figure 2-6, if R_1, R_2, R_3, and R_4 are equal, and a voltage, V_{IN}, is applied between points A and C, then the output between points B and D will show no potential difference.

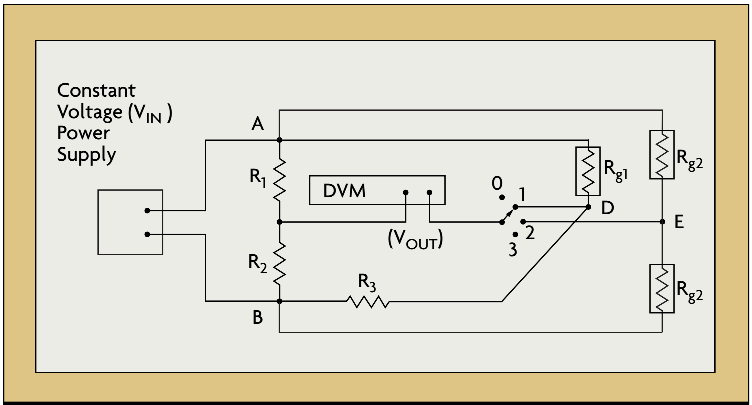


Figure 2-7: Chevron Bridge Circuit Schematic

However, if R_4 is changed to some value which does not equal R_1, R_2, and R_3, the bridge will become unbalanced and a voltage will exist at the output terminals. In a so-called ¼-bridge configuration, the variable strain sensor has resistance R_g, while the other arms are fixed value resistors.

The sensor, however, can occupy one, two, or four arms of the bridge, depending on the application. The total strain, or output voltage of the circuit (V_{OUT}) is equivalent to the difference between the voltage drop across R_1 and R_4, or R_g. This can also be written as:

$$V_{OUT} = V_{CD} - V_{CB}$$

For more detail, see Figure 2-6. The bridge is considered balanced when $R_1/R_2 = R_g/R_3$ and, therefore, V_{OUT} equals zero.

Any small change in the resistance of the sensing grid will throw the bridge out of balance, making it suitable for the detection of strain. When the bridge is set up so that R_g is the only active strain gage, a small change in R_g will result in an output voltage from the bridge. If the gage factor is GF, the strain measurement is related to the change in R_g as follows:

$$\text{Strain} = (\Delta R_g/R_g)/GF$$

The number of active strain gages that should be connected to the bridge depends on the application.

For example, it may be useful to connect gages that are on opposite sides of a beam, one in compression and the other in tension. In this arrangement, one can effectively double the bridge output for the same strain. In installations where all of the arms are connected to strain gages, temperature compensation is automatic, as resistance change due to temperature variations will be the same for all arms of the bridge.

In a four-element Wheatstone bridge, usually two gages are wired in compression and two in tension. For example, if R_1 and R_3 are in tension (positive) and R_2 and R_4 are in compression (negative), then the output will be proportional to the sum of all the strains measured separately. For gages located on adjacent legs, the bridge becomes unbalanced in proportion to the difference in strain. For gages on opposite legs, the bridge balances in proportion to the sum of the strains. Whether bending strain, axial strain, shear strain, or torsional strain is being measured, the strain gage arrangement will determine the relationship between the output and the type of strain being measured. As shown in Figure 2-6, if a positive tensile strain occurs on gages R_2 and R_3, and a negative strain is experienced by gages R_1 and R_4, the total output, V_{OUT}, would be four times the resistance of a single gage.

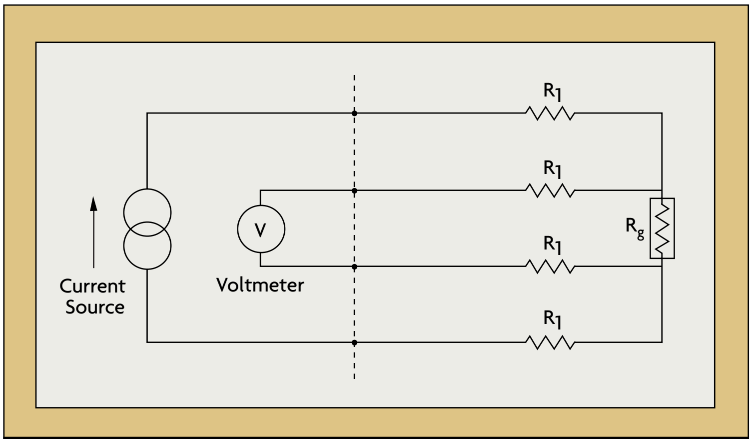


Figure 2-8: Four-Wire Ohm Circuit Schematic

The Chevron Bridge

The Chevron bridge is illustrated in Figure 2-7. It is a multiple channel arrangement that serves to compensate for the changes in bridge-arm resistances by periodically switching them. Here, the four channel positions are used to switch the digital voltmeter (DVM) between ¼-bridge (one active gage) and ½-bridge (two active gages) configurations. The DVM measurement device always shares the power supply and an internal ½-bridge. This arrangement is most popular for strain measurements on rotating machines, where it can reduce the number of slip rings required.

Four-Wire Ohm Circuit

Although the Wheatstone bridge is one of the most popular methods of measuring electrical resistance, other methods can also be used. The main advantage of a four-wire ohm circuit is that the lead wires do not affect the measurement because the voltage is detected directly across the strain gage element.

A four-wire ohm circuit installation might consist of a voltmeter, a current source, and four lead resistors, R_1, in series with a gage resistor, R_g (Figure 2-8). The voltmeter is connected to the ohms sense terminals of the DVM, and the current source is connected to the ohms source terminals of the DVM. To measure the value

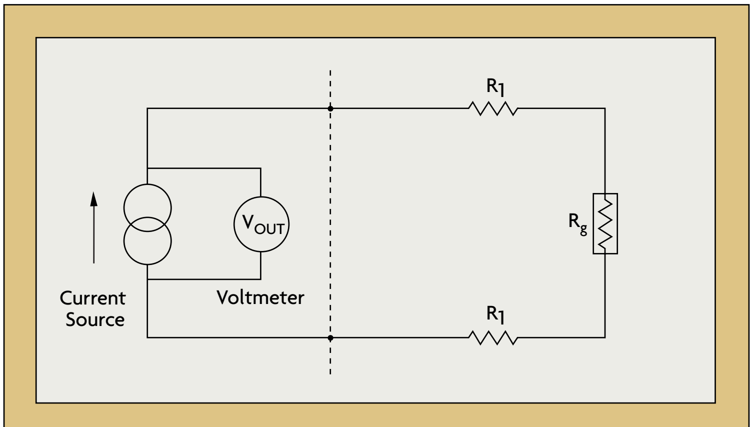


Figure 2-9: Constant Current Circuit Schematic

of strain, a low current flow (typically one milliampere) is supplied to the circuit. While the voltmeter measures the voltage drop across R_g, the absolute resistance value is computed by the multimeter from the values of current and voltage.

The measurement is usually done by first measuring the value of gage resistance in an unstrained condition and then making a second measurement with strain applied. The difference in the measured gage resistances divided by the unstrained resistance gives a fractional value of the strain. This value is used with the gage factor (GF) to calculate strain.

The four-wire circuit is also suitable for automatic voltage offset compensation. The voltage is first measured when there is no current flow. This measured value is then subtracted from the voltage reading when current is flowing. The resulting voltage difference is then used to compute the gage resistance. Because of their sensitivity, four-wire strain gages are typically used to measure low frequency dynamic strains. When measuring higher frequency strains, the bridge output needs to be amplified. The same circuit also can be used with a semiconductor strain-gage sensor and high speed digital voltmeter. If the DVM sensitivity is 100 microvolts, the current source is 0.44 milliamperes, the strain-gage element resistance is 350 ohms and its gage factor is 100, the resolution of the measurement will be 6 microstrains.

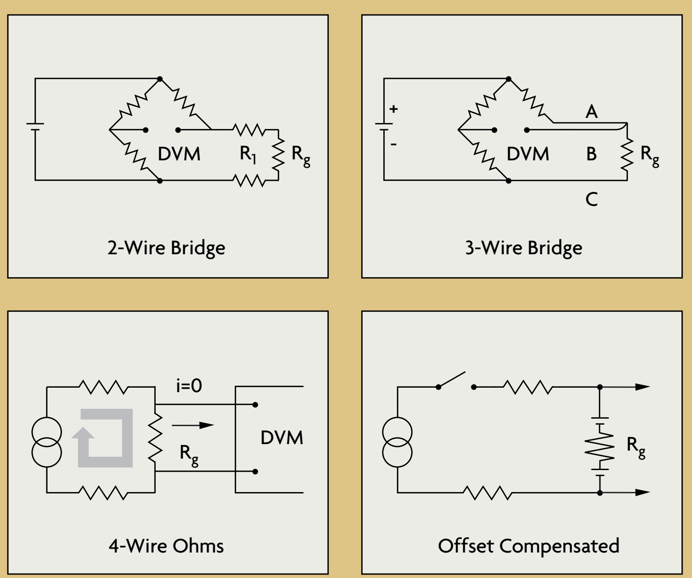


Figure 2-10: Alternative Lead-Wire Configurations

Constant Current Circuit

Resistance can be measured by exciting the bridge with either a constant voltage or a constant current source. Because R = V/I, if either V or I is held constant, the other will vary with the resistance. Both methods can be used.

While there is no theoretical advantage to using a constant current source (Figure 2-9) as compared to a constant voltage, in some cases the bridge output will be more linear in a constant current system. Also, if a constant current source is used, it eliminates the need to sense the voltage at the bridge; therefore, only two wires need to be connected to the strain gage element.

The constant current circuit is most effective when dynamic strain is being measured. This is because, if a dynamic force is causing a change in the resistance of the strain gage (R_g), one would measure the time varying component of the output (V_{OUT}), whereas slowly changing effects such as changes in lead resistance due to temperature variations would be rejected. Using this configuration, temperature drifts become nearly negligible.

Application & Installation

The output of a strain gage circuit is a very low-level voltage signal requiring a sensitivity of 100 microvolts or better. The low level of the signal makes it particularly susceptible to unwanted noise from other electrical devices. Capacitive coupling caused by the lead wires' running too close to AC power cables or ground currents are potential error sources in strain measurement. Other error sources may include magnetically induced voltages when the lead wires pass through variable magnetic fields, parasitic (unwanted) contact resistances of lead wires, insulation failure, and thermocouple effects at the junction of dissimilar metals. The sum of such interferences can result in significant signal degradation.

Shielding

Most electric interference and noise problems can be solved by shielding and guarding. A shield around the measurement lead wires will intercept interferences and may also reduce any errors caused by insulation degradation. Shielding also will guard the measurement from capacitive coupling. If the measurement leads are routed near electromagnetic interference sources such as transformers, twisting the leads will minimize signal degradation due to magnetic induction. By twisting the wire, the flux-induced current is inverted and the areas that the flux crosses cancel out. For industrial process applications, twisted and shielded lead wires are used almost without exception.

Guarding

Guarding the instrumentation itself is just as important as shielding the wires. A guard is a sheet-metal box surrounding the analog circuitry and is connected to the shield. If ground currents flow through the strain-gage element or its lead wires, a Wheatstone bridge circuit cannot distinguish them from the flow generated by the current source. Guarding guarantees that terminals of electrical components are at the same potential, which thereby prevents extraneous current flows.

Connecting a guard lead between the test specimen and the negative terminal of the power supply provides an additional current path around the measuring circuit. By placing a guard lead path in the path of an error-producing current, all of the elements involved (i.e., floating power supply, strain gage, all other measuring equipment) will be at the same potential as the test specimen. By using twisted and shielded lead wires and integrating DVMs with guarding, common mode noise error can virtually be eliminated.

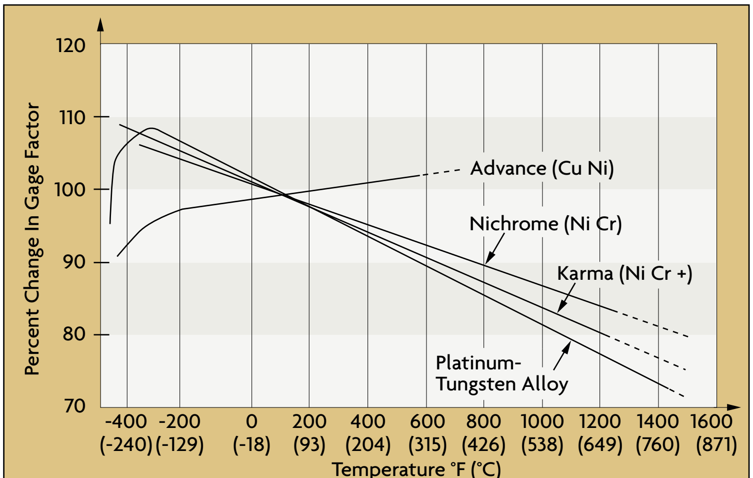


Figure 2-11: Gage-Factor Temperature Dependence

Lead-Wire Effects

Strain gages are sometimes mounted at a distance from the measuring equipment. This increases the possibility of errors due to temperature variations, lead desensitization, and lead-wire resistance changes. In a two-wire installation (Figure 2-10A), the two leads are in series with the strain-gage element, and any change in the lead-wire resistance (R_1) will be indistinguishable from changes in the resistance of the strain gage (R_g).

To correct for lead-wire effects, an additional, third lead can be introduced to the top arm of the bridge, as shown in Figure 2-10B. In this configuration, wire C acts as a sense lead with no current flowing in it, and wires A and B are in opposite legs of the bridge. This is the minimum acceptable method of wiring strain gages to a bridge to cancel at least part of the effect of extension wire errors. Theoretically, if the lead wires to the sensor have the same nominal resistance, the same temperature coefficient, and are maintained at the same temperature, full compensation is obtained. In reality, wires are manufactured to a tolerance of about 10%, and three-wire installation does not completely eliminate two-wire errors, but it does reduce them by an order of magnitude. If further improvement is desired, four-wire and offset-compensated installations (Figures 2-10C and 2-10D) should be considered.

In two-wire installations, the error introduced by lead-wire resistance is a function of the resistance ratio R_1/R_g. The lead error is usually not significant if the lead-wire resistance (R_1) is small in comparison to the gage resistance (R_g), but if the lead-wire resistance exceeds 0.1% of the nominal gage resistance, this source of error becomes significant. Therefore, in industrial applications, lead-wire lengths should be minimized or eliminated by locating the transmitter directly at the sensor.

Temperature and the Gage Factor

Strain-sensing materials, such as copper, change their internal structure at high temperatures. Temperature can alter not only the properties of a strain gage element, but also can alter the properties of the base material to which the strain gage is attached. Differences in expansion coefficients between the gage and base materials may cause dimensional changes in the sensor element.

Expansion or contraction of the strain-gage element and/or the base material introduces errors that are difficult to correct. For example, a change in the resistivity or in the temperature coefficient of resistance of the strain gage element changes the zero reference used to calibrate the unit.

The gage factor is the strain sensitivity of the sensor. The manufacturer should always supply data on the temperature sensitivity of the gage factor. Figure 2-11 shows the variation in gage factors of the various strain gage materials as a function of operating temperature. Copper-nickel alloys such as Advance have gage factors that are relatively sensitive to operating temperature variations, making them the most popular choice for strain gage materials.

Apparent Strain

Apparent strain is any change in gage resistance that is not caused by the strain on the force element. Apparent strain is the result of the interaction of the thermal coefficient of the strain gage and the difference in expansion between the gage and the test specimen. The variation in the apparent strain of various strain-gage materials as a function of operating temperature is shown in Figure 2-12. In addition to the temperature effects, apparent strain also can change because of aging and instability of the metal and the bonding agent.

Compensation for apparent strain is necessary if the temperature varies while the strain is being measured. In most applications, the amount of error depends on the alloy used, the accuracy required, and the amount of the temperature variation. If the operating temperature of the gage and the apparent strain characteristics are known, compensation is possible.

Stability Considerations

It is desirable that the strain-gage measurement system be stable and not drift with time. In calibrated instruments, the passage of time always causes some drift and loss of calibration. The stability of bonded strain-gage transducers is inferior to that of diffused strain-gage elements. Hysteresis and creeping caused by imperfect bonding is one of the fundamental causes of instability, particularly in high operating temperature environments.

Before mounting strain-gage elements, it should be established that the stressed force detector itself is uniform and homogeneous, because any surface deformities will result in instability errors. In order to remove any residual stresses in the force detectors, they should be carefully annealed, hardened, and stress-relieved using temperature aging. A transducer that uses force-detector springs, diaphragms, or bellows should also be provided with mechanical isolation. This will protect the sensor element from external stresses caused either by the strain of mounting or by the attaching of electric conduits to the transducer.

If stable sensors are used, such as deposited thin-film element types, and if the force-detector structure is well designed, balancing and compensation resistors will be sufficient

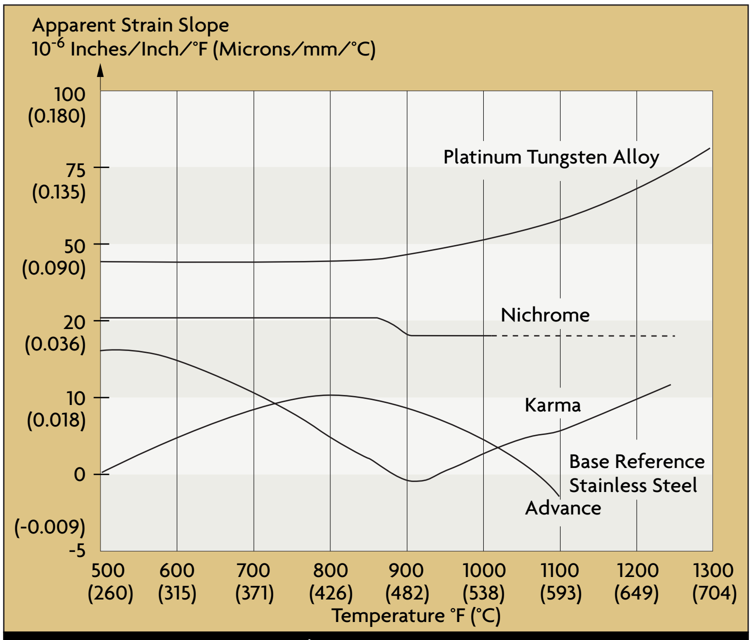


Figure 2-12: Apparent Strain Variation with Temperature

for periodic recalibration of the unit. The most stable sensors are made from platinum or other low-temperature coefficient materials. It is also important that the transducer be operated within its design limits. Otherwise, permanent calibration shifts can result. Exposing the transducer to temperatures outside its operating limits can also degrade performance. Similarly, the transducer should be protected from vibration, acceleration, and shock.

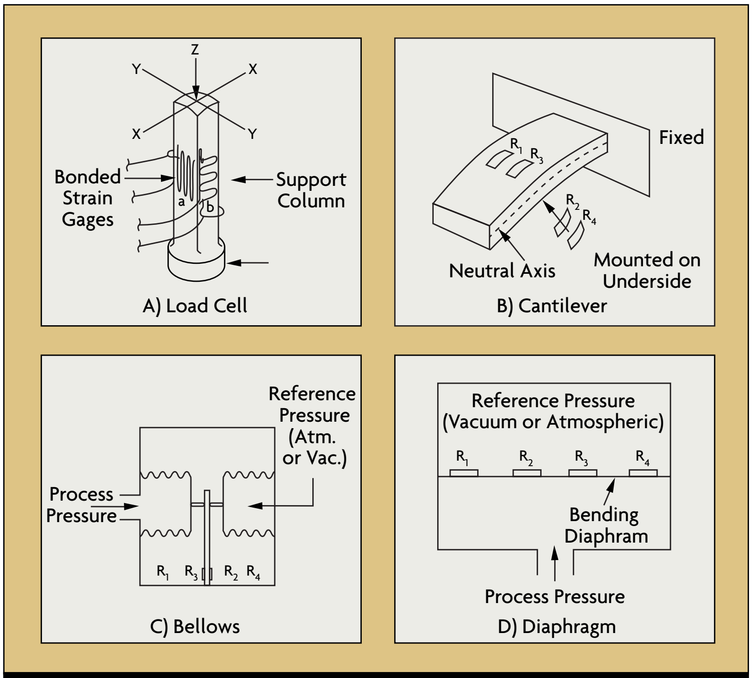


Figure 2-13: Strain Gage Installation Alternatives

Transducer Designs

Strain gages are used to measure displacement, force, load, pressure, torque or weight. Modern strain-gage transducers usually employ a grid of four strain elements electrically connected to form a Wheatstone bridge measuring circuit.

The strain-gage sensor is one of the most widely used means of load, weight, and force detection. In Figure 2-13A, a vertical beam is subjected to a force acting on the vertical axis. As the force is applied, the support column experiences elastic deformation and changes the electrical resistance of each strain gage. By the use of a Wheatstone bridge, the value of the load can be measured. Load cells are popular weighing elements for tanks and silos and have proven accurate in many other weighing applications.

Strain gages may be bonded to cantilever springs to measure the force of bending (Figure 2-13B). The strain gages mounted on the top of the beam experience tension, while the strain gages on the bottom experience compression. The transducers are wired in a Wheatstone circuit and are used to determine the amount of force applied to the beam.

Strain-gage elements also are used widely in the design of industrial pressure transmitters. Figure 2-13C shows a bellows type pressure sensor in which the reference pressure is sealed inside the bellows on the right, while the other bellows is exposed to the process pressure. When there is a difference between the two pressures, the strain detector elements bonded to the cantilever beam measure the resulting compressive or tensile forces.

A diaphragm-type pressure transducer is created when four strain gages are attached to a diaphragm (Figure 2-13D). When the process pressure is applied to the diaphragm, the two central gage elements are subjected to tension, while the two gages at the edges are subjected to compression. The corresponding changes in resistance are a measure of the process pressure. When all of the strain gages are subjected to the same temperature, such as in this design, errors due to operating temperature variations are reduced.

Installation Diagnostics

All strain gage installations should be checked using the following steps:

1. Measure the base resistance of the unstrained strain gage after it is mounted, but before wiring is connected.
2. Check for surface contamination by measuring the isolation resistance between the gage grid and the stressed force detector specimen using an ohmmeter, if the specimen is conductive. This should be done before connecting the lead wires to the instrumentation. If the isolation resistance is under 500 megaohms, contamination is likely.
3. Check for extraneous induced voltages in the circuit by reading the voltage when the power supply to

the bridge is disconnected. Bridge output voltage readings for each strain-gage channel should be nearly zero.

4. Connect the excitation power supply to the bridge and ensure both the correct voltage level and its stability.
5. Check the strain gage bond by applying pressure to the gage. The reading should be unaffected. (T)

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Process Pressure Measurement

Mechanical methods of measuring pressure have been known for centuries. U-tube manometers were among the first pressure indicators. Originally, these tubes were made of glass, and scales were added to them as needed. But manometers are large, cumbersome, and not well suited for integration into automatic control loops. Therefore, manometers are usually found in the laboratory or used as local indicators. Depending on the reference pressure used, they could indicate absolute, gauge, and differential pressure.

Differential pressure transducers often are used in flow measurement where they can measure the pressure differential across a venturi, orifice, or other type of primary element. The detected pressure differential is related to flowing velocity and therefore to volumetric flow. Many features of modern pressure transmitters have come from the differential pressure transducer. In fact, one might consider the differential pressure transmitter the model for all pressure transducers.

"Gauge" pressure is defined relative to atmospheric conditions. In those parts of the world that continue to use English units, gauge pressure is indicated by adding a "g" to the units descriptor. Therefore, the pressure unit "pounds per square inch gauge" is abbreviated psig. When using SI units, it is proper to add "gauge" to the units used, such as "Pa gauge." When pressure is to be measured in absolute units, the reference is full vacuum and the abbreviation for "pounds per square inch absolute" is psia.

Often, the terms pressure gauge, sensor, transducer, and transmitter are used interchangeably. The term pressure gauge usually refers to a self-contained indicator that converts the detected process pressure into the mechanical motion of a pointer. A pressure transducer might combine the sensor element of a gauge with a mechanical-to-electrical or mechanical-to-pneumatic converter and a power supply. A pressure transmitter is a standardized pressure measurement package consisting of three basic components: a pressure transducer, its power supply, and a signal conditioner/retransmitter that converts the transducer signal into a standardized output.

Pressure transmitters can send the process pressure of interest using an analog pneumatic (3-15 psig), analog electronic (4-20 mA dc), or digital electronic signal. When transducers are directly interfaced with digital data acquisition systems and are located at some distance from the data acquisition hardware, high output voltage signals are preferred. These signals must be protected against both electromagnetic and radio frequency interference (EMI/RFI) when traveling longer distances.

Pressure transducer performance-related terms also require definition. Transducer accuracy refers to the degree of conformity of the mea-

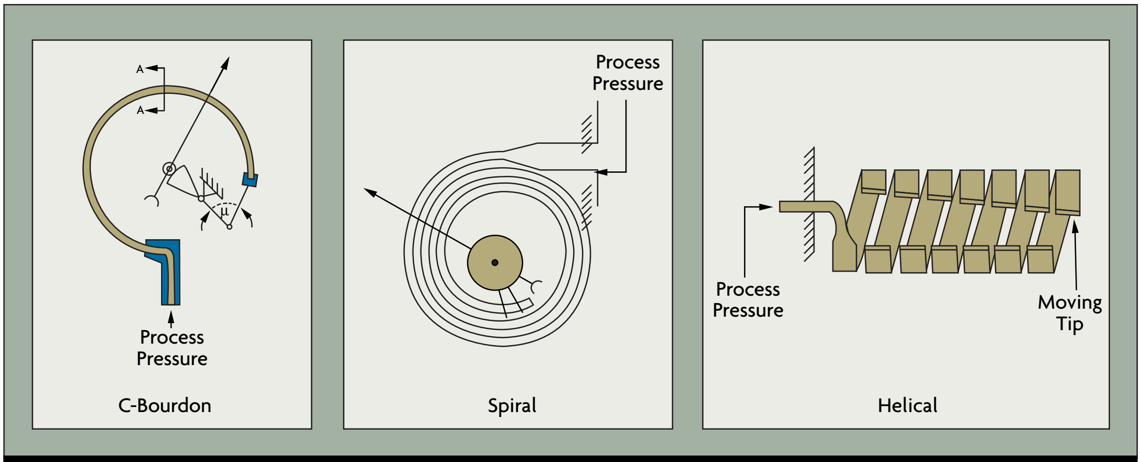


Figure 3-1: Bourdon Tube Designs

sured value to an accepted standard. It is usually expressed as a percentage of either the full scale or of the actual reading of the instrument. In case of percent-full-scale devices, error increases as the absolute value of the measurement drops. Repeatability refers to the closeness of agreement among a number of consecutive measurements of the same variable. Linearity is a measure of how well the transducer output increases linearly with increasing pressure. Hysteresis error describes the phenomenon whereby the same process pressure results in different output signals depending upon whether the pressure is approached from a lower or higher pressure.

From Mechanical to Electronic

The first pressure gauges used flexible elements as sensors. As pressure changed, the flexible element moved, and this motion was used to rotate a pointer in front of a dial. In these mechanical pressure sensors, a Bourdon tube, a diaphragm, or a bellows element detected the process pressure and caused a corresponding movement.

A Bourdon tube is C-shaped and has an oval cross-section with one end of the tube connected to the process pressure (Figure 3-1A). The other end is sealed and connected to the pointer or transmitter mechanism. To increase their sensitivity, Bourdon tube elements can be extended into spirals or helical coils (Figures 3-1B and 3-1C). This increases their effective angular length and therefore increases the movement at their tip, which in turn increases the resolution of the transducer.

The family of flexible pressure sensor elements also includes the bellows and the diaphragms (Figure 3-2). Diaphragms are popular because they require less space and because the motion (or force) they produce is sufficient for operating electronic transducers. They also are available in a wide range of materials for corrosive service applications.

After the 1920s, automatic control systems evolved, and by the 1950s pressure transmitters and centralized

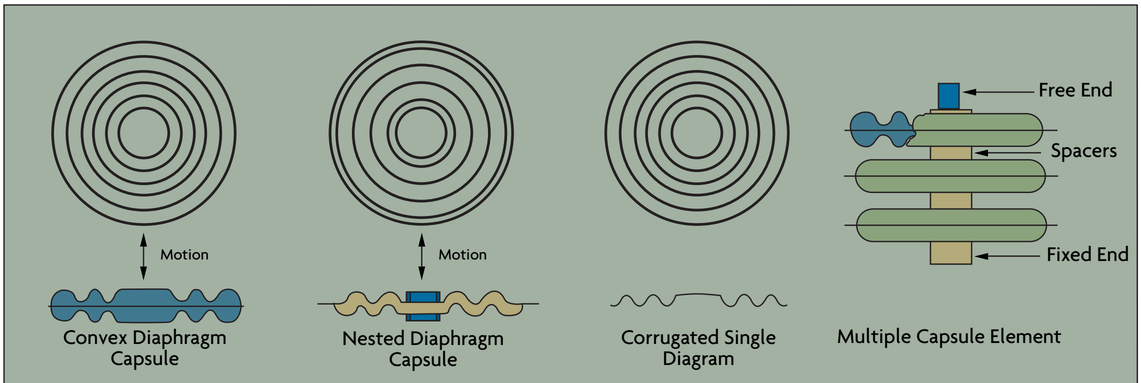


Figure 3-2: Pressure Sensor Diaphragm Designs

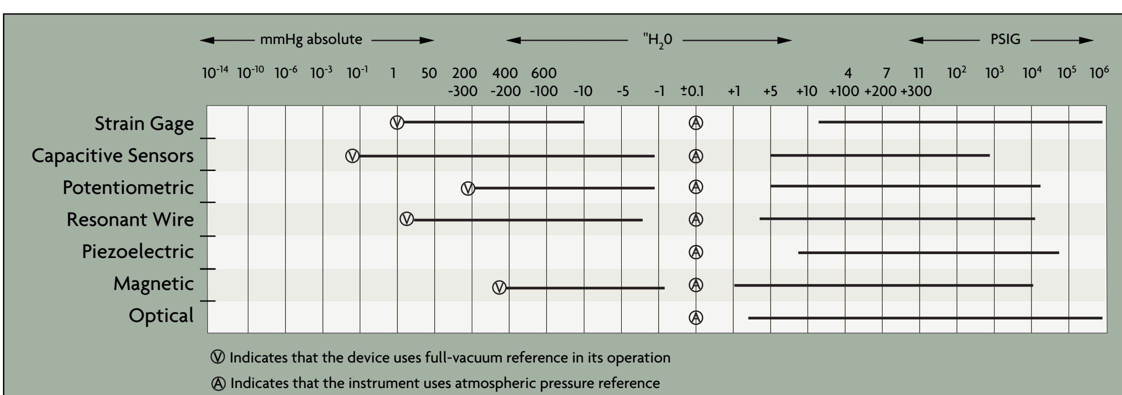


Figure 3-3: Electronic Pressure Sensor Ranges

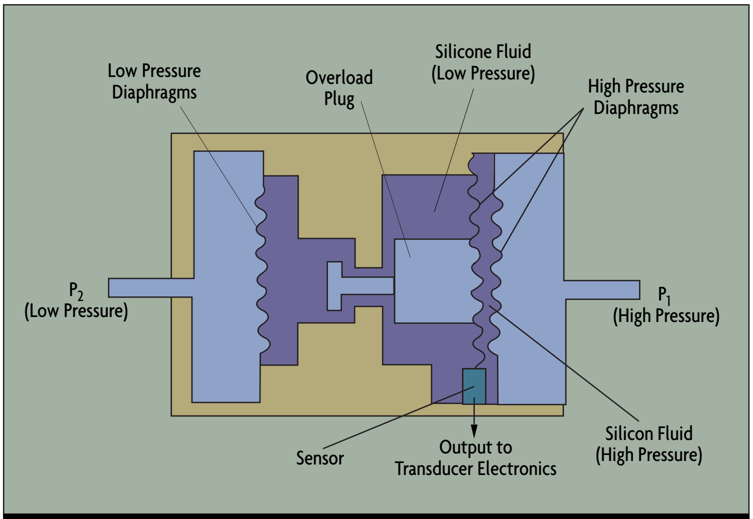


Figure 3-4: Strain-Gage Based Pressure Cell

control rooms were commonplace. Therefore, the free end of a Bourdon tube (bellows or diaphragm) no longer had to be connected to a local pointer, but served to convert a process pressure into a transmitted (electrical or pneumatic) signal. At first, the mechanical linkage was connected to a pneumatic pressure transmitter, which usually generated a 3-15 psig output signal for transmission over distances of several hundred feet, or even farther with booster repeaters. Later, as solid state electronics matured and transmission distances increased, pressure transmitters became electronic. The early designs generated dc voltage outputs (10-50 mV; 1-5 V; 0-100 mV), but later were standardized as 4-20 mA dc current output signals.

Because of the inherent limitations of mechanical motion-balance devices, first the force-balance and later the solid state pressure transducer were introduced. The first unbonded-wire strain gages were introduced in the late 1930s. In this device, the wire filament is attached to a structure under strain, and the resistance in the strained wire is measured. This design was inherently unstable and could not maintain calibration. There also were problems with degradation of the bond between the wire filament and the diaphragm, and with hysteresis caused by thermoelastic strain in the wire.

The search for improved pressure and strain sensors first resulted in the introduction of bonded thin-film and finally diffused semiconductor strain gages. These were first developed for the automotive industry, but shortly thereafter moved into the general field of pressure measurement and transmission in all industrial and scientific applications. Semiconductor pressure sensors are sensitive, inexpensive, accurate and repeatable. (For more details on strain gage operation, see Chapter 2.)

Many pneumatic pressure transmitters are still in operation, particu-

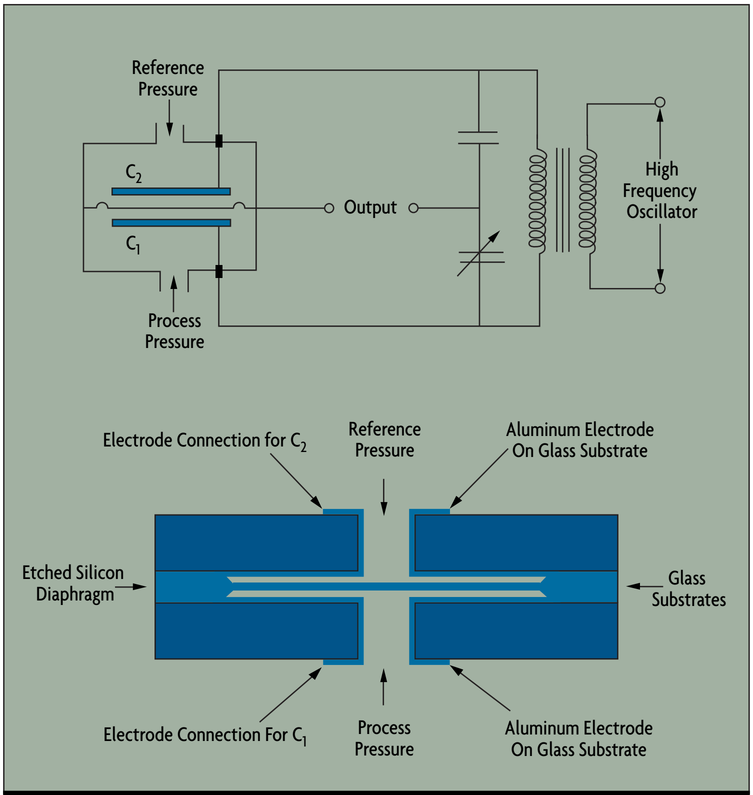


Figure 3-5: Capacitance-Based Pressure Cell

larly in the petrochemical industry. But as control systems continue to become more centralized and computerized, these devices have been replaced by analog electronic and, more recently, digital electronic transmitters.

Transducer Types

Figure 3-3 provides an overall orientation to the scientist or engineer who might be faced with the task of selecting a pressure detector from among the many designs available. This table shows the ranges of pressures and vacuums that various sensor types are capable of detecting and the types of internal references (vacuum or atmospheric pressure) used, if any.

Because electronic pressure transducers are of greatest utility for industrial and laboratory data acquisition and control applications, the operating principles and pros and cons of each of these is further elaborated in this section.

• Strain Gage

When a strain gage, as described in detail in Chapter 2, is used to measure the deflection of an elastic diaphragm or Bourdon tube, it becomes a component in a pressure transducer. Strain gage-type pressure transducers are widely used.

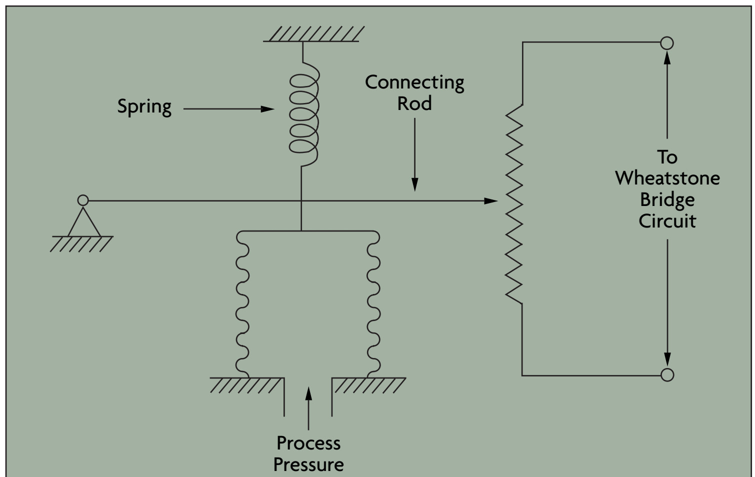


Figure 3-6: Potentiometric Pressure Transducer

Strain-gage transducers are used for narrow-span pressure and for differential pressure measurements. Essentially, the strain gage is used to measure the displacement of an elastic diaphragm due to a difference in pressure across the diaphragm. These devices can detect gauge pressure if the low pressure port is left open to the atmosphere or differential pressure if connected to two process pressures. If the low pressure side is a sealed vacuum reference, the transmitter will act as an absolute pressure transmitter.

Strain gage transducers are available for pressure ranges as low as 3 inches of water to as high as 200,000 psig (1400 MPa). Inaccuracy ranges from 0.1% of span to 0.25% of full scale. Additional error sources can be a 0.25% of full scale drift over six months and a 0.25% full scale temperature effect per 1000° F.


Differential pressure transducers in a variety of ranges and outputs.

• Capacitance

Capacitance pressure transducers were originally developed for use in low vacuum research. This capacitance change results from the movement of a diaphragm element (Figure 3-5). The diaphragm is usually metal or metal-coated quartz and is exposed to the process pressure on one side and to the reference pressure on the other. Depending on the type of pressure, the capacitive transducer can be either an absolute, gauge, or differential pressure transducer.

Stainless steel is the most common diaphragm material used, but for corrosive service, high-nickel steel alloys, such as Inconel or Hastelloy, give better performance. Tantalum also is used for highly corrosive, high temperature applications. As a special case, silver diaphragms can be used to measure the pressure of chlorine, fluorine, and other halogens in their elemental state.

In a capacitance-type pressure sensor, a high-frequency, high-voltage oscillator is used to charge the sensing electrode elements. In a two-plate capacitor sensor design, the movement of the diaphragm between the plates is detected as an indication of the changes in process pressure.

As shown in Figure 3-5, the deflection of the diaphragm causes a change in capacitance that is detected by a bridge circuit. This circuit can be operated in either a balanced or unbalanced mode. In balanced mode, the output voltage is fed to a null detector and the capacitor arms are varied to maintain the bridge at null. Therefore, in the balanced mode, the null setting itself is a measure of process pressure. When operated in unbalanced mode, the process pressure measurement is related to the ratio between the output voltage and the excitation voltage.

Single-plate capacitor designs are also common. In this design, the plate is located on the back side of the diaphragm and the variable capacitance is a function of deflection of the diaphragm. Therefore, the detected capacitance is an indication of the process pressure. The capacitance is converted into either a direct current or a voltage signal that can be read directly by panel meters or microprocessor-based input/output boards.

Capacitance pressure transducers are widespread in part because of their wide rangeability, from high vacuums in the micron range to 10,000 psig (70 MPa). Differential pressures as low as 0.01 inches of water can readily be measured. And, compared with strain gage transducers, they do not drift much. Better designs are available that are accurate to within 0.1% of reading or 0.01% of full scale. A typical temperature effect is 0.25% of full scale per 1000° F.

Capacitance-type sensors are often used as secondary standards, especially in low-differential and low-absolute pressure applications. They also are quite responsive, because the distance the diaphragm must physically travel is only a few microns. Newer capacitance pressure transducers are more resistant to corrosion and are less sensitive to stray capacitance and vibration effects that used to cause "reading jitters" in older designs.

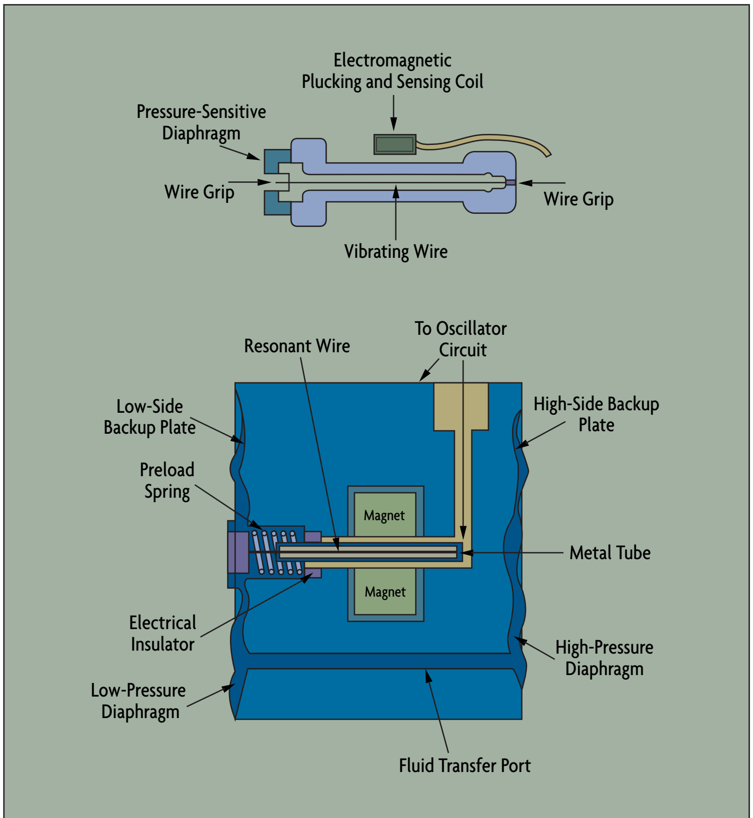


Figure 3-7: Resonant-Wire Pressure Transducer

Potentiometric

The potentiometric pressure sensor provides a simple method for obtaining an electronic output from a mechanical pressure gauge. The device consists of a precision potentiometer, whose wiper arm is mechanically linked to a Bourdon or bellows element. The movement of the wiper arm across the potentiometer

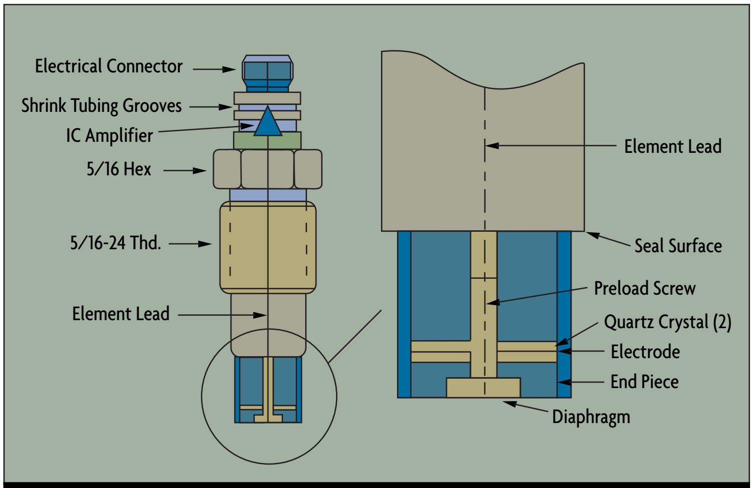


Figure 3-8: Typical Piezoelectric Pressure Sensor

converts the mechanically detected sensor deflection into a resistance measurement, using a Wheatstone bridge circuit (Figure 3-6).

The mechanical nature of the linkages connecting the wiper arm to the Bourdon tube, bellows, or diaphragm element introduces unavoidable errors into this type of measurement. Temperature effects cause additional errors because of the differences in thermal expansion coefficients of the metallic components of the system. Errors also will develop due to mechanical wear of the components and of the contacts.

Potentiometric transducers can be made extremely small and installed in very tight quarters, such as inside the housing of a 4.5-in. dial pressure gauge. They also provide a strong output that can be read without additional amplification. This permits them to be used in low power applications. They are also inexpensive. Potentiometric transducers can detect pressures between 5 and 10,000 psig (35 KPa to 70 MPa). Their accuracy is between 0.5% and 1% of full scale, not including drift and the effects of temperature.

Resonant Wire

The resonant-wire pressure transducer was introduced in the late 1970s. In this design (Figure 3-7), a wire is gripped by a static member at one end, and by the sensing diaphragm at the other. An oscillator circuit causes the wire to oscillate at its resonant frequency. A change in process pressure changes the wire tension, which in turn changes the resonant frequency of the wire. A digital counter circuit detects the shift. Because this change in frequency can be detected quite precisely, this type of transducer can be used for low differential pressure applications as well as to detect absolute and gauge pressures.

The most significant advantage of the resonant wire pressure transducer is that it generates an inherently digital signal, and therefore can be sent directly to a stable crystal clock in a microprocessor. Limitations include sensitivity to temperature variation, a nonlinear output signal, and some sensitivity to shock and vibration. These limitations typically are minimized by using a microprocessor to compensate for nonlinearities as well as ambient and process temperature variations.

Resonant wire transducers can detect absolute pressures from 10 mm Hg, differential pressures up to 750 in. water, and gauge pressures up to 6,000 psig (42 MPa). Typical accuracy is 0.1% of calibrated span, with six-month drift of 0.1% and a temperature effect of 0.2% per 1000° F.

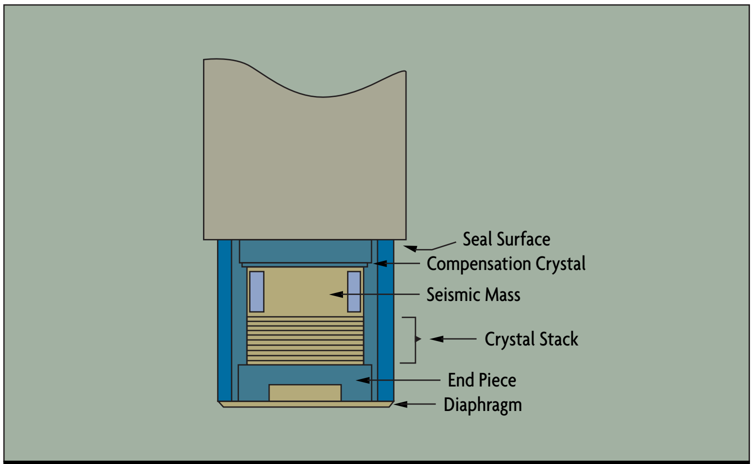


Figure 3-9: Acceleration-Compensated Piezoelectric Sensor

Piezoelectric

When pressure, force or acceleration is applied to a quartz crystal, a charge is developed across the crystal that is proportional to the force applied

(Figure 3-8). The fundamental difference between these crystal sensors and static-force devices such as strain gages is that the electric signal generated by the crystal decays rapidly. This characteristic makes these sensors unsuitable for the measurement of static forces or pressures but useful for dynamic measurements. (This phenomenon also is discussed in later chapters devoted to the measurement of dynamic force, impact, and acceleration.)

Analog pressure transmitter with adjustable zero and span.

Piezoelectric devices can further be classified according to whether the crystal's electrostatic charge, its resistivity, or its resonant frequency electrostatic charge is measured. Depending on which phenomenon is used, the crystal sensor can be called electrostatic, piezoresistive, or resonant.

When pressure is applied to a crystal, it is elastically deformed. This deformation results in a flow of electric charge (which lasts for a period of a few seconds). The resulting electric signal can be measured as an indication of the pressure which was applied to the crystal. These sensors cannot detect static pressures, but are used to measure rapidly changing pressures resulting from blasts, explosions, pressure pulsations (in rocket motors, engines, compressors) or other sources of shock or vibration. Some of these rugged sensors can detect pressure events having "rise times" on the order of a millionth of a second, and are described in more detail later in this chapter.

The output of such dynamic pressure sensors is often expressed in "relative" pressure units (such as psir instead of psig), thereby referencing

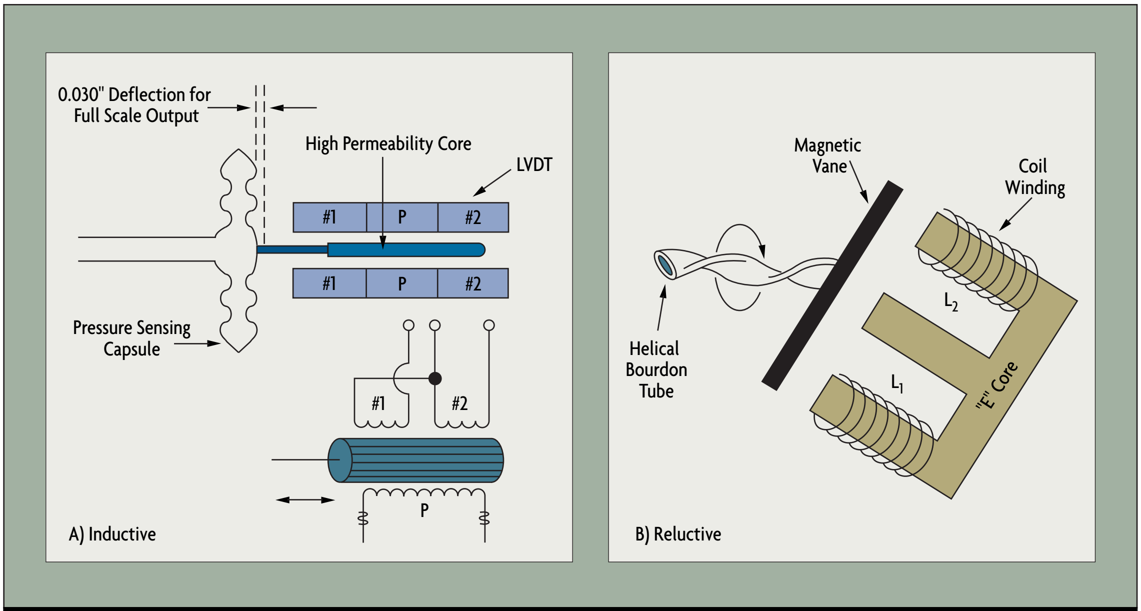


Figure 3-10: Magnetic Pressure Transducer Designs

the measurement to the initial condition of the crystal. The maximum range of such sensors is 5,000 or 10,000 psir. The desirable features of piezoelectric sensors include their rugged construction, small size, high speed, and self-generated signal. On the other hand, they are sensitive to temperature variations and require special cabling and amplification.

They also require special care during installation: One such consideration is that their mounting torque should duplicate the torque at which they were calibrated (usually 30 in.-lbs). Another factor that can harm their performance by slowing response speed is the depth of the empty cavity below the cavity. The larger the cavity, the slower the response. Therefore, it is recommended that the depth of the cavity be minimized and not be deeper than the diameter of the probe (usually about 0.25-in.).

Electrostatic pressure transducers are small and rugged. Force to the crystal can be applied longitudinally or in the transverse direction, and in either case will cause a high voltage output proportional to the force applied. The crystal's self-generated voltage signal is useful where providing power to the sensor is impractical or impossible. These sensors also provide high speed responses (30 kHz with peaks to 100 kHz), which makes them ideal for measuring transient phenomena.

Figure 3-9 illustrates an acceleration-compensated pressure sensor. In this design, the compensation is provided by the addition of a seismic mass and a separate "compensation crystal" of reverse polarity. These components are scaled to exactly cancel the inertial effect of the masses (the end piece and diaphragm) which act upon the pressure-sensing crystal stack when accelerated.

Because quartz is a common and naturally occurring mineral, these transducers are generally inexpensive. Tourmaline, a naturally occurring semi-precious form of quartz, has sub-microsecond responsiveness and is useful in the measurement of very rapid transients. By selecting the crystal properly, the designer can ensure both good linearity and reduced temperature sensitivity.

Although piezoelectric transducers are not capable of measuring static pressures, they are widely used to evaluate dynamic pressure phenomena associated with explosions, pulsations, or dynamic pressure conditions in motors, rocket engines, compressors, and other pressurized devices that experience rapid changes. They can detect pressures between 0.1 and 10,000 psig (0.7 KPa to 70 MPa). Typical accuracy is 1% full scale with an additional 1% full scale per 1000° temperature effect.

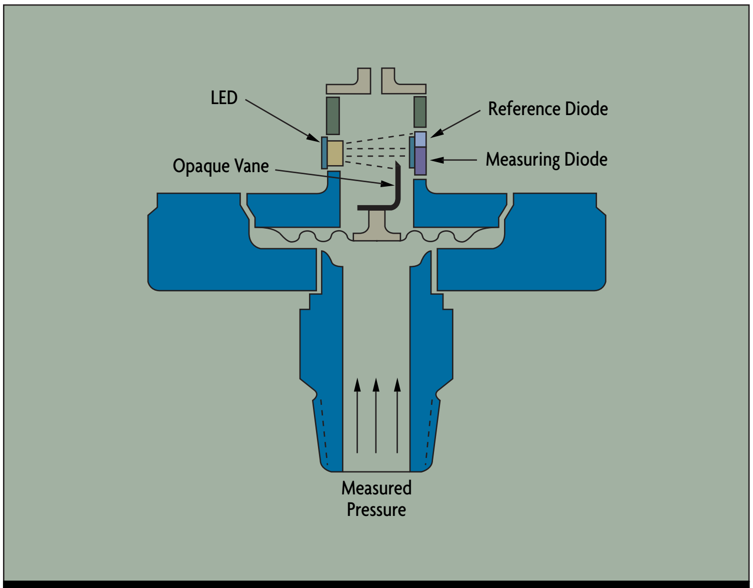


Figure 3-11: Optical Pressure Transducer

Piezoresistive pressure sensors operate based on the resistivity dependence of silicon under stress. Similar to a strain gage, a piezoresistive sensor consists of a diaphragm onto which four pairs of silicon resistors are bonded. Unlike the construction of a strain gage sensor, here the diaphragm itself is made of silicon and the resistors are diffused into the silicon during the manufacturing process. The diaphragm is completed by bonding the diaphragm to an unprocessed wafer of silicon.

If the sensor is to be used to measure absolute pressure, the bonding process is performed under vacuum. If the sensor is to be referenced, the cavity behind the diaphragm is ported either to the atmosphere or to the reference pressure source. When used in a process sensor, the silicon diaphragm is shielded from direct contact with the process materials by a fluid-filled protective diaphragm made of stainless steel or some other alloy that meets the corrosion requirements of the service.

Piezoresistive pressure sensors are sensitive to changes in temperature and must be temperature compensated. Piezoresistive pressure sensors can be used from about 3 psi to a maximum of about 14,000 psi (21 KPa to 100 MPa).

Resonant piezoelectric pressure sensors measure the variation in resonant frequency of quartz crystals under an applied force. The sensor can consist of a suspended beam that oscillates while isolated from all other forces. The beam is maintained in oscillation at its resonant frequency. Changes in the applied force result in resonant frequency changes. The relationship between the applied pressure P and the oscillation frequency is:

$$P = A(1-T_O/T) - B(1-T_O/T^2)$$

where T_O is the period of oscillation when the applied pressure is zero, T is the period of oscillation when the applied pressure is P, and A and B are calibration constants for the transducer.

These transducers can be used for absolute pressure measurements with spans from 0-15 psia to 0-900 psia (0-100 kPa to 0-6 MPa) or for differential pressure measurements with spans from 0-6 psid to 0-40 psid (0-40 kPa to 0-275 kPa).

Inductive/Reluctive

A number of early pressure transducer designs were based on magnetic phenomena. These included the use of inductance, reluctance, and eddy currents. Inductance is that property of an electric circuit that expresses the amount of electromotive force (emf) induced by a given rate of change of current flow in the circuit. Reluctance is resistance to magnetic flow, the opposition offered by a

Flush-mount pressure sensor fits ¼-in. NPT threads.

magnetic substance to magnetic flux. In these sensors, a change in pressure produces a movement, which in turn changes the inductance or reluctance of an electric circuit.

Figure 3-10A illustrates the use of a linear variable differential transformer (LVDT) as the working element of a pressure transmitter. The LVDT operates on the inductance ratio principle. In this design, three coils are wired onto an insulating tube containing an iron core, which is positioned within the tube by the pressure sensor.

Alternating current is applied to the primary coil in the center, and if the core also is centered, equal voltages will be induced in the secondary coils (#1 and #2). Because the coils are wired in series, this condition will result in a zero output. As the process pressure changes and the core moves, the differential in the voltages induced in the secondary coils is proportional to the pressure causing the movement.

LVDT-type pressure transducers are available with 0.5% full scale accuracy and with ranges from 0-30 psig (0-210 kPa) to 0-10,000 psig (0-70 MPa). They can detect absolute, gauge, or differential pressures. Their main limitations are susceptibility to mechanical wear and sensitivity to vibration and magnetic interference.

Reluctance is the equivalent of resistance in a magnetic circuit. If a change in pressure changes the gaps in the magnetic flux paths of the two cores, the ratio of inductances

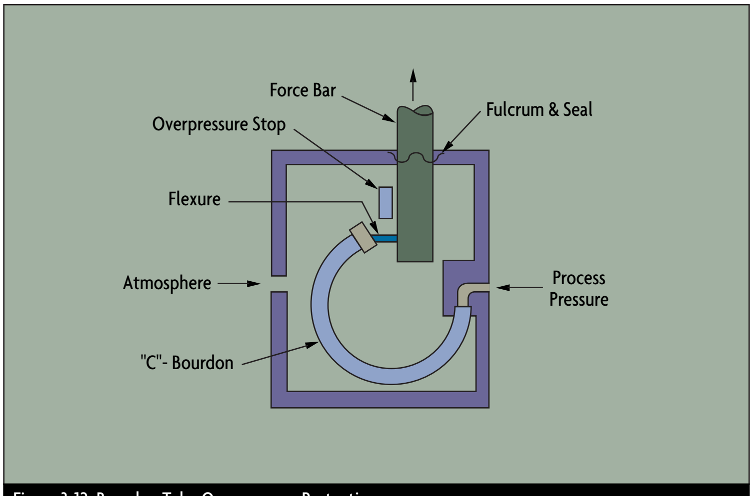


Figure 3-12: Bourdon Tube Overpressure Protection

L1/L2 will be related to the change in process pressure (Figure 3-10B).

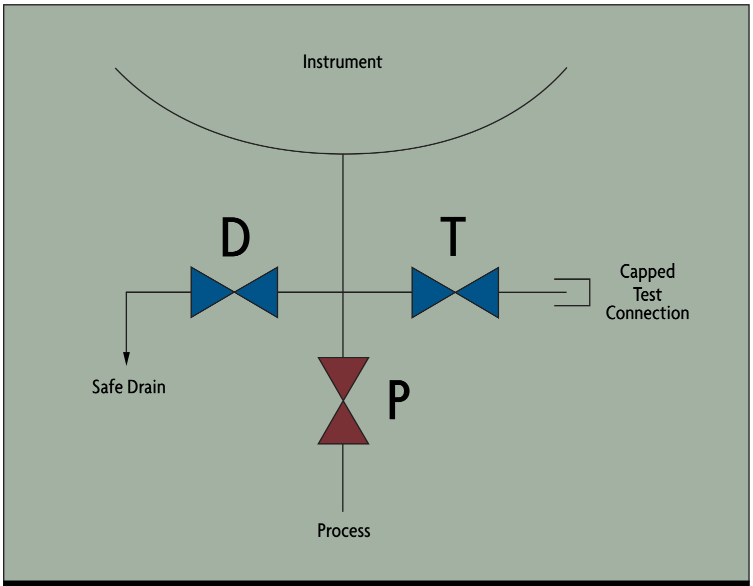


Figure 3-13: Three-Valve Manifold for Instrument Isolation

Reluctance-based pressure transducers have a very high output signal (on the order of 40 mV/volt of excitation), but must be excited by ac voltage. They are susceptible to stray magnetic fields and to temperature effects of about 2% per 1000° F. Because of their very high output signals, they are often used in applications where high resolution over a relatively small range is desired. They can cover pressure ranges from 1 in. water to 10,000 psig (250 Pa to 70 MPa). Typical accuracy is 0.5% full scale.

Optical

Optical pressure transducers detect the effects of minute motions due to changes in process pressure and generate a corresponding electronic output signal (Figure 3-11). A light emitting diode (LED) is used as the light source, and a vane blocks some of the light as it is moved by the diaphragm. As the process pressure moves the vane between the source diode and the measuring diode, the amount of infrared light received changes.

The optical transducer must compensate for aging of the LED light source by means of a reference diode, which is never blocked by the vane. This reference diode also compensates the signal for build-up of dirt or other coating materials on the optical surfaces. The optical pressure transducer is immune to temperature effects, because the source, measurement and reference diodes are affected equally by changes in temperature. Moreover, because the amount of movement required to make the measurement is very small (under 0.5 mm), hysteresis and repeatability errors are nearly zero.

Optical pressure transducers do not require much maintenance. They have excellent stability and are designed for long-duration measurements. They are available with ranges from 5 psig to 60,000 psig (35 kPa to 413 MPa) and with 0.1% full scale accuracy.

Practical Considerations

In industrial applications, good repeatability often is more important then absolute accuracy. If process pressures vary over a wide range, transducers with good linearity and low hysteresis are the preferred choice.

Ambient and process temperature variations also cause errors in pressure measurements, particularly in detecting low pressures and small differential pressures. In such applications, temperature compensators

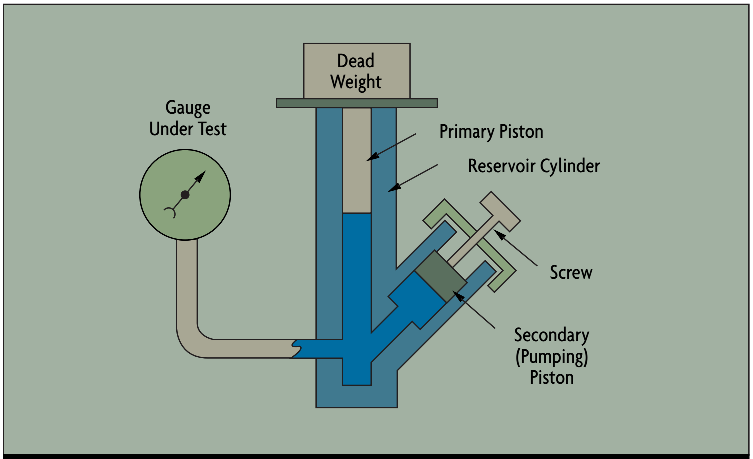


Figure 3-14: Dead-Weight Tester Schematic

Thick-film silicon pressure sensor is available in ranges from 10 to 30,000 psia.

must be used.

Power supply variations also lower the performance of pressure transducers. The sensitivity (S) of a transducer determines the amount of change that occurs in the output voltage (V_O) when the supply voltage (V_S) changes, with the measured pressure (Pm) and the rated pressure of the transducer (Pr) remaining constant:

$$V_O = (S)V_S(Pm/Pr)$$

In a pressure measurement system, the total error can be calculated using the root-sum-square method: the total error is equal to the square root of the sums of all the individual errors squared.

Selection Criteria

Pressure transducers usually generate output signals in the millivolt range (spans of 100 mV to 250 mV). When used in transmitters, these are often amplified to the voltage level (1 to 5 V) and converted to current loops, usually 4-20 mA dc.

The transducer housing should be selected to meet both the electrical area classification and the corrosion requirements of the particular installation. Corrosion protection must take into account both splashing of corrosive liquids or exposure to corrosive gases on the outside of the housing, as well as exposure of the sensing element to corrosive process materials. The corrosion requirements of the installation are met by selecting corrosion-resistant materials, coatings, and by the use of chemical seals, which are discussed later in this chapter.

If the installation is in an area where explosive vapors may be present, the transducer or transmitter and its power supply must be suitable for these environments. This is usually achieved either by placing them inside purged or explosion-proof housings, or by using intrinsically safe designs.

Probably the single most important decision in selecting a pressure transducer is the range. One must keep in mind two conflicting considerations: the instrument's accuracy and its protection from overpressure. From an accuracy point of view, the

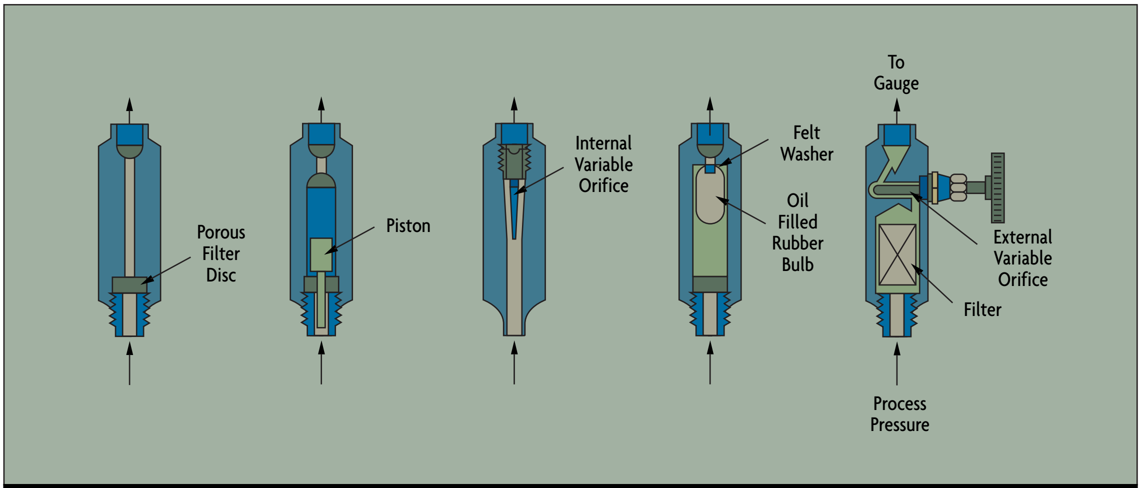


Figure 3-15: Pulsation Damper & Snubber Designs

range of a transmitter should be low (normal operating pressure at around the middle of the range), so that error, usually a percentage of full scale, is minimized. On the other hand, one must always consider the consequences of overpressure damage due to operating errors, faulty design (waterhammer), or failure to isolate the instrument during pressure-testing and start-up. Therefore, it is important to specify not only the required range, but also the amount of overpressure protection needed.

Most pressure instruments are provided with overpressure protection of 50% to 200% of range (Figure 3-12). These protectors satisfy the majority of applications. Where higher overpressures are expected and their nature is temporary (pressure spikes of short duration—seconds or less), snubbers can be installed. These filter out spikes, but cause the measurement to be less responsive. If excessive overpressure is expected to be of longer duration, one can protect the sensor by installing a pressure relief valve. However, this will result in a loss of measurement when the relief valve is open.

If the transmitter is to operate under high ambient temperatures, the housing can be cooled electrically (Peltier effect) or by water, or it can be relocated in an air-conditioned area. When freezing temperatures are expected, resistance heating or steam tracing should be used in combination with thermal insulation.

When high process temperatures are present, one can consider the use of various methods of isolating the pressure instrument from the process. These include loop seals, siphons, chemical seals with capillary tubing for remote mounting, and purging.

Maintenance

Without exception, pressure sensors require scheduled, periodic maintenance and/or recalibration. It is necessary to periodically remove the transducer from the process and to make sure that this procedure does not require shutting down the process and does not cause injury or damage. Because the process fluid may be toxic, corrosive, or otherwise noxious to personnel or the environment, it is necessary to protect against the release of such fluids during maintenance.

A three-way manifold (Figure 3-13) can provide such protection. In the illustration, valve P is used to isolate the process and valve D serves to discharge the trapped process fluid from the instrument into some safe containment. The purpose of valve T is to allow the application of a known calibration or test pressure to the instrument. As all the components of the manifold are pre-assembled into a compact package, space and field assembly time are saved and chances for leaks are reduced.

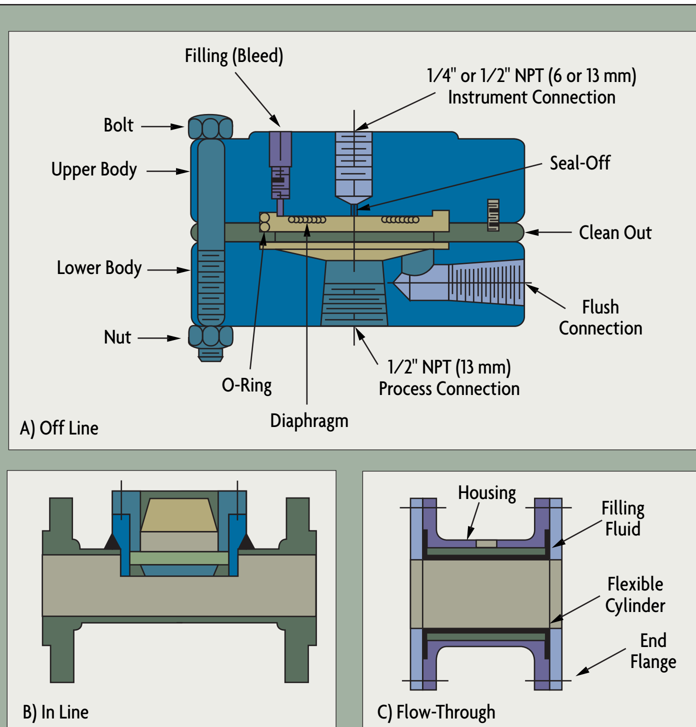


Figure 3-16: Chemical Seal Alternatives

Calibration

Pressure transducers can be recalibrated on-line or in a calibration laboratory. Laboratory recalibration typically is preferred, but often is not possible or necessary. In the laboratory, there usually are two types of calibration devices: deadweight testers that provide primary, base-line standards, and "laboratory" or "field" standard calibration devices that are periodically recalibrated against the primary. Of course, these secondary standards are less accurate than the primary, but they provide a more convenient means of testing other instruments.

A deadweight tester consists of a pumping piston with a screw that presses it into the reservoir, a primary piston that carries the dead weight, and the gauge or transducer to be tested (Figure 3-14). It works by loading the primary piston (of cross sectional area A), with the amount of weight (W) that corresponds to the desired calibration pressure (P = W/A). The pumping piston then pressurizes the whole system by pressing more fluid into the reservoir cylinder, until the dead weight lifts off its support.

Today's deadweight testers are more accurate and more complex than the instrument in Figure 3-14, but the essential operating principles are the same. Sophisticated features include temperature compensation and the means to rotate the piston in its cylinder to negate the effects of friction.

In the United States, the National Institute of Standards & Technology (NIST) provides certified weights and calibrates laboratory piston gauges by measuring the diameter of the piston. Deadweight testers can be used to calibrate at pressure levels as low as 5 psig (35 kPa) and as high as 100,000 psig (690 MPa). Tilting type, air-lubricated designs can detect pressures in the mm Hg range. NIST calibrated deadweight testers can be accurate to 5 parts in 100,000 at pressures below 40,000 psig (280 MPa). For an industrial quality deadweight tester, error is typically 0.1% of span.

A typical secondary standard used for calibrating industrial pressure transducers contains a precision power supply, an accurate digital readout, and a high-accuracy resonant (quartz) pressure sensor. It is precise enough to be used to calibrate most industrial pressure transducers, but must be NIST-traceable to be used as an official calibration standard. The best accuracy claimed by the manufacturers is typically 0.05% full scale.

Installation & Accessories

When possible, pressure instrumentation should be installed in visible, readily accessible locations. Readouts should be located at eye elevation. Headroom should be provided for instrument removal, as well as any space for tools and test equipment that might be needed.

In some applications, it is desirable to prevent the process fluid from coming in contact with the sensing element. The process may be noxious, poisonous, corrosive, abrasive, have the tendency to gel, freeze or decompose at ambient temperatures, or be hotter or colder than the sensor can

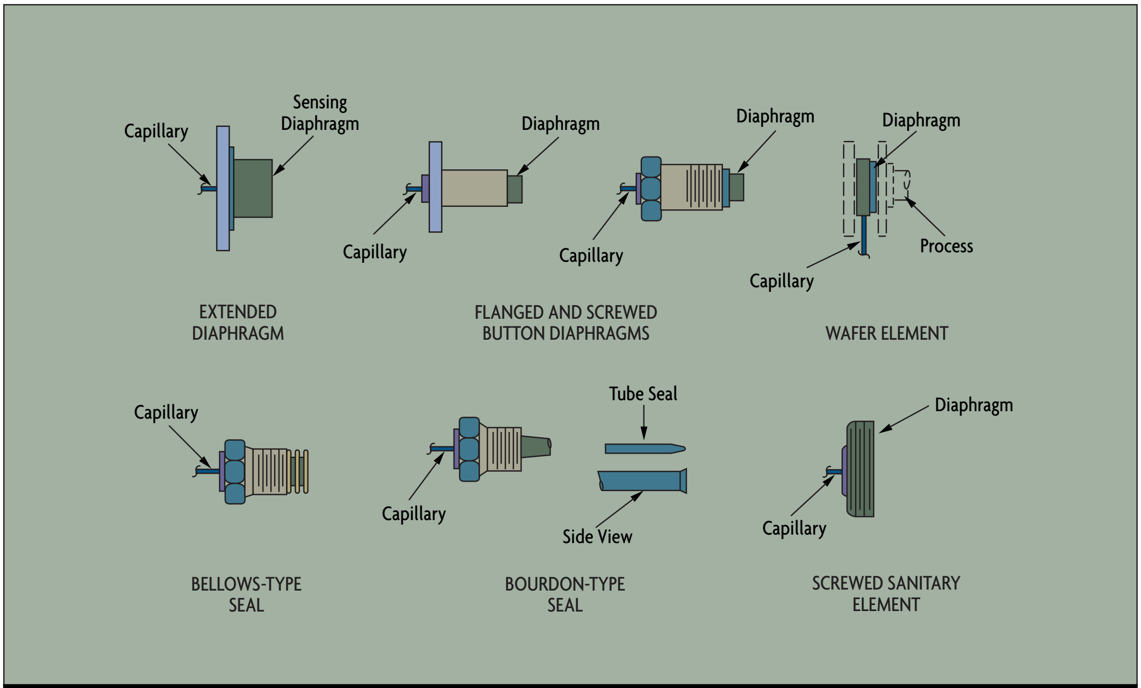


Figure 3-17: Volumetric Seal Element Designs

tolerate. Other reasons for inserting accessories between the process and the pressure instrument are to filter out potentially plugging solids or to remove potentially damaging pressure spikes or vibrations.

• Snubbers & Pulsation Dampers

An unprotected pressure sensor on the discharge of a positive displacement pump or compressor would never come to rest, and its pointer would cycle continuously. To filter out pressure spikes, or to average out pressure pulses, snubbers and pulsation dampers are installed between the process and the instrument (Figure 3-15).

The first design shown in the illustration uses a corrosion-resistant porous metal filter to delay the pressure reading by about 10 seconds. Other designs provide shorter delays via fixed or variable pistons or restrictions. The advantage of an adjustable restriction is that if, for example, a pressure gauge is placed on the discharge of a compressor, one can see when the pointer cycling has stopped. Naturally, when one is interested in the measurement of fast, transient pressures (such as to initiate safety interlocks on rising pressures), snubbers must not be used, as they delay the response of the safety system.

• Chemical Seals

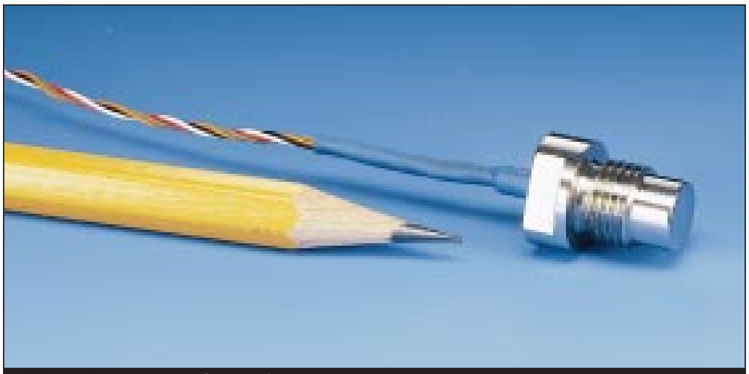
The chemical seal is also known as a "diaphragm protector." Its main components (the upper and lower body and the clean-out ring) are shown in Figure 3-16A. The pressure instrument is screwed into the upper body, which can be made of standard materials because it contacts only the non-corrosive filling fluid, usually a silicone oil. The top section with the filled diaphragm capsule can be removed with the pressure instrument while the operator cleans out the material accumulated in the bottom housing. This lower body is made of "pipe specification" (process compatible) materials and can be continuously or periodically cleaned by purging.

The seal shown in Figure 3-16A is an off-line design; an in-line design is shown in Figure 3-16B. In-line devices are less likely to plug, but the process has to be shut down if maintenance is required. The ultimate in self-cleaning designs is shown in Figure 3-16C, in which all sharp edges and dead-ended cavities (where solids could accumulate) have been eliminated. The flexible cylinder can be made of a variety of plastics, including Teflon®, and is available in spool and wafer configurations.

As the process pressure changes, the amount of liquid displaced by the sealing diaphragm is small, and is sometimes insufficient to fill and operate bellows-type sensors. In that case, larger displacement "rolling" diaphragms are used. Volumetric seal elements (Figure 3-17) also can eliminate cavities and sharp edges where material might accumulate. They also are well suited for high pressure and high viscosity applications such as extruders.

Adding seals to a press measurement device can cause the following problems:

- Long or large bore capillaries increase the volume of the filling fluid, increasing the temperature error.
- Smaller diameter diaphragms are stiff and increase error, particularly at low temperatures.
- Filling fluid viscosity, acceptable at normal ambient temperatures, may be unacceptably high at low temperatures.
- Long capillary lengths or smaller bores can cause slow response.
- Uneven heating/cooling of seals and capillaries can cause errors.
- Some fill fluids expand excessively with temperature and damage the instrument by overextending the diaphragm.
- High temperature and/or high vacuum may vaporize the fill fluid and damage the instrument.
- Fluid may contract excessively at low temperatures, bottoming the diaphragm and preventing operation.
- Frozen fill fluid also will prevent



Miniature pressure sensor fits in tight spots.

operation.

For a successful seal installation, the following must also be considered:

- Process and ambient temperature range.
- Relative elevation of the seals and the instrument and the hydrostatic head of the fill fluid. Instrument should be rezeroed after installation to correct for elevation.
- Temperature, pressure, and physical damage potentials during cleaning and emptying.
- Possible consequences of diaphragm rupture in terms of hazard and contamination.
- Identical seals and capillary lengths for both sides of a differential pressure device.
- Seal and instrument performance at maximum temperature/minimum pressure and minimum pressure/temperature combinations.

Wet Legs & Seal Pots

When one or both impulse lines to a differential pressure device are filled with a stable, process compatible fluid, the installation is called a "wet-leg" installation. The net effect of the legs' height above the instrument and specific gravity of the fluid must be considered in the calibration. Wet leg design must also allow for the filling and draining of the leg(s).

Seal pots are used with wet legs when the instrument displaces a large volume of liquid as the measurement changes. A seal pot is a small pressure vessel about one quart in volume that is mounted at the top of the wet leg line. If two wet legs are used in a differential application, the pots must be mounted at the same elevation. Each pot acts as a reservoir in the impulse line where large volume changes will result in minimal elevation change so that seal liquid is not dumped into the process line and elevation shifts of the wet leg liquid do not cause measurement errors. T

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High Pressure & Vacuum

The term "high pressure" is relative, as, in fact, are all pressure measurements. What the term actually means depends greatly on the particular industry one is talking about. In synthetic diamond manufacturing, for example, normal reaction pressure is around 100,000 psig (6,900 bars) or more, while some fiber and plastic extruders operate at 10,000 psig (690 bars). Yet, in the average plant, pressures exceeding 1,000 psig (69 bars) are considered high.

In extruder applications, high pressures are accompanied by high temperatures, and sticky materials are likely to plug all cavities they might enter. Therefore, extruder pressure sensors are inserted flush with the inner diameter of the pipe and are usually continuously cooled.

High Pressure Designs

In the case of the button repeater (Figure 4-1A), the diaphragm can detect extruder pressures up to 10,000 psig and can operate at temperatures up to 8000°F (4300°C) because of its self-cooling design. It operates on direct force balance between the process pressure (P1) acting on the sensing diaphragm and the pressure of the output air signal (P2) acting on the balancing diaphragm. The pressure of the output air signal follows the process pressure in inverse ratio to the areas of the two diaphragms. If the diaphragm area ratio is 200:1, a 1,000-psig increase in process pressure will raise the air output signal by 5 psig.

The button repeater can be screwed into a ½-in. coupling in the extruder discharge pipe in such a way that its 316 stainless steel diaphragm is inserted flush with the inside of the pipe. Self-cooling is provided by the continuous flow of instrument air.

Another mechanical high pressure sensor uses a helical Bourdon element (Figure 4-1B). This device may include as many as twenty coils and can measure pressures well in excess of 10,000 psig. The standard element material is heavy-duty stainless steel, and the measurement error is around 1% of span. Helical Bourdon tube sensors provide high overrange protection and are suitable for fluctuating pressure service, but must be protected from plugging. This protection can be provided by high-pressure, button diaphragm-type chemical seal elements that also are rated for 10,000-psig service.

An improvement on the design shown in Figure 4-1B detects tip motion optically, without requiring any mechanical linkage. This is desirable because of errors introduced by linkage friction. In such units, a reference diode also is provided to compensate for the aging of the light source, for temperature variations, and for dirt build-up on the optics. Because the sensor movement is usually small (0.02 in.), both hysteresis and repeatability

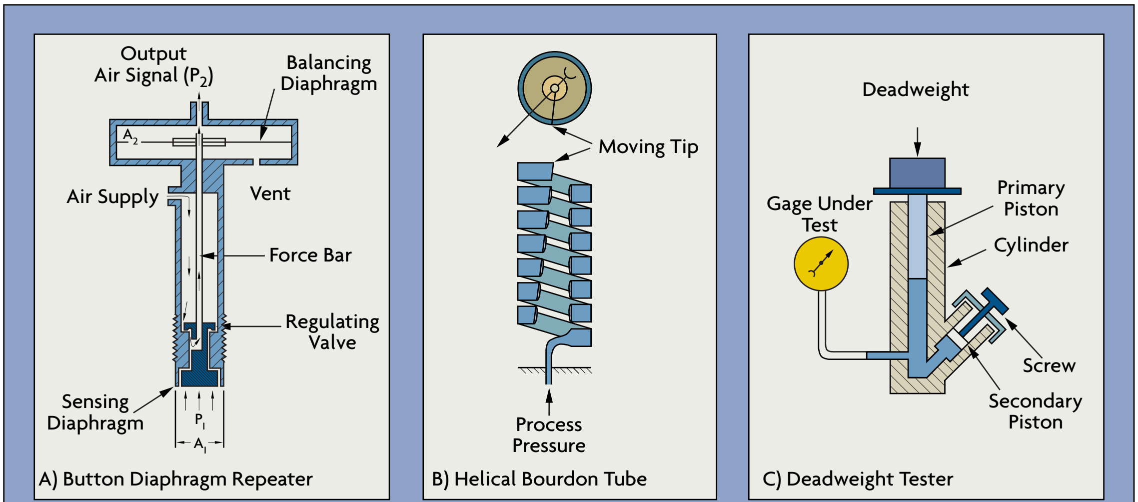

Figure 4-1: Mechanical High Pressure Sensors

errors typically are negligible. Such units are available for measuring pressures up to 60,000 psig.

(capacitance, potentiometric, inductive, reluctive) are also capable of detecting pressures up to 10,000

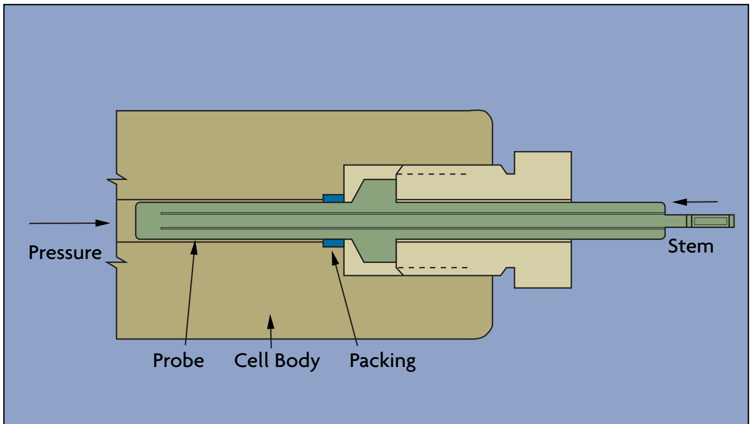

Figure 4-2: Bulk Modulus Cell

psig, but none can go as high as the strain gage.

Deadweight testers also are used as primary standards in calibrating high-pressure sensors (Figure 4-1C). The tester generates a test reference pressure when an NIST-certified weight is placed on a known piston area, which imposes a corresponding pressure on the filling fluid. (For more details, see Chapter 3 of this volume.) NIST has found that at pressures exceeding 40,000 psig, the precision of their test is about 1.5 parts in 10,000. Typical inaccuracy of an industrial deadweight tester is 1 part in 1,000 or 0.1%.

In the area of electronic sensors for high-pressure measurement, the strain gage is without equal (see Chapter 2 for more details on strain gage operation). Strain gage sensors can detect pressures in excess of 100,000 psig and can provide measurement precision of 0.1% of span or 0.25% of full scale. Temperature compensation and periodic recalibration are desirable because a 1000°F temperature change or six months of drift can also produce an additional 0.25% error. Other electronic sensors

Very High Pressures

The bulk modulus cell consists of a hollow cylindrical steel probe closed at the inner end with a projecting stem on the outer end (Figure 4-2). When exposed to a process pressure, the probe is compressed, the probe tip is moved to the right by the isotropic contraction, and the stem moves further outward. This stem motion is then converted into a pressure reading. The hysteresis and temperature sensitivity of this unit is similar to that of other elastic element pressure sensors. The main advantages of this sensor are its fast response and safety: in effect, the unit is not subject to failure. The bulk modulus cell can detect pressures up to 200,000 psig with 1% to 2% full span error.

In another high-pressure design, Manganin, gold-chromium, platinum, or lead wire sensors are wound helically on a core. The electrical resistance of these wire materials will change in proportion to the pressure experienced on their surfaces. They are reasonably insensitive to temperature variations. The pressure-resistance relationship of Manganin is positive, linear, and substantial. Manganin cells can be obtained for pressure ranges up to 400,000 psig and can provide 0.1% to 0.5% of full scale measurement precision. The main limitation of the Manganin cell is its delicate nature, making it vulnerable to damage from pressure pulsations or viscosity effects.

Some solids liquefy under high pressures. This change-of-state phenomenon also can be used as an indication of process pressure. Bismuth, for example, liquefies at between 365,000 and 375,000 psig and, when it does, it also contracts in volume. Other materials such as mercury have similar characteristics, and can be used to signal that the pressure has reached a particular value.

Vacuum Measurement

Engineers first became interested in vacuum measurements in the 1600s, when they noted the inability of pumps to raise water more than about 30 ft. The Duke of Tuscany in

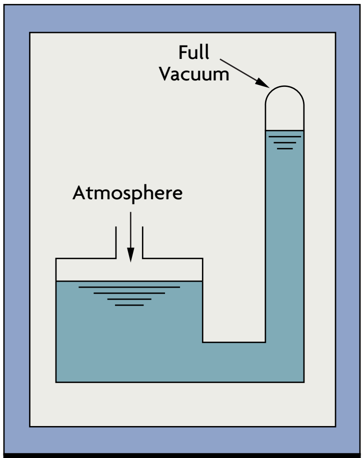

Figure 4-3: Barometer Operation

Italy commissioned Galileo to investigate the "problem." Galileo, among others, also devised a number of experiments to investigate the properties of air. Among the tools used for these experiments were pistons to measure force and a water barometer (about 34 ft. tall) (760 mm). The height of a mercury column is therefore a direct measure of the atmospheric pressure.

In 1644, French mathematician Blaise Pascal asked a group of mountaineers to carry a barometer into the Alps and proved that air pressure decreases with altitude. once at the unknown low pressure and again at a higher reference pressure. The pressurized new volume is then an indication of the initial absolute pressure. Versions of the McLeod Gauge continue to be used today as a standard for calibrating vacuum gauges.

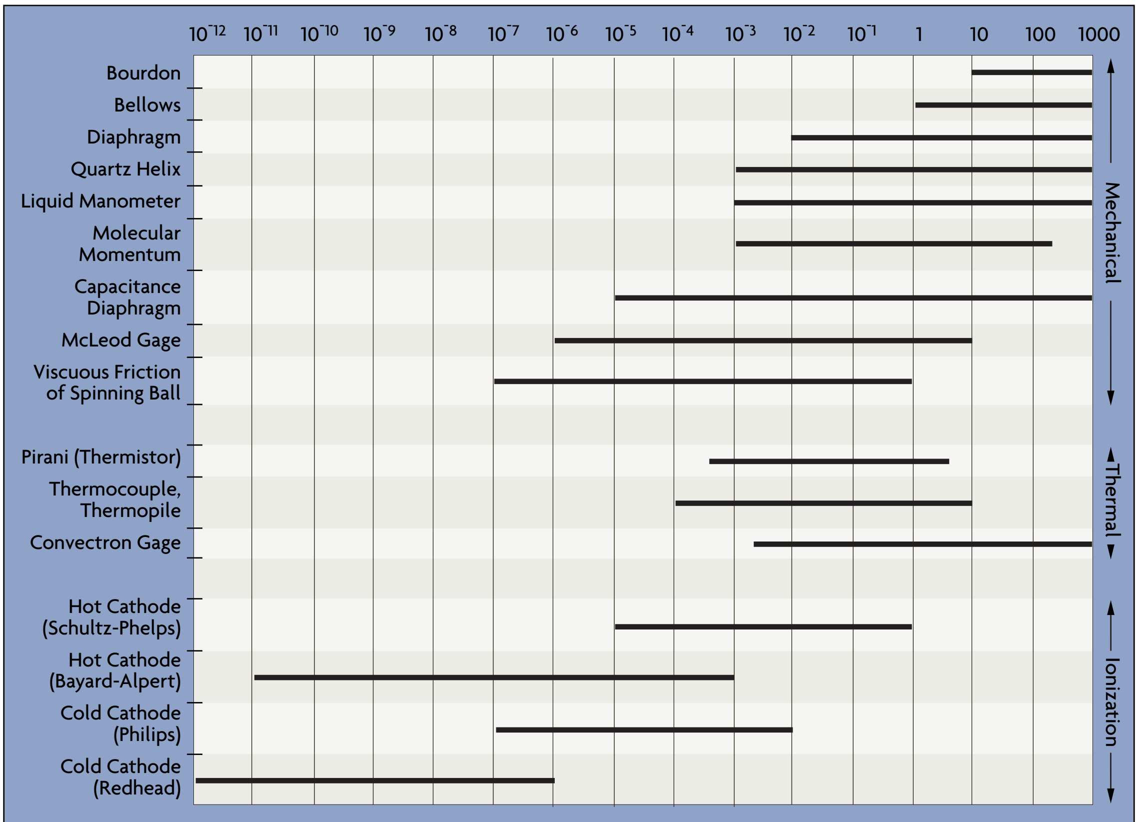

Figure 4-4: Vacuum Gauge Measurement Ranges

to measure vacuum pressure.

After Galileo's death in 1642, Evangelista Torricelli carried on the work of vacuum-related investigation and invented the mercury barometer (Figure 4-3). He discovered that the atmosphere exerts a force of 14.7 lb. per square in. (psi) and that, inside a fully evacuated tube, the pressure was enough to raise a column of mercury to a height of 29.9 in. The average barometric pressure at sea level can balance the height of a 760 mm mercury column, and this pressure is defined as a standard Atmosphere. The value for 1/760th of an atmosphere is called a torr, in honor of Torricelli.

In 1872, McLeod invented the McLeod vacuum detector gauge, which measures the pressure of a gas by measuring its volume twice,

Applications

Vacuum gauges in use today fall into three main categories: mechanical, thermal, and ionization. Their pressure ranges are given in Figure 4-4. In general, for high vacuum services (around 10^{-6} torr), either cold cathode or Bayard-Alpert hot cathode gauges are suitable. Neither is particularly accurate or stable, and both require frequent calibration.

For vacuums in the millitorr range (required for sputtering applications), one might consider a hot cathode ion gauge. For more accurate measurements in this intermediate range, the capacitance manometer is a good choice. For intermediate vacuum applications (between 10^{-4} and 10^{-2} torr), capacitance manometers are the best in terms of performance, but are also the most expensive. The lowest priced gauge is the thermocouple type, but its error is the greatest. Digital Pirani gauges can represent a good compromise solution, with accuracy between that of capacitance and thermocouple sensors.

For low vacuums (higher pressures) between atmospheric and 10^{-2} torr, Bourdon tubes, bellows, active strain gages, and capacitance sensors are all suitable.

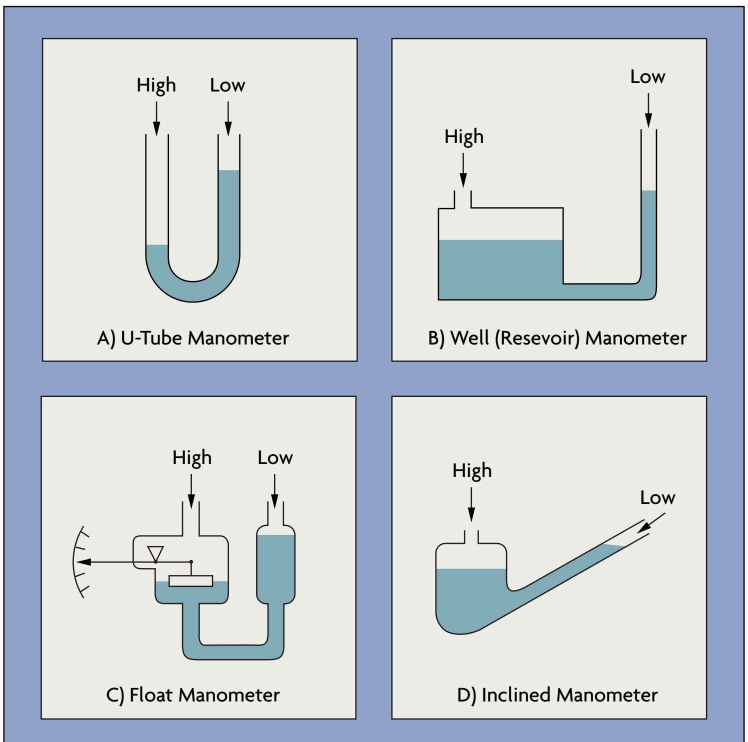

Figure 4-5: Manometer Designs

Mechanical Designs

Mechanical gauges measure pressure or vacuum by making use of the mechanical deformation of tubes or diaphragms when exposed to a difference in pressure. Typically, one side of the element is exposed to a reference vacuum and the instrument measures the mechanical deformation that occurs when an unknown vacuum pressure is exposed to the other side.

Quartz Bourdon Tube: Similar to a standard Bourdon tube, this gauge uses a quartz helix element, but instead of moving linkages, the deformation rotates a mirror. When used for vacuum detection, two quartz Bourdon elements are formed into a helix. The reference side contains a sealed vacuum and the measurement side is connected to the unknown process vacuum. The pressure difference between the two sides causes an angular deflection that is detected optically.

The optical readout has a high resolution, about one part in 100,000. Advantages of this sensor are its precision and the corrosion resistance of quartz. Its main limitation is high price.

Manometer: A basic manometer can consist of a reservoir filled with a liquid and a vertical tube (Figure 4-5). When detecting vacuums, the top of the column is sealed evacuated. A manometer without a reservoir is simply a U-shaped tube, with one leg sealed and evacuated and the other connected to the unknown process pressure (Figure 4-5A). The difference in the two column heights indicates the process vacuum. An inclined manometer (Figure 4-5D) can consist of a well and transparent tube mounted at an angle. A small change in vacuum pressure will cause a relatively large movement of the liquid. Manometers are simple, low cost, and can detect vacuums down to 1 millitorr.

Capacitance Manometer: A capacitance sensor operates by measuring the change in electrical capacitance that results from the movement of a sensing diaphragm relative to some fixed capacitance electrodes (Figure 4-6). The higher the process vacuum, the farther it will pull the measuring diaphragm away from the fixed capacitance plates. In some designs, the diaphragm is allowed to move. In others, a variable dc voltage is applied to keep the sensor's Wheatstone bridge in a balanced condition. The amount of voltage required is directly related to the pressure.

The great advantage of a capacitance gauge is its ability to detect extremely small diaphragm movements. Accuracy is typically 0.25 to 0.5% of reading. Thin diaphragms can measure down to 10^{-5} torr, while thicker diaphragms can measure in the low vacuum to atmospheric range. To cover a wide vacuum range, one can connect two or more capacitance sensing heads into a multi-range package.

The capacitance diaphragm gauge is widely used in the semiconductor industry, because its Inconel body and diaphragm are suitable for the corrosive services of this industry. They are also favored because of their high accuracy and immunity to contamination.

McLeod Gauge: Originally invented in 1878, the McLeod gauge measures the pressure of gases by compressing a known volume with a fixed pressure. The new volume is then a measure of the initial absolute pressure. Little changed since the day it was invented, the McLeod gauge has been used until recently for calibrating other gauges. It covers the vacuum range between 1 and 10^{-6} torr.

Molecular Momentum: This vacuum gauge is operated with a rotor that spins at a constant speed. Gas molecules in the process sample come in contact with the rotor and are propelled into the restrained cylinder. The force of impact drives the cylinder to a distance proportional to the energy transferred, which is a measure of the number of gas molecules in that space. The full scale of the instrument depends on the gas being measured. The detector has to be calibrated for each application.

Viscous Friction: At high vacuums, viscosity and friction both depend on pressure. This instrument measures vacuums down to 10^{-7} torr by detecting the deceleration caused by molecular friction on a ball that is spinning in a magnetic field. Vacuum is determined by measuring the length of time it takes for the ball to drop from 425 to 405 revolutions per second after drive power is turned off. The higher the vacuum, the lower the friction and therefore the more time it will take. This design is accurate to 1.5% of reading, is resistant to corrosion, and can operate at temperatures up to 7500° F.

Thermal Designs: The thermal conductivity of a gas changes with its pressure in the vacuum range. If an element heated by a constant power source is placed in a gas, the resulting surface temperature of the element will be a function of the surrounding vacuum. Because the sensor is an electrically heated wire, thermal vacuum sensors are often called hot wire gauges. Typically, hot wire gauges can be used to measure down to 10^{-3} mm Hg.

Pirani: In this design, a sensor wire is heated electrically and the pressure of the gas is determined by measuring the current needed to keep the wire at a constant temperature. The thermal conductivity of each gas is different, so the gauge has to be calibrated for the individual gas being measured. A Pirani gauge will not work to detect pressures above 1.0 torr, because, above these pressures, the thermal conductivity of the gases no longer changes with pressure. The Pirani gauge is linear in the 10^{-2} to 10^{-4} torr range. Above these pressures, output is roughly logarithmic. Pirani gauges are inexpensive, convenient, and reasonably accurate. They are 2% accurate at the calibration point and 10% accurate over the operating range.

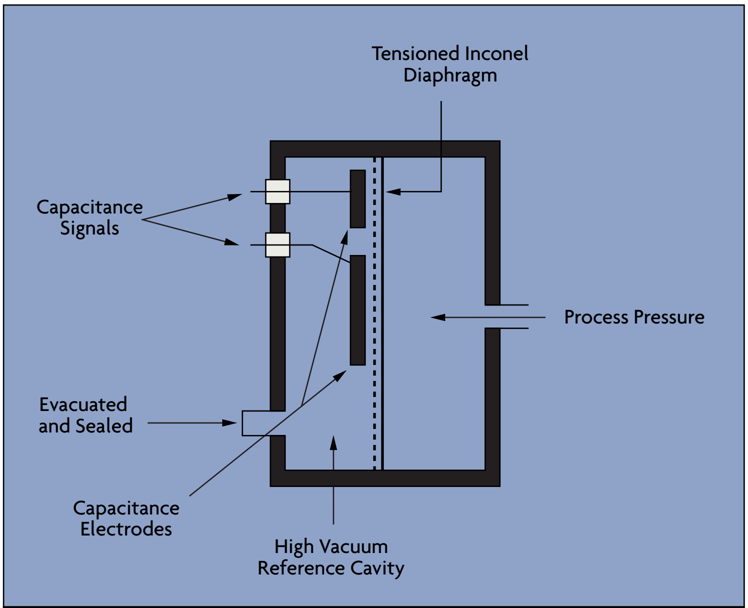

Figure 4-6: Capacitance Vacuum Manometer

Thermocouple: The thermocouple gauge relates the temperature of a filament in the process gas to its vacuum pressure. The filament is heated by a constant current of 20-200 mA dc, and the thermocouple generates an output of about 20 mV dc. The heater wire temperature increases as pressure is reduced.

Typical thermocouple gauges measure 1 millitorr to 2 torr. This range can be increased by use of a gauge controller with a digital/analog converter and digital processing. Using an industry standard thermocouple sensor, such a gauge controller can extend the range of a thermocouple sensor to cover from 10^{-3} to 1,000 torr, thereby giving it the same range as a convection-type Pirani gauge but at a lower price.

Convection Gauge: Similar to the Pirani gauge, this sensor uses a temperature-compensated, gold-plated tungsten wire to detect the cooling effects of both conduction and convection, and thereby extends the sensing range. At higher vacuums, response depends on the thermal conductivity of the gas, while at lower vacuums it depends on convective cooling by the gas molecules. Measurement range is from 10^{-3} to 1,000 torr. With the exception of its expanded range, features and limitations of this sensor are the same as those of Pirani and most thermocouple gauges.

Combined Gauges: To get around the range limitations of certain sensors, gauge manufacturers have devised means for electronically linking multiple sensor heads. For example, one manufacturer offers a wide-range vacuum gauge that incorporates two pressure sensors in one housing: a fast response diaphragm manometer for measurements between 1,500 torr and 2 torr, and a Pirani gauge for measuring between 2 torr and 1 millitorr. The gauge controller automatically switches between the two sensors.

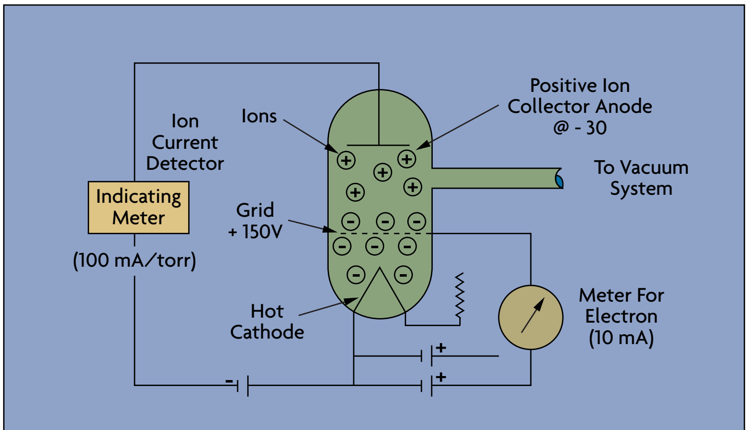

Figure 4-7: Hot-Cathode Vacuum Gauge

Ionization Types: Ionization detectors have been available since 1916. They measure vacuum by making use of the current carried by ions formed in the gas by the impact of electrons. Two types are available: hot cathode and cold cathode.

Refined by Bayard-Alpert in 1950, the hot filament off the hot-cathode gauge emits electrons into the vacuum, where they collide with gas molecules to create ions (Figure 4-7). These positively charged ions are accelerated toward a collector where they create a current in a conventional ion gauge detector circuit. The amount of current formed is proportional to the gas density or pressure. Most hot-cathode sensors measure vacuum in the range of 10^{-2} to 10^{-10} torr.

Newer instruments extend this range significantly by using a modulated electron beam, synchronously detected to give two values for ion current. At pressures below 10^{-3} torr, there is little difference in the two values. At higher pressures, the ratio between the two readings increases monotonically, allowing the gauge to measure vacuums up to 1 torr.

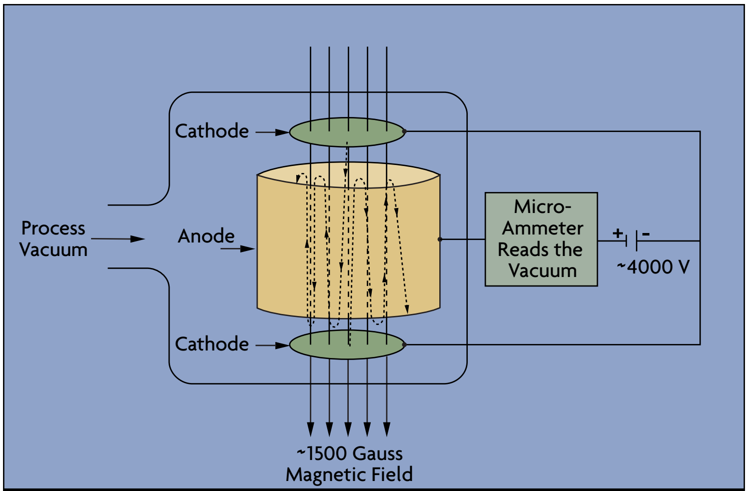

Figure 4-8: Cold-Cathode Vacuum Gauge

Because most high-vacuum systems were made of glass in 1950, it made sense to enclose the electrode structure in glass. Today, however, a modern vacuum system may be made entirely of metal. One argument in favor of this is that glass decomposes during routine degassing, producing spurious sodium ions and other forms of contamination. Nevertheless, glass gauges for the time being do remain the most popular hot cathode sensors.

Cold Cathode: The major difference between hot and cold cathode sensors is in their methods of electron production. In a cold cathode device, electrons are drawn from the electrode surface by a high potential field. In the Phillips design (Figure 4-8), a magnetic field around the tube deflects the electrons, causing them to spiral as they move across the magnetic field to the anode. This spiraling increases the opportunity for them to encounter and ionize the molecules. Typical measuring range is from 10^{-10} to 10^{-2} torr. The main advantages of cold cathode devices are that there are no filaments to burn out, they are unaffected by the inrush of air, and they are relatively insensitive to vibration. T

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Pressure Gauges & Switches

Pressure gauges and switches are among the most often used instruments in a plant. But because of their great numbers, attention to maintenance—and reliability—can be compromised. As a consequence, it is not uncommon in older plants to see many gauges and switches out of service. This is unfortunate because, if a plant is operated with a failed pressure switch, the safety of the plant may be compromised. Conversely, if a plant can operate safely while a gauge is defective, it shows that the gauge was not needed in the first place. Therefore, one goal of good process instrumentation design is to install fewer but more useful and more reliable pressure gauges and switches.

One way to reduce the number of gauges in a plant is to stop installing them on the basis of habit (such as placing a pressure gauge on the discharge of every pump). Instead, review the need for each device individually. During the review one should ask: "What will I do with the reading of this gauge?" and install one only if there is a logical answer to the question. If a gauge only indicates that a pump is running, it is not needed, since one can hear and see that. If the gauge indicates the pressure (or pressure drop) in the process, that information is valuable only if one can do something about it (like cleaning a filter); otherwise it is useless. If one approaches the specification of pressure gauges with this mentality, the number of gauges used will be reduced. If a plant uses fewer, better gauges, reliability will increase.

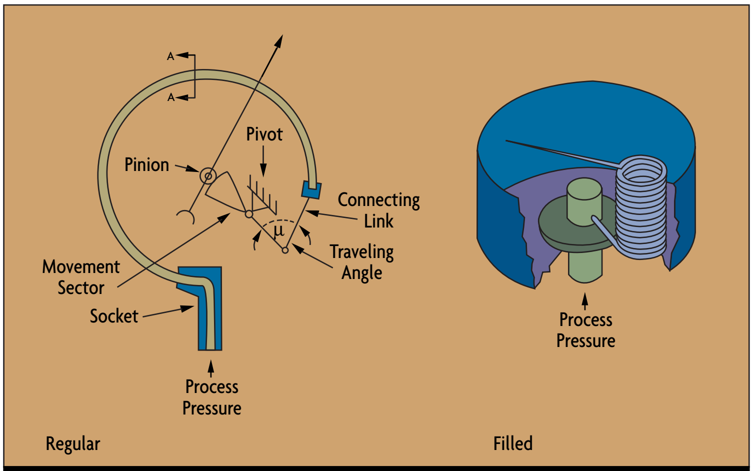

Figure 5-1: Pressure Gauge Designs

Pressure Gauge Designs

Two common reasons for gauge (and switch) failure are pipe vibration and water condensation, which in colder climates can freeze and damage the

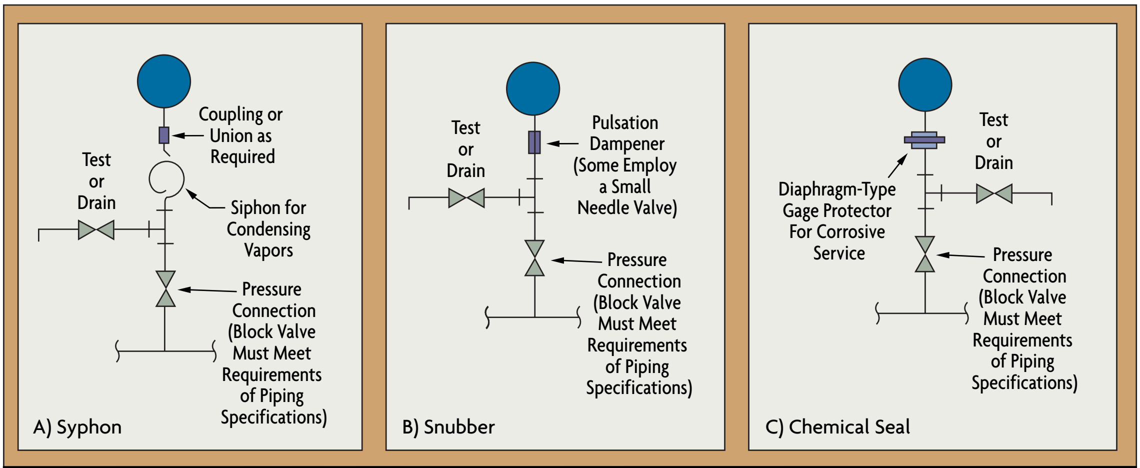

Figure 5-2: Pressure Gauge Accessories

gauge housing. Figure 5-1 illustrates the design of both a traditional and a more reliable, "filled" pressure gauge.


Pressure switches with adjustable setpoints.

The delicate links, pivots, and pinions of a traditional gauge are sensitive to both condensation and vibration. The life of the filled gauge is longer, not only because it has fewer moving parts, but because its housing is filled with a viscous oil. This oil filling is beneficial not only because it dampens pointer vibration, but also because it leaves no room for humid ambient air to enter. As a result, water cannot condense and accumulate.

Available gauge features include illuminated dials and digital readouts for better visibility, temperature compensation to correct for ambient temperature variation, differential gauges for differential pressures, and duplex gauges for dual pressure indication on the same dial. Pressure gauges are classified according to their precision, from grade 4A (permissible error of 0.1% of span) to grade D (5% error).

Protective Accessories

The most obvious gauge accessory is a shutoff valve between it and the process (Figure 5-2), which allows blocking while removing or performing maintenance. A second valve is often added for one of two reasons: draining of condensate in vapor service (such as steam), or, for higher accuracy applications, to allow calibration against an external pressure source.

Other accessories include pipe coils or siphons (Figure 5-2A), which in steam service protect the gauge from temperature damage, and snubbers or pulsation dampeners (Figure 5-2B), which can both absorb pressure shocks and average out pressure fluctuations. If freeze protection is needed, the gauge should be heated by steam or electric tracing.

Chemical seals (Figure 5-2C) protect the gauge from plugging up in viscous or slurry service, and prevent corrosive, noxious or poisonous process materials from reaching the sensor. They also keep the process fluid from freezing or gelling in a dead-ended sensor cavity. The seal protects the gauge by placing a diaphragm between the process and the gauge. The cavity between the gauge and the diaphragm is filled with a stable, low thermal expansion, low viscosity and non-corrosive fluid. For high temperature applications, a sodium-potassium eutectic often is used; at ambient temperatures, a mixture of glycerine and water; and at low temperatures, ethyl alcohol, toluene, or silicon oil.

The pressure gauge can be located for better operator visibility if the chemical seal is connected to the gauge by a capillary tube. To maintain accuracy, capillary tubes should not be exposed to excessive temperatures and should not exceed 25 feet (7.5 m) in length. The chemical seal itself can be of four designs: off line, "flow-through" type self-cleaning, extended seal elements, or wafer elements that fit between flanges.

The spring rate of the diaphragm in the chemical seal can cause measurement errors when detecting low pressures (under 50 psig, 350 kPa) and in vacuum service (because gas bubbles dissolved in the filling fluid might come out of solution). For these reasons, pressure repeaters often are preferred to seals in such service. Pressure repeaters are available with 0.1% to 1% of span accuracy and with absolute pressure ranges from 0-5 mm Hg to 0-50 psia (0-0.7 to 0-350 kPa).

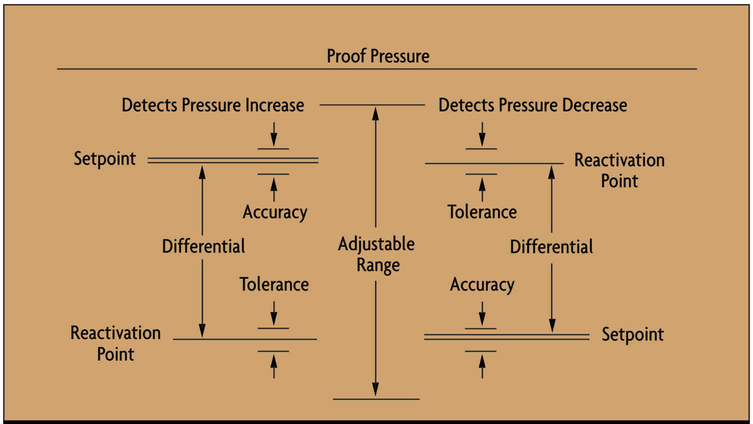

Figure 5-3: Pressure Switch Terminology


Pressure gauges come in a wide variety of ranges and units.

Pressure Switches

Pressure switches serve to energize or de-energize electrical circuits as a function of whether the process pressure is normal or abnormal. The electric contacts can be configured as single pole double throw (SPDT), in which case the switch is provided with one normally closed (NC) and one normally open (NO) contact. Alternately, the switch can be configured as double pole double throw (DPDT), in which case two SPDT switches are furnished, each of which can operate a separate electric circuit. The switch housings can meet any of the NEMA standards from Type 1 (general purpose) to Type 7 (explosion proof), or Type 12 (oil tight).

Figure 5-3 illustrates the terminology used to describe pressure switch functionality and performance. When the pressure reaches the setpoint (which is adjustable within the range), the switch signals an "abnormal condition" and it does not return to "normal" (the reactivation point) until the pressure moves away from the abnormal condition by the "differential" (also called dead-band). The precision of setpoint actuation is called its "accuracy," while the precision of reactivation is called "tolerance." T

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Force, Acceleration, & Torque

The fundamental operating principles of force, acceleration, and torque instrumentation are closely allied to the piezoelectric and strain gage devices used to measure static and dynamic pressures discussed in earlier chapters. It is often the specifics of configuration and signal processing that determine the measurement output.

An accelerometer senses the motion of the surface on which it is mounted and produces an electrical output signal related to that motion. Acceleration is measured in feet per second squared, and the product of the acceleration and the measured mass yields the force. Torque is a twisting force, usually encountered on shafts, bars, pulleys, and similar rotational devices. It is defined as the product of the force and the radius over which it acts. It is expressed in units of weight times length, such as lb.-ft. and N-m.

Force Sensors

The most common dynamic force and acceleration detector is the piezoelectric sensor (Figure 6-1). The word piezo is of Greek origin, and it means "to squeeze." This is quite appropriate, because a piezoelectric sensor produces a voltage when it is "squeezed" by a force that is proportional to the force applied. The fundamental difference between these devices and static force detection devices such as strain gages is that the electrical signal generated by the crystal decays rapidly after the application of force. This makes these devices unsuitable for the detection of static force.

The high impedance electrical signal generated by the piezoelectric crystal is converted (by an amplifier) to a low impedance signal suitable for such an instrument as a digital storage oscilloscope. Digital storage of the signal is required in order to allow analysis of the signal before it decays.

Depending on the application requirements, dynamic force can be measured as either compression, tensile, or torque force. Applications may include the measurement of spring or sliding friction forces, chain tensions, clutch release forces, or peel strengths of laminates, labels, and pull tabs.

A piezoelectric force sensor is almost as rigid as a comparably proportioned piece of solid steel. This stiffness and strength allows these sensors to be directly inserted into machines as part of their structure. Their rigidity provides them with a high natural frequency, and their

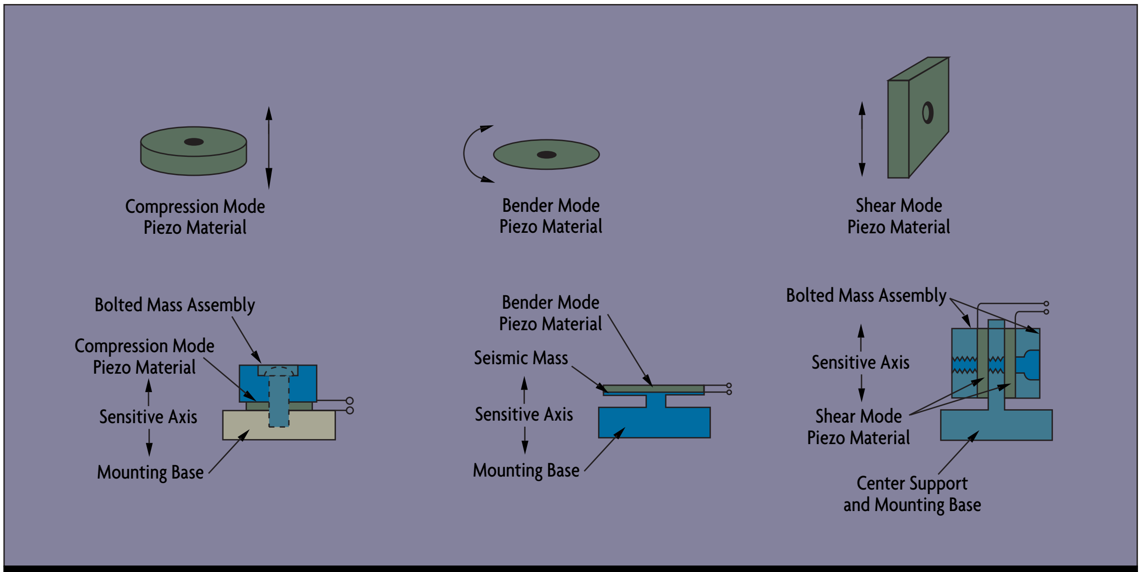

Figure 6-1: Piezoelectric Sensor Element Designs

Tiny accelerometer is useful for low-mass laboratory applications.

corresponding rapid rise time makes them ideal for measuring such quick transient forces as those generated by metal-to-metal impacts and by high frequency vibrations. To ensure accurate measurement, the natural frequency of the sensing device must be substantially higher than the frequency to be measured. If the measured frequency approaches the natural frequency of the sensor, measurement errors will result.

• Impact Flowmeters

The impact flowmeter is also a force sensor. It measures the flow rate of free flowing bulk solids at the discharge of a material chute. The chute directs the material flow so that it impinges on a sensing plate (Figure 6-2). The impact force exerted on the plate by the material is proportional to the flow rate.

The construction is such that the sensing plate is allowed to move only in the horizontal plane. The impact force is measured by sensing the horizontal deflection of the plate. This deflection is measured by a linear variable differential transformer (LVDT). The voltage output of the LVDT is converted to a pulse frequency modulated signal. This signal is transmitted as the flow signal to the control system.

Impact flowmeters can be used as alternatives to weighing systems to measure and control the flow of bulk solids to continuous processes as illustrated in Figure 6-2. Here, an impact flowmeter is placed below the material chute downstream of a variable speed screw feeder. The feed rate is set in tons per hour, and the control system regulates the speed of the screw feeder to attain the desired feed rate. The control system uses a PID algorithm to adjust the speed as needed to keep the flow constant. Impact flowmeters can measure the flow rate of some bulk materials at rates from 1 to 800 tons per hour and with repeatability and linearity within 1%.

Acceleration & Vibration

Early acceleration and vibration sensors were complex mechanical contraptions (Figure 6-3) and were better suited for the laboratory than the plant floor. Modern accelerometers, however, have benefited from the advance of technology: their cost, accuracy, and ease of use all have improved over the years.

Early accelerometers were analog electronic devices that were later converted into digital electronic and microprocessor-based designs. The air-bag controls of the automobile industry use hybrid micro-electro-mechanical systems (MEMS). These devices rely on what was once considered a flaw in semiconductor design: a "released layer" or loose piece of circuit material in the micro-space above the chip surface. In a digital circuit, this loose layer interferes with the smooth flow of electrons, because it reacts with the surrounding analog environment.

In a MEMS accelerometer, this loose layer is used as a sensor to measure acceleration. In today's

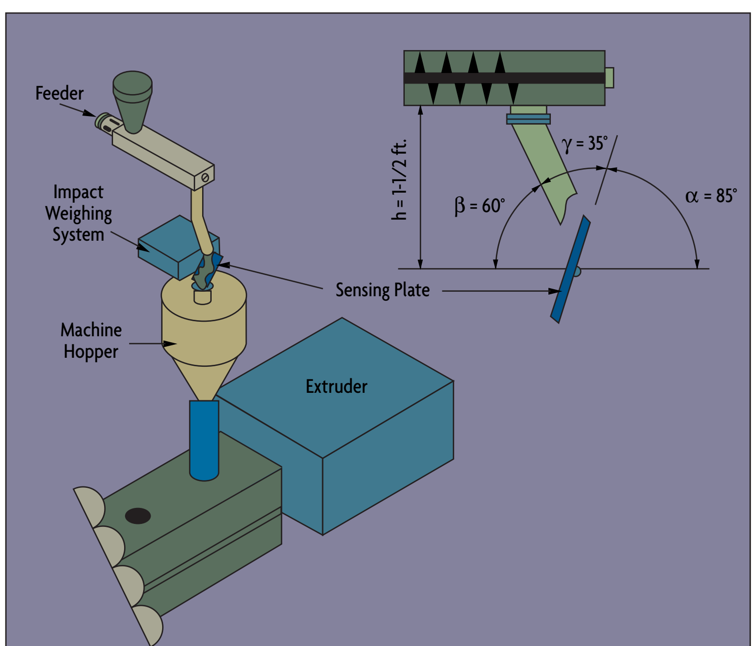

Figure 6-2: Impact Flowmeter Application

autos, MEMS sensors are used in air bag and chassis control, in side-impact detection and in antilock braking systems. Auto industry acceleration sensors are available for frequencies from 0.1 to 1,500 Hz, with dynamic ranges of 1.5 to 250 G around 1 or 2 axes, and with sensitivities of 7.62 to 1333 mV/G.

Industrial applications for accelerometers include machinery vibration monitoring to diagnose, for example, out-of-balance conditions of rotating parts. An accelerometer-based vibration analyzer can detect abnormal vibrations, analyze the vibration signature, and help identify its cause.

Another application is structural testing, where the presence of a structural defect, such as a crack, bad weld, or corrosion can change the vibration signature of a structure. The structure may be the casing of a motor or turbine, a reactor vessel, or a tank. The test is performed by striking the structure with a hammer, exciting the structure with a known forcing function. This generates a vibration pattern that can be recorded, analyzed, and compared to a reference signature.

Acceleration sensors also play a role in orientation and direction-finding. In such applications, miniature triaxial sensors detect changes in roll, pitch, and azimuth (angle of horizontal deviation), or X, Y, and Z axes. Such sensors can be used to track drill bits in drilling operations, determine orientation for buoys and sonar systems, serve as compasses, and replace gyroscopes in inertial navigation systems.

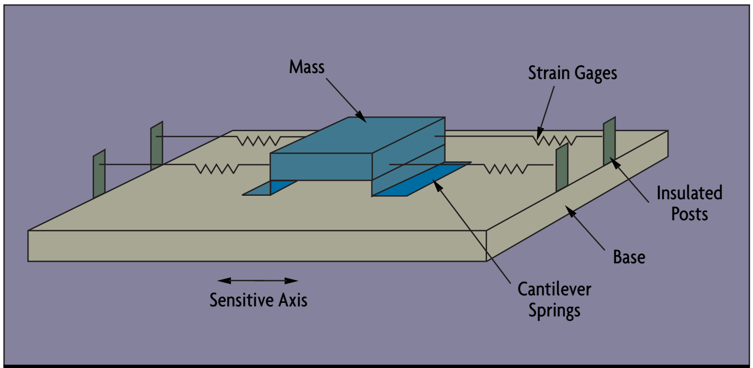

Figure 6-3: Early Mechanical Vibration Sensor


Industrial accelerometer with associated electronics.

Mechanical accelerometers, such as the seismic mass accelerometer, velocity sensor, and the mechanical magnetic switch, detect the force imposed on a mass when acceleration occurs. The mass resists the force of acceleration and thereby causes a deflection or a physical displacement, which can be measured by proximity detectors or strain gages (Figure 6-3). Many of these sensors are equipped with dampening devices such as springs or magnets to prevent oscillation.

A servo accelerometer, for example, measures accelerations from 1 microG to more than 50 G. It uses a rotating mechanism that is intentionally imbalanced in its plane of rotation. When acceleration occurs, it causes an angular movement that can be sensed by a proximity detector.

Among the newer mechanical accelerometer designs is the thermal accelerometer: This sensor detects position through heat transfer. A seismic mass is positioned above a heat source. If the mass moves because of acceleration, the proximity to the heat source changes and the temperature of the mass changes. Polysilicon thermopiles are used to detect changes in temperature.

In capacitance sensing accelerometers, micromachined capacitive plates (CMOS capacitor plates only

60 microns deep) form a mass of about 50 micrograms. As acceleration deforms the plates, a measurable change in capacitance results. But piezoelectric accelerometers are perhaps the most practical devices for measuring shock and vibration. Similar to a mechanical sensor, this device includes a mass that, when accelerated, exerts an inertial force on a piezoelectric crystal.

In high temperature applications where it is difficult to install microelectronics within the sensor, high impedance devices can be used. Here, the leads from the crystal sensor are connected to a high gain amplifier. The output, which is proportional to the force of acceleration, is then read by the high gain amplifier. Where temperature is not excessive, low impedance microelectronics can be embedded in the sensor to detect the voltages generated by the crystals. Both high and low impedance designs can be mechanically connected to the structure's surface, or secured to it by adhesives or magnetic means. These piezoelectric sensors are suited for the measurement of short durations of acceleration only.

Piezoresistive and strain gage sensors operate in a similar fashion, but strain gage elements are temperature sensitive and require compensation. They are preferred for low frequency vibration, long-duration shock, and constant acceleration applications. Piezoresistive units are rugged, and can operate at frequencies up to 2,000 Hz.

Torque Measurement

Torque is measured by either sensing the actual shaft deflection caused by a twisting force, or by detecting the effects of this deflection. The surface of a shaft under torque will experience compression and tension, as shown in Figure 6-4. To measure torque, strain gage elements usually are mounted in pairs on the shaft, one gauge measuring the increase in length (in the direction in which the surface is under tension), the other measuring the decrease in length in the other direction.

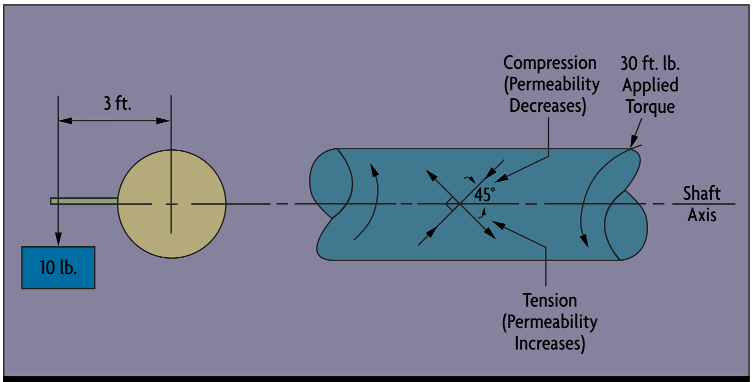

Figure 6-4: Torque on a Rotating Shaft

Early torque sensors consisted of mechanical structures fitted with strain gages. Their high cost and low reliability kept them from gaining general industrial acceptance. Modern technology, however, has lowered the cost of making torque measurements, while quality controls on production have increased the need for accurate torque measurement.

Torque Applications

Applications for torque sensors include determining the amount of power an engine, motor, turbine, or other rotating device generates or consumes. In the industrial world, ISO 9000 and other quality control specifications are now requiring companies to measure torque during manufacturing, especially when fasteners are applied. Sensors make the required torque measurements automatically on screw and assembly machines, and can be added to hand tools. In both cases, the collected data can be accumulated on dataloggers for quality control and reporting purposes.

Other industrial applications of torque sensors include measuring metal removal rates in machine tools; the calibration of torque tools and sensors; measuring peel forces, friction, and bottle cap torque; testing springs; and making biodynamic measurements.

Sensor Configurations

Torque can be measured by rotating strain gages as well as by stationary proximity, magnetostrictive, and magnetoelastic sensors. All are temperature sensitive. Rotary sensors must be mounted on the shaft, which may not always be possible because of space limitations.

A strain gage can be installed directly on a shaft. Because the shaft is rotating, the torque sensor can be connected to its power source and signal conditioning electronics via a slip ring. The strain gage also can be connected via a transformer, eliminating the need for high maintenance slip rings. The excitation voltage for the strain gage is inductively coupled, and the strain gage output is converted to a modulated pulse frequency (Figure 6-5). Maximum speed of such an arrangement is 15,000 rpm.

Strain gages also can be mounted on stationary support members or on the housing itself. These “reaction” sensors measure the torque that is transferred by the shaft to the restraining elements. The resultant reading is not completely accurate, as it disregards the inertia of the motor.

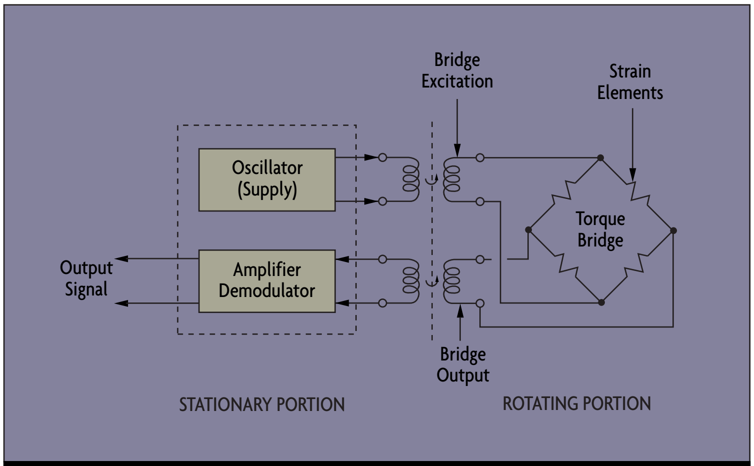

Figure 6-5: Inductive Coupling of Torque Sensors

Strain gages used for torque measurements include foil, diffused semiconductor, and thin film types. These can be attached directly to the shaft by soldering or adhesives. If the centrifugal forces are not large—and an out-of-balance load can be tolerated—the associated electronics, including battery, amplifier, and radio frequency transmitter all can be strapped to the shaft.


Reaction torque cell with flange mounts.

Proximity and displacement sensors also can detect torque by measuring the angular displacement between a shaft’s two ends. By fixing two identical toothed wheels to the shaft at some distance apart, the angular displacement caused by the torque can be measured. Proximity sensors or photocells located at each toothed wheel produce output voltages whose phase difference increases as the torque twists the shaft.

Another approach is to aim a single photocell through both sets of toothed wheels. As torque rises and causes one wheel to overlap the other, the amount of light reaching the photocell is reduced. Displacements caused by torque can also be detected by other optical, inductive, capacitive, and potentiometric sensors. For example, a capacitance-type torque sensor can measure the change in capacitance that occurs when torque causes the gap between two capacitance plates to vary.

The ability of a shaft material to concentrate magnetic flux—magnetic permeability—also varies with torque and can be measured using a magnetostrictive sensor. When the shaft has no loading, its permeability is uniform. Under torsion, permeability and the number of flux lines increase in proportion to torque. This type of sensor can be mounted to the side of the shaft using two primary and two secondary windings. Alternatively, it can be arranged with many primary and secondary windings on a ring around the shaft.

A magnetoelastic torque sensor detects changes in permeability by measuring changes in its own magnetic field. One magnetoelastic sensor is constructed as a thin ring of steel tightly coupled to a stainless steel shaft. This assembly acts as a permanent magnet whose magnetic field is proportional to the torque applied to the shaft. The shaft is connected between a drive motor and the driven device, such as a screw machine. A magnetometer converts the generated magnetic field into an electrical output signal that is proportional to the torque being applied. T

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Load Cell Designs

Before strain gage-based load cells became the method of choice for industrial weighing applications, mechanical lever scales were widely used. Mechanical scales can weigh everything from pills to railroad cars and can do so accurately and reliably if they are properly calibrated and maintained. The method of operation can involve either the use of a weight balancing mechanism or the detection of the force developed by mechanical levers. The earliest, pre-strain gage force sensors included hydraulic and pneumatic designs.

In 1843, English physicist Sir Charles Wheatstone devised a bridge circuit that could measure electrical resistances. As was discussed in detail in Chapter 2, the Wheatstone bridge circuit is ideal for measuring the resistance changes that occur in strain gages. Although the first bonded resistance wire strain gage was developed in the 1940s, it was not until modern electronics caught up that the new technology became technically and economically feasible. Since that time, however, strain gages have proliferated both as mechanical scale components and in stand-alone load cells.

Today, except for certain laboratories where precision mechanical balances are still used, strain gage load cells dominate the weighing industry. Pneumatic load cells are sometimes used where intrinsic safety and hygiene are desired, and hydraulic load cells are considered in remote locations, as they do not require a power supply. Strain gage load cells offer accuracies from within 0.03% to 0.25% full scale and are suitable for almost all industrial applications.

In applications not requiring great accuracy—such as in bulk material handling and truck weighing—mechanical platform scales are still widely used. However, even in these applications, the forces transmitted by mechanical levers often are detected by load cells because of their inherent compatibility with digital, computer-based instrumentation. The features and capabilities of the various load cell designs are summarized in Figure 7-1.

Figure 7-1: Load Cell Performance Comparison

TYPE OF LOAD CELL	WEIGHT RANGE	ACCURACY (FS)	APPLICATIONS	ADVANTAGES	DISADVANTAGES
Mechanical Cells					
Hydraulic	Up to 10,000,000 lb	0.25%	Tanks, bins and hoppers Hazardous areas	Takes high impacts, insensitive to temperature	Expensive, complex
Pneumatic	Wide	High	Food industry, hazardous areas	Intrinsically safe Contains no fluids	Slow response Requires clean, dry air
Strain Gage Cells					
Bending Beam	10-5,000 lb	0.03%	Tanks, platform scales	Low cost, simple construction	Strain gages are exposed, require protection
Shear Beam	10-5,000 lb	0.03%	Tanks, platforms scales, off-center loads	High side load rejection, better sealing and protection	
Canister	to 500,000 lb	0.05%	Truck, tank, track, and hopper scales	Handles load movements	No horizontal load protection
Ring and Pancake	5-500,000 lb		Tanks, bins, scales	All stainless steel	No load movement allowed
Button and Washer	0-50,000 lb 0-200 lb typ.	1%	Small scales	Small, inexpensive	Loads must be centered, no load movement permitted
Other Types					
Helical	0-40,000 lb	0.2%	Platform, forklift, wheel load, automative seat weight	Handles off-axis loads, overloads, shocks	
Fiber Optic		0.1%	Electrical transmission cables, stud or bolt mounts	Immune to RFI/EMI and high temps, intrinsically safe	
Piezoresistive		0.03%		Extremely sensitive, high signal output level	High cost, nonlinear output

Operating Principles

Load cell designs can be distinguished according to the type of output signal generated (pneumatic, hydraulic, electric) or according to the way they detect weight (bending,

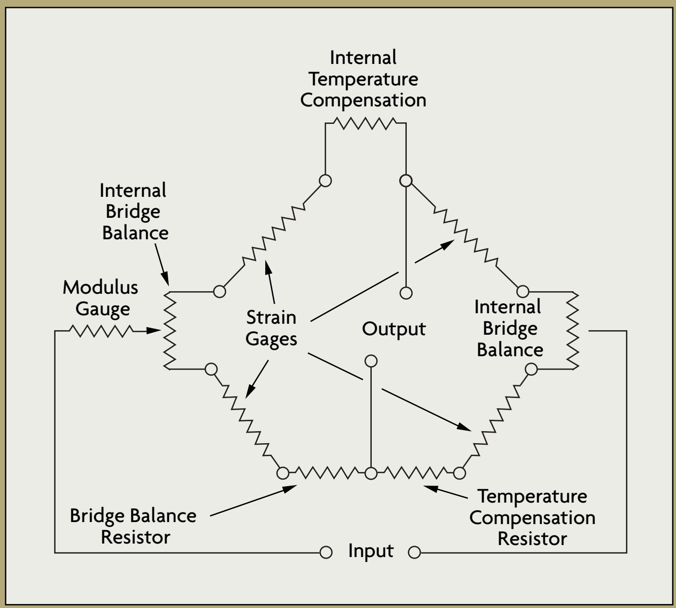

Figure 7-2: Wheatstone Circuit with Compensation

shear, compression, tension, etc.)

Hydraulic load cells are force -balance devices, measuring weight as a change in pressure of the internal filling fluid. In a rolling diaphragm type hydraulic load cell, a load or force acting on a loading head is transferred to a piston that in turn compresses a filling fluid confined within an elastomeric diaphragm chamber. As force increases, the pressure of the hydraulic fluid rises. This pressure can be locally indicated or transmitted for remote indication or control. Output is linear and relatively unaffected by the amount of the filling fluid or by its temperature. If the load cells have been properly installed and calibrated, accuracy can be within 0.25% full scale or better, acceptable for most process weighing applications. Because this sensor has no electric components, it is ideal for use in hazardous areas.

One drawback is that the elastomeric diaphragm limits the maximum force that can be exerted on the piston to about 1,000 psig. All-metal load cells also are available and can accommodate much higher pressures. Special metal diaphragm load cells have been constructed to detect weights up to 10,000,000 pounds.

Typical hydraulic load cell applications include tank, bin, and hopper weighing. For maximum accuracy, the weight of the tank should be obtained by locating one load cell at each point of support and summing their outputs. As three points define a plane, the ideal number of support points is three. The outputs of the cells can be sent to a hydraulic totalizer that sums the load cell signals and generates an output representing their sum. Electronic totalizers can also be used.

Pneumatic load cells also operate on the force-balance principle. These devices use multiple dampener chambers to provide higher accuracy than can a hydraulic device. In some designs, the first dampener chamber is used as a tare weight chamber. Pneumatic load cells are often used to measure relatively small weights in industries where cleanliness and safety are of prime concern.

The advantages of this type of load cell include their being inherently explosion proof and insensitive to temperature variations. Additionally, they contain no fluids that might contaminate the process if the diaphragm ruptures. Disadvantages include relatively slow speed of response and the need for clean, dry,

Button-style compression load cells.

regulated air or nitrogen.

Strain-gage load cells convert the load acting on them into electrical signals. The gauges themselves are bonded onto a beam or structural member that deforms when weight is applied. In most cases, four strain gages are used to obtain maximum sensitivity and temperature compensation. Two of the gauges are usually in tension, and two in compression, and are wired with compensation adjustments as shown in Figure 7-2. When weight is applied, the strain changes the electrical resistance of the gauges in proportion to the load.


"S" beam load cell for compression or tension applications.

Other load cells are fading into obscurity, as strain gage load cells continue to increase their accuracy and lower their unit costs. Some designs, however do continue to enjoy limited use:

- *Piezoresistive:* Similar in operation to strain gages, piezoresistive sensors generate a high level output signal, making them ideal for simple weighing systems because they can be connected directly to a readout meter. The availability of low cost linear amplifiers has diminished this advantage, however. An added drawback of piezoresistive devices is their nonlinear output.
- *Inductive and reluctance:* Both of these devices respond to the weight-proportional displacement of a ferromagnetic core. One changes the inductance of a solenoid coil due to the movement of its iron core; the other changes the reluctance of a very small air gap.
- *Magnetostrictive:* The operation of this sensor is based on the change in permeability of ferromagnetic materials under applied stress. It is built from a stack of laminations forming a load-bearing column around a set of primary and secondary transformer windings. When a load is applied, the stresses cause distortions in the flux pattern, generating an output signal proportional to the applied load. This is a rugged sensor and continues to be used for force and weight measurement in rolling mills and strip mills.

New Sensor Developments

In the area of new sensor developments, *fiber optic* load cells are gaining attention because of their immunity to electromagnetic and radio frequency interference (EMI/RFI), suitability for use at elevated temperatures, and intrinsically safe nature. Work continues on the development of optical load sensors. Two techniques are showing promise: measuring the micro-bending loss effect of single-mode optical fiber and measuring forces using the Fiber Bragg Grating (FBG) effect. Optical sensors based on both technologies are undergoing field trials in Hokkaido, Japan, where they are being used to measure snow loads on electrical transmission lines.

A few fiber optic load sensors are commercially available. One fiber optic strain gage can be installed by drilling a 0.5 mm diameter hole into a stud or bolt, and then inserting the strain gage into it. Such a sensor is completely insensitive to off-axis and torsion loads.

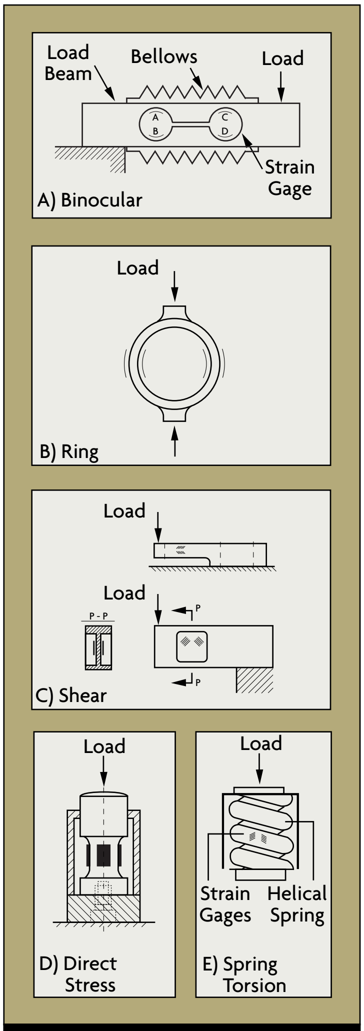

Figure 7-3: Load Cell Spring Elements

Micromachined silicon load cells have not yet arrived, but their development is underway. At the Universiteit Twente in the Netherlands, work is progressing on a packaged monolithic load cell using micromachining techniques, and it is possible that silicon load cells might dominate the industry in the future.

Strain Gage Configurations

The spring elements in a load cell (also called the "beam") can respond to direct stress, bending, or shear. They are usually called by names such as bending beam, shear beam, column, canister, helical, etc. (Figure 7-3). The two most popular designs for industrial weighing applications are the bending beam and the shear beam cells.

The ***bending beam*** sensor is one of the most popular load cell designs because of its simplicity and relatively low cost. It consists of a straight beam attached to a base at one end and loaded at the other. Its shape can be that of a cantilever beam, a "binocular" design (Figure 7-3A) or a "ring" design (Figure 7-3B). Strain gages are mounted on the top and bottom to measure tension and compression forces. Because the strain gages are vulnerable to damage, they are typically covered by a rubber bellows. The beam itself often is made of rugged alloy steel and protected by nickel plating.

In medical instrumentation, robotics, or similar low-load applications, smaller mini-beam sensors are available for measuring loads of up to about 40 pounds (18 kg). For loads up to 230 grams, the beam is made of beryllium copper, and for larger loads stainless steel is used. In this design, strain gages typically are protected by a urethane coating.

Ring or pancake designs are round and flat bending beam sensors consisting of bonded foil strain gages encapsulated in a stainless steel housing. The entire package resembles a flat pancake (Figure 7-3B). Compression-only sensors can be mounted in a protective, self-aligning assembly that limits load movement and directs the load toward the center of the pancake. Compression-tension designs have a threaded hole running completely through the center of the sensor. Stabilizing diaphragms are welded to the sensing load button.

Typical high-capacity canister load cell.

Shear beam sensors measure the shear caused by a load. A bending beam sensor cannot measure shear, because shear stresses change across the cross section of the cell. In a shear sensor, the I-beam construction produces a uniform shear that can be accurately measured by strain gages. A shear beam sensor (Figure 7-3C) is provided with a pair of strain gages installed on each side of the I-beam, with grid lines oriented along the principal axes. Advantages of a shear beam sensor over a bending beam include better handling of side loads and dynamic forces, as well as a faster return to zero.

Direct stress (or column/canister) load cells are essentially bending beam sensors mounted in a column inside a rugged, round container (Figure 7-3D). The beam sensor is mounted upright, with two of the four strain gages mounted in the longitudinal direction. The other two are oriented transversely. The column may be square, circular, or circular with flats machined on the sides to accommodate the strain gages.

If provided with a rocker assembly or with self-aligning strut bearings, a canister load cell can tolerate a certain amount of tank movement and is relatively insensitive to the point of loading. Also, the canister protects the strain gages from physical and environmental damage. Canister cells range in size from 1-1/2 in. diameter "studs" with 100-500 lb. capacity to 6-1/2 in. diameter compression cells suitable for weighing trucks, tanks, and hoppers up to 500,000 lb.

Helical load cells are better able to handle off-axis loading than are canister-type compression cells (Figure 7-3E). The operation of a helical load cell is based on that of a spring. A spring balances a load force by its own torsional moment. The torsional reaction travels from the top of the helix to the bottom. By measuring this torsional moment with strain gages mounted on the spring, a helical load cell can provide reasonably accurate load measurement without the need for expensive mounting structures. Forces caused by asymmetrical or off-axis loading have little effect on the spring, and the strain gage sensors can measure both tension and compression forces.

A helical load cell can be mounted on rough surfaces, even where the upper and lower surfaces are not parallel, and total error can still remain within 0.5%. The helical load cell also is resistant to shock and overload (it can handle a thousandfold overload), making it ideal for force or load measurements on vehicle axles, seats, or in forklift applications.

Button and flat washer bonded strain gage load cells are available in sizes from 1/4 to 1-1/2 in. diameter. The smallest sensors are available only in compression styles, but some of the larger cells have threaded holes for also measuring tension. While most of the tiny sensors handle up to about 200 lb., some are capable of measuring up to 50,000 lb. Because these little cells have no fixtures or flexures, off-axis loading and shifting loads cannot be tolerated.

On the other hand, button and flat washer load cells are extremely convenient and easy to use. Even the smallest sensor is built of stainless steel, has a built in, full four-arm Wheatstone bridge, and can measure up to 200 lb. at temperatures up to 1500°F. T

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Weighing Applications

The designs of the earliest weighing systems were based on the work of Archimedes and Leonardo Da Vinci. They used the positioning of calibrated counterweights on a mechanical lever to balance and thereby determine the size of unknown weights. A variation of this device uses multiple levers, each of a different length and balanced with a single standard weight. Later, calibrated springs replaced standard weights, and improvements in fabrication and materials have made these scales accurate and reliable.

But the introduction of hydraulic and electronic (usually strain gage-based) load cells represented the first major design change in weighing technology. In today's processing plants, electronic load cells are preferred in most applications, although mechanical lever scales are still used if the operation is manual and the operating and maintenance personnel prefer their simplicity.

Mechanical lever scales also are used for a number of applications such as motor truck scales, railroad track scales, hopper scales, tank scales, platform scales and crane scales. The zero and span shifts they experience due to gradual temperature changes can be corrected by manual adjustment or the application of correction factors. Compensation for rapid or uneven temperature changes is much more difficult, and they often cannot be corrected. Because of the accuracy and reliability of well maintained and calibrated mechanical scales, they are used as standards for trade and are acceptable to government authorities.

Spring-balance scales also are simple, and, if made of high-grade alloys (having a modulus of elasticity unaffected by temperature variations), they can be quite accurate if properly calibrated and maintained. They are inexpensive and are best suited for light loads.

The function of any weighing system is to obtain information on gross, net, or bulk weight, or some combination of these. Obtaining the net weight of a vessel's contents requires two measurements: the total weight and the weight of the unloaded container. Net weight is obtained by subtracting one from the other.

Bulk weighing involves the weighing of large quantities. The total weight is often obtained by making incremental measurements and adding up these incremental weights to arrive at the total. This allows a reduction in the size of the weighing system, reducing the cost and sometimes increasing accuracy.

Belts can also be used for bulk weighing. This is a less accurate

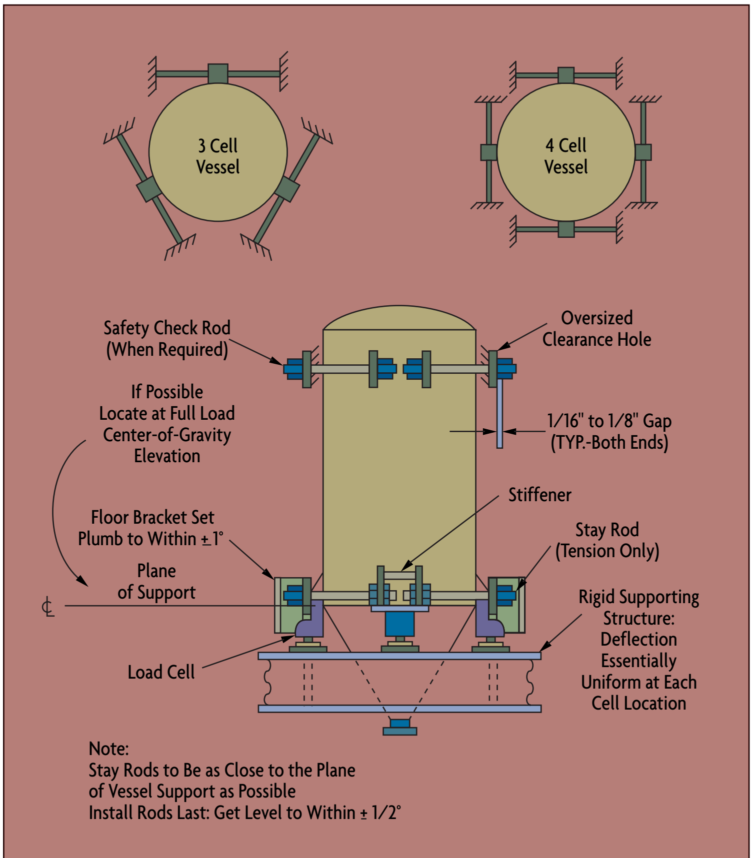

Figure 8-1: Tank Staying Arrangement

method, whereby the total bulk weight is obtained by integrating the product of the belt speed and the belt loading over some time period.

Batch weighing systems satisfy the requirements of industrial recipes by accurately dispensing a number of materials into a common receiving vessel for blending or reaction.

Weighing System Design

When a load is applied to the center line of a cylindrical load cell, it causes tension, or compression. When applied to a beam, it causes shear, or bending. Beams can be installed in either single-ended or double-ended configurations. Factors in making the decision between the two options include structural and stabilization requirements and the associated considerations of cost, complexity, and maintenance. The selected load cell should always be suitable for the operating environment in terms of its corrosion resistance, electrical safety (intrinsically safe designs are available), hose-down requirements, etc.

The first step in selecting load cells is to determine the total weight to be supported (gross weight). This is the sum of the net weight of the tank contents, the weight of the vessel and attached equipment—including relief valves, instruments, mixers and their motors, ladders, heating jackets and their contents—and any weight that might be imposed on the tank by piping or conduits. If the tare weight of the vessel is excessive compared with the contents, the accuracy of the measurement will be reduced.

Pressurized vessels and vessels with vapor phase heating jackets require additional compensation because the weight of the vapors will vary as temperature and pressure change. Even if the tank contains only air, a 5,000-gallon vessel will gain 45 lbs. if the pressure is increased by one atmosphere at ambient temperature.

Performance Considerations

Weighing system performance is affected by many factors including: temperature, vibration, structural movement, environment, and maintenance. Temperature compensation is usually provided for most systems and its range should always exceed the expected range of ambient and operating temperature variations. When the process vessel is hot (or cold), tank-to-cell temperature isolation pads can be provided.

Temperature compensation adjustments for zero and span are built into most high quality strain gage load cell circuits. For operation outside the typical temperature limits of -4 to 160°F, added correction is needed, or the temperature around the load cell should be controlled. The load cell should also be protected from strong radiant heat, particularly if it reaches only one side of the cell.

In the metal processing industry, load cells must be able to operate continuously at temperatures as high as 500°F. The bonding substances used as backings on strain gages typically limit their application for high temperatures. For high

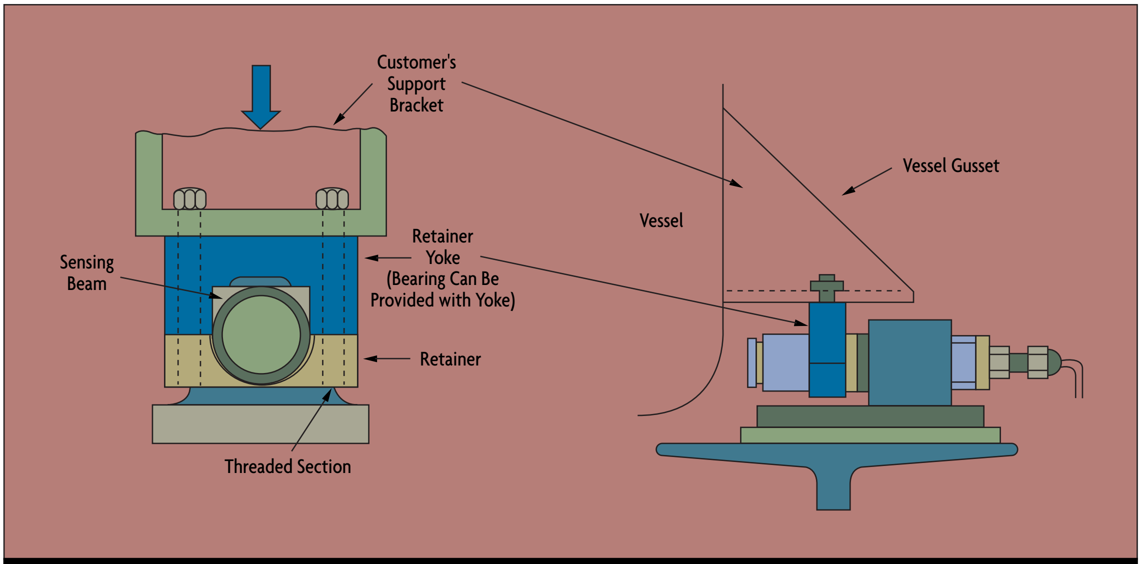

Figure 8-2: Cantilever Load Cells Reduce Staying Requirements

temperature applications, strain sensing wire alloys can be installed with inorganic (ceramic) bonding cement. Alternatively, a flame spray technique can be used, where molten aluminum oxide is sprayed on the strain sensing grid to hold it in place. Such installations can tolerate short-term operations up to 1000°F.

Vibration influences can be minimized by isolating the weighing system supports from structures or concrete foundations that support motors or other vibrating equipment or are affected by nearby vehicular traffic. Vibration absorption pads are available to isolate the load cells from the vibration of the tank, but performance will be best if isolation pads are used at the vibration source. Similarly, weight transmitters can be provided with filtering for the removal of noise caused by vibration, but it is best if vibration does not exist in the first place. During weighing, it is desirable to stop all in- and outflows and to turn off all motors and mixers that are attached to the weighed tank, if at all possible.

In agitated vessels, baffle plates should be added to reduce surging and gyration of the contents.

The load cell environment is a dynamic one and therefore requires periodic checking. This should include an attempt to keep the cell(s), cable, and associated junction box clear of debris, ice, or standing water (or other liquids), and shielded from heat, direct sunlight, and wind. Cells should also be protected from lightning and electrical surges. Maintenance should include checking the load cell environment, structures, wiring and junction boxes (for moisture and to tighten terminals), adjustment of stay and check rods, and periodic calibration and checking to make sure that the load is balanced.

Load cells can withstand up to 200% of their capacity in side loads. If a vessel is bumped by a vehicle or is otherwise disturbed, the cells should be checked for damage and be recalibrated. Maintenance related checking should be performed with the vessel both loaded and unloaded, and at all possible vessel/structure temperatures.

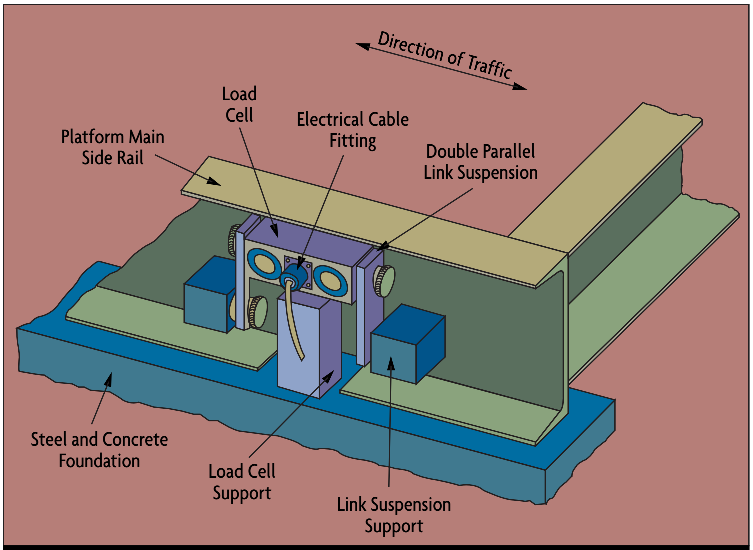

Figure 8-3: End-Loaded Shear-Beam Installation

Vessel Support Structure

The next step in the design process is the selection of the required structural supports for the tank. Tension support can only be used to weigh small vessels because of the limited weight ranges of tension cells. In tension-type installations, one to four cells are used (usually one), while in compression-type installations usually three or more are used. When accuracy is not critical (0.5% full scale or less) and the tank contains a liquid, costs can be reduced by replacing load cells with dummy cells or with flexure beams. Vertical round tanks are typically supported off three, while four are used for square or horizontal round vessels. It is preferable that all load cells in the system be of the same capacity.

Vessels that are very large, have unbalanced loads, contain hazardous materials, or are at risk of overturning might use more cells. If wind shielding is not provided for the vessel, cell capacity must be increased to also provide for the uplift and downthrust caused by the worst case of wind-induced tipping.

Three cells are best for accurate weighing because three points define a plane and therefore the load will be equalized naturally. Four or more cells require load adjustments. The minimum load cell range (size) is obtained by dividing the gross weight by the number of support points. One usually selects the next standard cell which exceeds the calculated requirement. Some application engineers will add a safety factor of 25% to the gross weight before making the above calculation. Others will also add a dynamic loading factor if, prior to weighing, the load is dropped onto the scale. It also is preferable that all load cells in the system be of the same capacity.

The vessel support structure must be rigid and stable, while leaving the tank completely free to move in the vertical. Each weighing system structure should be independent of structures supporting other vessels or vehicular traffic.

The combined deflection of the structure supporting the cells and the structure supported by the cells, when going from unloaded to fully loaded (including vessel wall flexure), should not exceed 1/1,200th of the distance between any two cells. This corresponds to an angle of 0.5°. Some shear beam mounting yokes allow a little more.

Support leg bowing also adds torque to the support beam. Uneven loading due to wind shear, uplift, and download must also be considered in order for the structural design to meet structure performance specifications. A wind shield is essential, if without it any one of the load cells could be totally unloaded. For most cells, wind effect without shields will cause errors under 0.1% full scale.

The support structure should be level to within 1/8 in.; otherwise, shims should be placed under the cell(s) to provide a level loading plane. In both compression and tension applications, the vessel load must be transferred through the load cell to the centerline of the web of the supporting steel. This will prevent twisting of the beams. Gussets should be provided at the support locations.

Vessel Stabilization

To provide unrestricted vertical motion while allowing for horizontal thermal expansion, stay rods and check rods are used. They are made from threaded rods and nuts and serve to provide lateral restraint. Their nuts are adjusted snug to the gusset of the vessel support bracket and to a rigid bracket on the structure. Nuts should be finger tight and then secured with jam nuts (Figure 8-1).

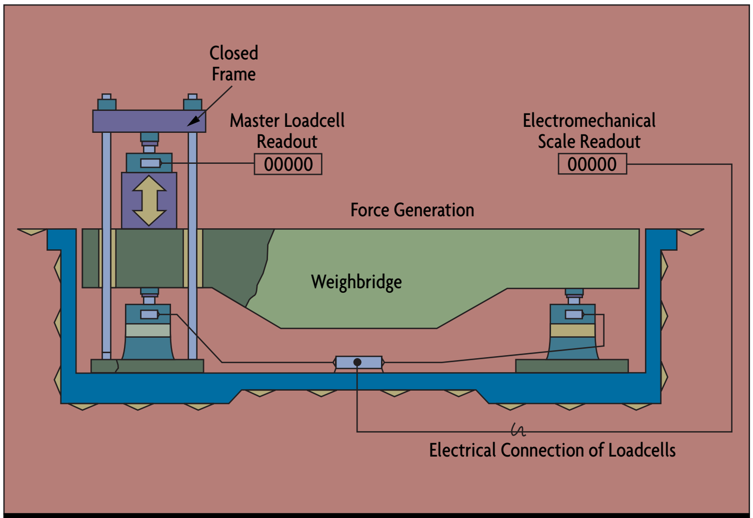

Figure 8-4: Master Load Cell for Weighbridge Calibration

Rods must be level and installed perpendicular to the direction of thermal expansion of the vessel. This allows unrestricted vertical movement without producing a side load. Stay rods should be installed as close as possible to the plane of vessel support. On long, round, horizontal tanks, the axial vessel stay rod connection should be near the center of the vessel, and lateral restraints should be located near the ends. This helps to avoid large axial thermal expansion.

Check rods are identical to stay rods except that their fit is made loose by providing a 1/8-in. gap at the nut and oversized rod holes. Check rods may be mounted above or below the support plane or vertically to prevent vessel overturn. On suspended vessels, check rods also serve as back-up hangers.

To determine the required size and location for stabilization systems, external forces (seismic, agitator, etc.) must be evaluated. The most stable support plane is at the center of gravity of the tank when it is full. Suspended vessels require check or stay rods only when horizontal vessel movement can be caused by external forces. For minor forces, bumpers may be sufficient.

Thermal expansion of vessels relative to their supports can cause undesirable side loads on the load cells. Some load-cell designs provide for horizontal vessel movement to relieve side loading. Load cell rods suspending a vessel must remain plumb to within 0.5°. Single and double-ended shear beam cell designs can eliminate or minimize the need for stay or check rods (Figure 8-2), while cylindrical cells always require both.

In terms of allowing horizontal movement, load cell designs can be "fixed" (allowing no movement), "linear" (allowing linear movement), or "full" (allowing any horizontal tank movement). Fixed and linear cells are mounted in support positions that are farthest apart, with the linear movement being allowed in a line that intersects the fixed cell.

Load cell adaptors are used in vehicle scales where large horizontal forces occur due to the deceleration or acceleration of the vehicles on the scale. The adaptor suspends the weighing platform from the top of the load cell through swivel links connected to the lower plate and the platform. The load cell is supported by a base plate that absorbs heavy side loads when the horizontal deflection exceeds the clearances around the base plate. Similar designs are available for double-ended shear beams (Figure 8-3).

Piping Connections

If a pipe is attached to a weighed vessel, it will introduce vertical and horizontal forces. The total vertical force (V) generated by all piping connected to a weighed vessel should be less than 30 times the system accuracy (A) multiplied by the maximum live load (L):

$$V < 30\ AL$$

The forces imposed by the pipe supports, the pipe, and the pipe contents—plus the spring forces resulting from pipe movement due to thermal expansion—must all be included in V, and in the evaluation of horizontal forces. The horizontal forces acting on the vessel should be zero.

Following are some general rules to assist in obtaining an acceptable design:

- Piping must align with the vessel connection without requiring any force.
- The length of pipe between the vessel and the first pipe support should be long enough to provide vertical flexure, but not so long that the pipe will sag and add weight to the vessel.
- Load cell supports should also support the first two pipe supports. The up and down motion of the pipe supports must be limited.
- When possible, use a lighter schedule pipe because it will provide more flexibility. For example, schedule 10S is more flexible than 40S.
- The transmission of horizontal forces should be eliminated by the use of expansion joints and by piping designs having 90° turns in two planes.
- Flexible fittings, universal joints, and hose may only be used when making horizontal connections and must align normal to the tank connection, without force. Braid-jacketed hose should not be used. Flexible rubber boots are acceptable for making vertical connections.
- When a hopper and its hood are independently supported and sealed with a boot, weighing error can occur due to the pressure change caused by in-rushing or out-flowing material. Hood venting (and, therefore, vacuum breaking) is required to eliminate this error source.
- Hose should not be used to make turns.
- Do not use rigid insulation on flexible joints.
- On horizontal round tanks, the best location for the pipe entrance is near the "fixed" load cell.

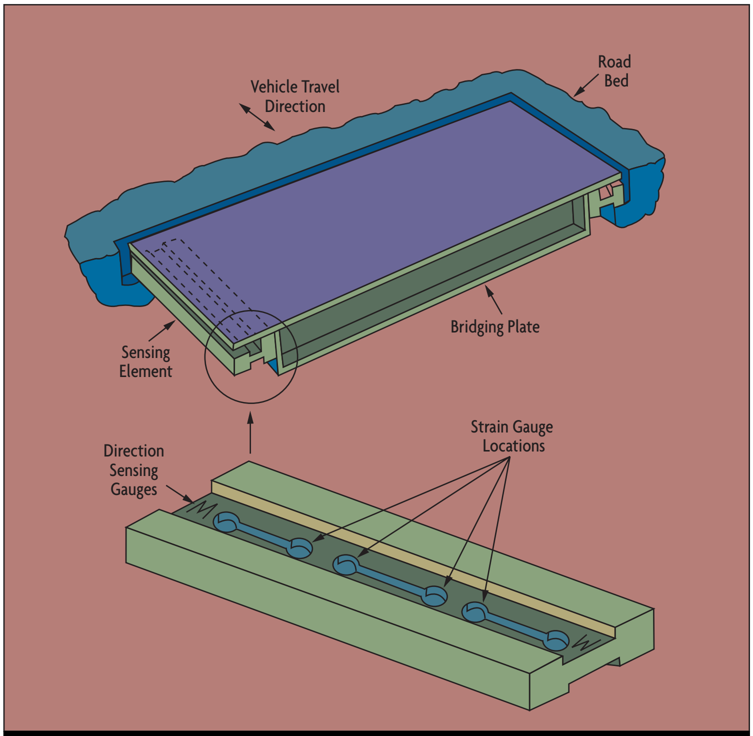

Figure 8-5: Treadle Scale Design

- The electrical devices on the tank (including load cells) should be wired using flexible conduit that is "looped."

Installation & Calibration

To check if the transducers and load cells are functioning properly, the following should be evaluated: Does the weight indication return to zero when the system is empty or unloaded? Does the indicated weight double when the weight is doubled? Does the indicated weight remain the same when the location of the load changes (uneven loading)? If the answers are yes, the cells and transducers are probably in good condition and need no attention.

Before calibration, the mechanical system should be examined and the cell installation checked for the following:

- Inspect the load cell cables, and coil and protect any excess.
- The load should be equally distributed among multiple load cells of multiple load cell installations. If they differ by more than 10%, the load should be rebalanced and adjusted with shims.
- When calibrating, installing, or removing a cell, the vessel should be lifted without unloading or overloading the other cells. The design of the system should provide for jacking and the horizontal removal of the cell.
- Dummy load cells should be used in place of operational ones until all construction and welding are completed.

The calibration of the vessel requires hangers or shelves to support the calibration weights. For an ASME vessel, they must be added when the vessel is fabricated. Calibration to an accuracy of 0.25% full scale or better is usually performed with dead weights and is the only calibration method recognized by weights and measures agencies. All calibration starts by zeroing the system:

- During deadweight calibration, the vessel is evenly loaded to 10% of the live load capacity using standard weights. The weight indication is recorded and the weights are removed. Next, process material is added to the vessel until the weight indicator registers the same (10%) weight as it did with the calibration weights. Now the calibration weights are loaded on the vessel again and the reading (now about 20%) is recorded. These steps are repeated until 100% of capacity is reached.
- Live weight calibration is a novel and faster method, which uses pre-weighed people instead of calibration weights. The procedure is identical to deadweight calibration. This method should not be used if there is a risk of injury.
- The "material transfer" method of calibration uses some other scale to verify weight. This method is limited by the accuracy of the reference scale and risks some error due to possible loss of material in transfer.
- A master cell can also be used for calibration as long as the master is about three times more accurate than the accuracy expected from the calibrated system. The calibration procedure involves incremental loading and the evaluation at each step of the output signals of both the calibrated weighbridge and of the master load cell (Figure 8-4). The number of divisions used and the method of applying the force (hydraulic or servomotor) is up to the user.

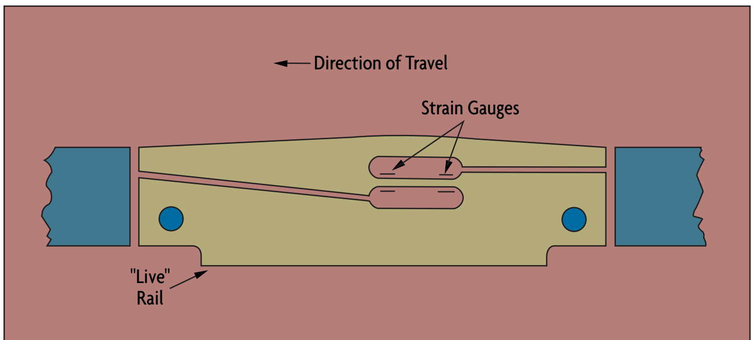

Figure 8-6: Monorail Weighing Transducer

If a load cell system is causing problems, four tests can be conducted:

Mechanical Inspection: Check the load cell for physical damage. If it has been physically deformed—bent, stretched or compressed relative to its original shape—it is not repairable and must be replaced. Look for distortion or cracks on all metal surfaces. Flexure surfaces must be parallel to each other and perpendicular to both end surfaces. Check all cables along their entire length. Nicked or abraded cables can short out a load cell.

Zero Balance (No Load): Shifts in the zero balance are usually caused by residual stress in the sensing area. Residual stresses result from overloading the cell or from repeated operation cycles. With a voltmeter, measure the load cell's output when there is no weight on the cell. It should be within 0.1% of the specified zero output signal. If the output is outside the zero balance tolerance band, the cell is damaged but perhaps correctable.

Bridge Resistance: Measure the resistance across each pair of input and output leads. Compare these readings against the specification of the load cell. Out-of-tolerance readings are usually caused by the failure of one or more elements, typically the result of electrical transients or lightning strikes.

Resistance to Ground: Connect all the input, output, sense and ground leads together, and measure the resistance between the load cell body and the leads with an ohmmeter. The reading should be at least 5,000 megaohms. If the load cell fails this test, repeat the test without the ground wire. If it still fails, the load cell requires repair. If it passes, the problem may be in the load-cell cable. It is usually the infiltration of moisture that causes short circuiting (current flow) between the load cell's electronics and the cell body.

Specialized Installations

Leg-mounted load cells measure stress changes in the vessel's support structure and can determine tank weights to between 0.1% and 0.5% full-scale accuracy. These cells can be installed on existing tank supports, and several can be mounted or bolted to the legs of a vessel. The legs can be made of I-beams, pipes, concrete-filled pipes, or angle iron.

These load cells are available in single and double-axis designs. Double-axis cells are able to provide perpendicular strain monitoring of thermal or other (interfering) stresses, which can eliminate errors from the primary signal. If single-axis cells are used, a second cell can be installed perpendicular to the first to measure and eliminate errors caused by thermal stresses.

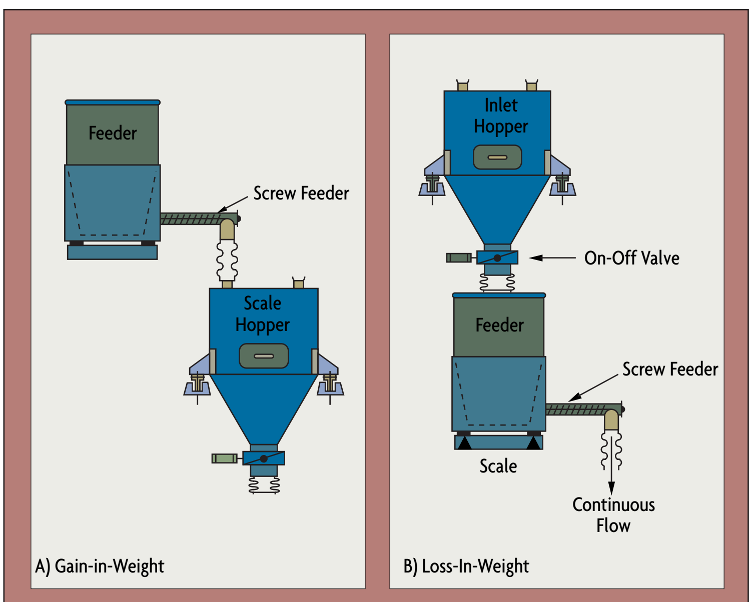

Figure 8-7: Load Cell Configurations for Solids Batching

These cells are very temperature sensitive and therefore require sun and wind shielding and insulation. Locating the cell on an I-beam web will minimize temperature error. The base metal of single-axis cells must exactly match the vessel leg material, or errors will be introduced. If dual-axis cells are used, they compensate for material differences and this will not be a concern. The best design is to mount a dual-axis cell at the center of the I-beam web. The next best is to install two single-axis cells mounted opposite each other on the face of the flange where the flange is joined to the web.

Treadle scales eliminate the complexity of building vehicle scales from individual load cells, weighbridges, and stabilization hardware, and therefore are less expensive (Figure 8-5). A treadle scale is a self-contained unit that can be readily lowered into a shallow pit. In addition to being accurate, directional strain gages are provided to sense vehicle motion.

Monorail weighing transducers measure "live" loads using integrated load cell and flexure assemblies built into a single self-supporting module (Figure 8-6). The strain gage arrangement in this module detects the correct weight independent of load position. The sloping arrangement on the top of the module decouples the load from the "pusher" during weight measurement and thereby eliminates these forces.

Belt weighing systems are used on flat or trough belts. Flat belts are more accurate, but also tend to spill more material. This type of weighing system consists of load cells supporting a set of rollers, including three idler rollers on either side that stabilize and support the belt and its contents as they move over the scale. Delivered weight is determined by integrating the product of weight and belt speed signals.

The weighing system should be located away from the material loading impact and spread area, and on the opposite end from the drive pulley to avoid high belt tension. Belts should be single-ply, flexible, and should track without lateral movement. The belt tension should be maintained by weight-and-pulley to minimize jamming or resistance to movement. Belt tension should be adjusted after monitoring the system's response with more or less tension. A loose belt causes side load error because of belt slap or wrap, while a tight belt can cause the load cell to measure belt tension instead of load.

Load cells are widely used in applications requiring precision weighing of solid and liquid materials. Depending on whether the receiver or dispenser is being weighed, these applications are referred to as gain-in-weight or loss-in-weight configurations (Figure 8-7).

Loss-in-weight scales measure the rate at which the total weight in the dispensing tank changes. They are used to control small mass flow rates into a process. These scales consist of a small load cell system, a differentiating measurement and control system and a variable speed dispenser. Normally, the speed of the dispenser is adjusted to maintain the mass flow rate into the process; during the refill cycle, it is held constant at its last setting.

The scale hopper is weighed by load cells connected via a summing box to a weight transmitter. The control system runs the screw feeder at a high rate of speed (bulk rate) until the total target weight is approached. At that point the control system slows the screw feeder down to a "dribble rate". The screw feeder continues charging at the dribble rate for a short period of time, stopping just before the target weight is attained.

The difference between the target weight and the weight at which the screw feeder is stopped is called the "pre-act" weight. This pre-act difference setting allows the control system to consider the in-flight material that is still falling from the screw feeder into the scale hopper. The pre-act weight can be adjusted either manually or automatically, and its correct setting is critical for high accuracy applications.

In the case of loss-in-weight batching, a feeder is provided with an on-off valve at its inlet and with a variable speed screw feeder at its outlet. The entire feeder, including the inlet hopper and the screw feeder, is mounted on load cells. When the feeder inlet valve is closed, the slope at which the total weight is dropping indicates the continuous discharge from the feeder. This slope is controlled by "loss-in-weight" controls, which calculate the rate at which the total weight is changing. The feed rate is set in pounds per hour, and the control system regulates the speed of the screw feeder to maintain this desired discharge feed rate.

The control system speeds up the screw feeder when the feed rate is below setpoint, and slows it down when it is above setpoint. When the feeder is nearly empty, the control system switches the feeder into its refill mode. In this mode, the inlet valve is opened and it is kept open until the desired full weight is reached. T

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Information Resources

ORGANIZATIONS

NAME/ADDRESS	PHONE	WEB ADDRESS
American Institute of Chemical Engineers (AIChE) 345 East 47 Street, New York, NY 10017-2395	212/705-7338	www.aiche.org
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American Society of Mechanical Engineers (ASME) 345 East 47 Street, New York, NY 10017	212/705-7722	www.asme.org
American Society for Testing and Materials (ASTM) 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959	610/832-9585	www.astm.org
American Vacuum Society (AVS) 120 Wall Street, 32nd Floor, New York, NY 10005	212/248-0200	www.vacuum.org
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International Organization for Standardization (ISO) 1, rue de Varembé, Case postale 56, CH-1211 Geneva 20, Switzerland	+41 22 749 01 11	www.iso.ch
Institute of Electrical & Electronics Engineers (IEEE) 445 Hoes Lane, Piscataway, NJ 08855-1331	732/981-0060	www.ieee.org
ISA—The International Society for Measurement and Control 67 Alexander Drive, Research Triangle Park, NC 27709	919/549-8411	www.isa.org
National Electrical Manufacturers Association (NEMA) 1300 North 17th Street, Suite 1847, Rosslyn, VA 22209	703/841-3200	www.nema.org
National Fire Protection Association (NFPA) 1 Batterymarch Park, Quincy, MA 02269-9101	617/770-3000	www.nfpa.org
National Institute of Standards and Technology Gaithersburg, MD 20899-0001	301/975-3058	www.nist.gov
Society of Automotive Engineers (SAE) 400 Commonwealth Drive, Warrendale, PA 15096-0001	724/776-4841	www.sae.org
Underwriters Laboratories 333 Pfingsten Road, Northbrook, IL 60062	847/272-8800	www.ul.com

APPLICABLE STANDARDS

Acceleration, IEC:68-2-7	Pressure Gauges, ANSI: B40.1
Accelerometers, IEEE: 337	Pressure Measurement, ASME: PTC 19.2
Electrical Instruments in Hazardous Atmospheres, ISA: RP12.1,4,6,10,11	Pressure Transducers, Calibration, ANSI: B88.1
Electrical Transducers, Terminology, ISA: S.37.1	Pressure Transducers, Potentiometric, ISA: S37.6
Electrical Transducers, Testing, ANSI: S2.11	Shock and Vibration, ANSI: S2.2, S2.4, S2.10, S2.11
Hazardous Areas, IEC: 79-10	Strain Gages, Calibration, ASTM: E251-67
Intrinsically Safe Circuits, IEC: 79-3, UL: 913	Strain Gage Transducers, ISA: S37.3, 5
Piezoelectric Crystals, IEEE: 179	Vacuum Gauges, Calibration, AVS: 6.2, 6.4, 6.5
Piezoelectric Acceleration Transducers, ISA: RP37.2	Vacuum Gauges, Ionization, ASTM: E297-70
Piezoelectric Pressure Transducers, ISA: S37.10	Vibration, IEC: 69-2-6
Potentiometers, Laboratory, ANSI: C100.2	Weighing Scales, ASME: PTC 19.5.1

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Glossary

A

Absolute pressure: Pressure referenced to full vacuum. In English (pounds per square inch) units, designated as PIA.

Accuracy: Degree of conformity of a measured value to an accepted standard value or closeness of a reading or indication of a sensor to the actual value of the quantity being measured.

Accuracy rating: A number that defines a limit that the measurement errors will not exceed under some reference operating conditions. It includes the combined effects of conformity, hysteresis, dead band and repeatability errors.

Accuracy, units: The maximum positive or negative deviation (inaccuracy) observed in testing a device. It can be expressed in terms of the measured variable (plus-minus 1°C), or as a percentage of the actual reading (%AR), of the full scale (%FS), of upper range value (%URL), of the span or of scale length.

Admittance: Admittance of an AC circuit is analogous to the conductivity of a DC circuit; it is the reciprocal of the impedance of an AC circuit.

Air consumption: The maximum rate at which air is consumed by an instrument while operating within its operating range, usually expressed in units of standard cubic feet per minute.

Alphanumeric: A character set containing both letters and numbers.

Alternating current (AC): A flow of electric charge (electric current) that undergoes periodic reverses in direction. In North America, the household current alternates at a frequency of 60 times per second.

Ambient pressure: The atmospheric pressure of the medium surrounding a particular sensor. When no specific information is available, it is assumed to be 14.7 PSIA.

Ambient temperature: The average or mean temperature of the atmospheric air which is surrounding a sensor or instrument. If the sensor is a heat generator, this term refers to the temperature of the surroundings when the sensor is in operation. The ambient temperature is usually stated under the assumption that the sensor is not exposed to the sun or other radiant energy sources.

Ambient temperature compensation: An automatic correction which prevents the reading of a sensor or instrument from being affected by variations in ambient temperature. The compensator specifications state the temperature range within which the compensation is effective.

American National Standards Institute (ANSI): A professional organization in the United States responsible for accepting and designating the standards developed by other organizations as national standards.

Ampere (A or amp): The unit of electric current flow, defined as the rate at which one coulomb of electric charge ($6.25x10^{18}$ electrons) is transferred in a second.

Amplifier: A device that generates an output which is stronger than and bears some predetermined relationship (often linear) to its input. It generates the amplified output signal while drawing power from a source other than the signal itself.

Analog signal: A signal that continuously represents a variable or condition.

Analog-to-digital (A/D) conversion: A generic term referring to the conversion of an analog signal into a digital form.

Analog-to-digital converter (ADC): An electronic device that converts analog signals to an equivalent digital form.

Attenuation: The reciprocal of gain; a dimensionless ratio defining the decrease in signal magnitude as it passes between two points or two frequencies. Large values of attenuation are expressed in decibels (dB).

B

Backlash: The relative movement of interlocked mechanical parts which occurs when motion is reversed.

Baud rate: Serial communications data transmission rate expressed in bits per second (bps).

Bipolar: A signal range that includes both positive and negative values (i.e., -10 V to +10 V).

Bode diagram: A plot of log amplitude ratio and phase angle values used in describing transfer functions.

Breakdown voltage: Threshold voltage at which circuit components begin to be damaged.

Byte (B): Eight related bits of data or an eight-bit binary number. Also denotes the amount of memory required to store one byte of data.

C

Calibrate: To ascertain that the output of a device properly corresponds to the information it is measuring, receiving or transmitting. This might involve the location of scale graduations, adjustment to bring the output within specified tolerance or ascertaining the error by comparing the output to a reference standard.

Calibration: The process of adjusting an instrument or compiling a deviation chart so that its reading can be correlated to the actual values being measured.

Calibration curve: A graphical representation of the calibration report, which report can be in the form of a table or chart.

Calibration cycle: The application of known values of a measured variable and the recording of the corresponding output readings over the range of the instrument in both ascending and descending directions.

Calibration traceability: The relationship of the calibration process to the calibration steps performed by a national standardizing laboratory.

Capacitance: The capability of a device to store electric charge. Its unit is the farad, which expresses the ratio of stored charge in coulombs to the impressed potential difference in volts.

Capacitor: A device designed to store electric charge. It usually consists of two conductors that are electrically isolated by a nonconductor (dielectric). The plates of a perfect capacitor are separated by a vacuum (dielectric constant of 1.0), in which case no current flows between the plates.

Chemical seal: A diaphragm assembly which detects the pressure of a process and transmits it to a (usually stable and inert) filling fluid, which then transmits that pressure to an instrument.

Common mode rejection: The ability of a circuit to discriminate against a common mode voltage.

Common mode voltage: A voltage of the same polarity on both sides of a differential input relative to ground.

Compensator: A device which eliminates the effect of an unmeasured variable or condition on the measurement of interest.

Compound detector: A detector whose measurement range extends both above and below zero.

Conductance, conductivity: The reciprocal of resistance in a DC circuit is conductance. Its unit is the mho. The unit of conductivity is the cm-mho or cm/ohm.

Controller: A device that operates automatically to regulate a controlled variable.

Coulomb: The amount of electric charge which is transferred in one second by a current flow of one ampere.

D

Damping: The suppression of oscillation. The viscosity of a fluid is used in viscous damping, while the induced current in electrical conductors is used to effect magnetic damping.

Dead band: The range through which an input can be changed without causing an observable response.

Dead time: The interval between the initiation of a change in input and the start of the resulting observable response.

Decibel (dB): Unit for expressing a logarithmic measure of the ratio of two signal levels.

Dielectric: A non-conductor of DC current.

Dielectric constant: Expresses the degree of non-conductivity of different substances, with full vacuum defined as 1.0.

Distributed control system (DCS): Typically a large-scale process control system characterized by a distributed network of processors and I/O subsystems that encompass the functions of control, user interface, data collection, and system management.

Dither: A useful oscillation of small magnitude, introduced to overcome the effects of friction, hysteresis, or clogging.

Drift: Undesired change in the input-output relationship over a period of time.

Dynamic range: Ratio of the largest to smallest signal level a circuit can handle, normally expressed in dB.

E

Electromotive force: Force that causes the movement of electricity, such as potential difference of voltage. A measure of voltage in an electrical circuit.

Elevation: A range in which the zero value of the measured variable exceeds the lower range value.

Error: The difference between the measured signal value or actual reading and the true (ideal) or desired value.

Error, common mode: Error caused by an interference that appears between both measuring terminals and ground.

Error, normal mode: Error caused by an interference that appears between the two measuring terminals.

Error, random: The amount of error that remains even after calibrating a sensor. Also called "precision", while "repeatability" is defined as twice that—the diameter instead of the radius of the circle within which the readings fall.

Error, systematic: A repeatable error, which either remains constant or varies according to some law, when the sensor is measuring the same value. This error can be eliminated by calibration.

F

Farad: The unit of capacitance, equivalent to one coulomb of stored charge per volt of applied potential difference. As this is a very large unit, one trillionth of it, the picofarad (pf), is commonly used.

Fieldbus: All-digital communication network used to connect process instrumentation and control systems. Designed to replace systems based on 4-20 mA analog signals with bidirectional, multivariable data communication capability.

Fieldbus Foundation: Austin, Texas-based nonprofit consortium of instrumentation suppliers that is developing a standard digital communication network (fieldbus) for process control applications. The network developed by the Foundation is referred to as the Foundation Fieldbus.

Force balance: Instruments which operate by force-balance between the detected variable and the generated output require no motion and therefore tend to be more maintenance free than motion-balance devices.

Frequency: The number of cycles in a specified time period over which an event occurs. Normally expressed in cycles per second (hertz, Hz).

Frequency response: The frequency-dependent characteristics that determine the phase and amplitude relationship between sinusoidal input and output.

G

Gain (magnitude ratio): For a linear system or element, the ratio of the magnitude (amplitude) of a steady-state sinusoidal output relative to a causal input. In an electrical circuit, the amount of amplification used (sometimes expressed in decibels, dB).

Gain accuracy: Measure of deviation of the gain (of an amplifier or other device) from the ideal gain.

Gain, dynamic: For a sinusoidal signal, the magnitude ratio of the steady-state amplitude of the output signal to the amplitude of the input.

Gain, static: The ratio of change of steady state value to a step change in input, provided that the output does not saturate.

Ground: The electrical neutral line having the same potential as the surrounding earth; the negative side of a direct current power system; the reference point for an electrical system.

H

Hertz (Hz): Unit of frequency, defined as one cycle per second.

Hunting: An undesirable oscillation which continues for some time after the external stimulus has disappeared.

Hysteresis: The property of an element or sensor whereby output is dependent not only on the value of the input, but on the direction of the current traverse. (The reading of the same value thus differs as a function of whether the measurement is taken when the variable is increasing or decreasing.)

I

Impedance: The opposition to the flow of AC current, the equivalent of resistance in DC circuits. Its unit is the ohm. The impedance of an AC circuit is one ohm if a potential difference of one volt creates a current flow of one ampere within it.

Inductance: The property by which an electromotive force (emf) is induced in a conductor when the magnetic field is changing about it. This is usually caused by changes in the current flow in the circuit or in a neighboring circuit.

Input/output (I/O): The analog or digital signals entering or leaving a DCS or other central control or computer system involving communications channels, operator interface devices, and/or data acquisition and control interfaces.

Integral control: A control mode which generates a corrective output signal in proportion to the time integral of the past error. It eliminates the offset inherent in proportional control.

Intrinsically safe: Equipment or wiring which is incapable of releasing sufficient electrical or thermal energy to ignite a hazardous mixture of hydrocarbon vapors and air. In such equipment, electrical energy is limited so that it cannot generate a spark or otherwise ignite a flammable mixture.

ISA: Formerly the Instrument Society of America, now referred to as the International Society for Measurement & Control.

L

Laser: Narrow, intense beam of coherent light.

Linearity: The closeness to which a curve approximates a straight line; the deviation of an instrument's response from a straight line.

Linear stroke: For a transducer, the calibrated mechanical movement over which its electrical output linearity meets specifications.

Loop gain characteristics: Of a closed loop, the characteristic curve of the ratio of the change in the return signal

to the change in the error signal for all real frequencies.
Loop transfer function: Of a closed loop, the transfer function obtained by taking the ratio of the Laplace transform of the return signal to the Laplace transform of its corresponding error signal.
Lower range limit (LRL): The lowest value of a measured variable that a device can be adjusted to measure.
Lower range value (LRV): The lowest value of a measured variable that a device is adjusted to measure.

M

Manipulated variable: A quantity or condition which is varied as a function of an actuating error signal so as to change the value of the directly controlled variable.
Measurement signal: The electrical, mechanical, pneumatic, digital or other variable applied to the input of a device. It is the analog of the measured variable produced by the transducer.
Measurement variable: A quantity, property or condition which is being measured. Sometimes referred to as the "measurand."
Milliamp (mA): One thousandth of an ampere.
Millivolt (mV): One thousandth of a volt.
Multiplexer (Mux): A switching device that sequentially connects multiple inputs or outputs in order to process several signal channels with a single A/D or D/A converter.

N

Noise: Any undesirable electrical signal, whether from external sources such as AC power lines, motors, electrical storms, radio transmitters, or from internal sources such as electrical components.
Non-linearity: The deviation from the best fit straight line that passes through zero.
Normal-mode rejection ratio: The ability of an instrument to reject electrical interference across its input terminals, normally of line frequency (50-60 Hz).
Nyquist theorem: The law that provides the basis for sampling continuous information. It states that the frequency of data sampling should be at least twice the maximum frequency at which the information might vary. This theorem should be observed in order to preserve patterns in the information or data, without introducing artificial, lower frequency patterns.

O

Ohm meter: A device used to measure electrical resistance.
One-to-one repeater: A diaphragm-operated device which detects process pressure and generates an air (or nitrogen) output signal of equal pressure.
Optical isolation: Two networks or circuits in which an LED transmitter and receiver are used to maintain electrical discontinuity between the circuits.
Output settling time: Time required for the analog output voltage to reach its final value within specified limits.
Output signal: A signal delivered by a device, element or system.
Output slew rate: Maximum rate of change of analog output voltage from one level to another.
Overtravel: That part of a stroke which falls between the end of the calibrated range and the travel stop.

P

Phase: A time-based relationship between a periodic function and a reference.
Phase shift: The angle in degrees between an energizing voltage waveform and an output signal waveform.
Polarity: In electricity, the quality of having two charged poles, one positive and one negative.
Port: A communications connection on an electronic or computer-based device.
Power supply: A separate unit or part of a system that provides power (pneumatic, electric, etc.) to the rest of the system.
Pressure, ambient: The pressure of the medium surrounding a device.
Pressure, design: The pressure used in the design of a vessel or other equipment for the purpose of determining the minimum permissible wall thickness or size of parts for a given maximum working pressure (MWP) at a given temperature.
Pressure, maximum working: The maximum permissible operating pressure at a specified temperature. This is the highest pressure to which the device will be subjected during regular use.
Pressure, operating: The actual (positive or negative) pressure at which a device operates under normal conditions.
Pressure, rupture: The burst pressure of a device (determined by testing).
Pressure, static: The steady-state pressure applied to a device.
Pressure, supply: The pressure at which a utility (such as air) is supplied to a device.
Pressure, surge: Operating pressure plus the increment to which a device can be subjected for a very short time

during temporary pressure surges caused by such phenomena as pump start-up or valve shut-off.

Pretravel: That part of a stroke which falls below the calibrated range, between zero and the travel stop.

Primary element: The element which converts a measured variable into a force, motion or other form suitable for measurement.

Process: Physical or chemical change of matter or conversion of energy.

Process measurement: The acquisition of information that establishes the magnitude of process quantities.

Programmable logic controller (PLC): Computer-based industrial monitoring and control package with applications mostly in the areas of safety, sequential or logical operations, where control actions are based on equipment and alarm status.

Proportional control: A control mode which generates an output correction in proportion to the error (the process variable's deviation from setpoint).

Proportional-integral-derivative (PID): Also referred to as a 3-mode controller, combining proportional, integral, and derivative control actions.

PSIA: Pounds per square inch absolute, the pressure unit used when the zero reference is full vacuum.

PSIG: Pounds per square inch gauge, the pressure unit used when the zero reference is the barometric pressure of the atmosphere.

R

Radio frequency: The frequency range between ultrasonic and infrared. AM broadcast frequencies range from 540 to 1,800 kHz, while FM broadcasts from 88 to 108 MHz.

Radio frequency interference (RFI): Noise induced upon signal wires by ambient radio-frequency electromagnetic radiation, with the effect of obscuring the instrument signal.

Ramp: The total (transient plus steady-state) time response resulting from a sudden increase in the rate of change from zero to some finite value of an input stimulus.

Range: The region between the limits within which a quantity is measured, received or transmitted, expressed by stating the lower and upper range values.

Reactance: The opposition to the flow of AC current, which is created by either inductance or capacitance. In such a circuit, total impedance is therefore the sum of reactance and resistance. Its unit is the ohm.

Reference input: An external signal serving as a setpoint or as a standard of comparison for a controlled variable.

Reliability: The probability that a device will perform its objective adequately for the period of time specified, under the operating conditions specified.

Remote terminal unit (RTU): Industrial control and data collection device similar to a PLC but designed for remote data collection, transfer and communication via wire-based or radio telemetry links to DCS or computer systems.

Repeatability: The maximum difference between output readings when the same input is applied consecutively. This is the closeness of agreement among consecutive measurements of an output for the same value of input under the same operating conditions, approaching from the same direction. It is usually measured as non- repeatability and expressed as a percentage of span.

Reproducibility: The closeness of agreement among repeated measurements of an output for the same value of the input made under the same operating conditions over a period of time, approaching from both directions. It includes hysteresis, dead band, drift, and repeatability.

Resistance, resistivity: Resistance is the opposition to the flow of current in a DC circuit. Its unit is the ohm, which is defined as the resistance that will give a one ampere current flow, if a one volt potential difference is applied in the circuit Resistivity is the reciprocal of conductivity; its unit is the ohm/cm.

Resolution: The smallest change in input which produces a detectable change in output; the smallest increment of change that can be detected by a measurement system. Resolution can be expressed in bits, in proportions, in percent of actual reading or in percent of full scale. For example, a 12-bit system has a resolution of one part in 4,096 or 0.0244% of full scale.

Resonance: A condition of oscillation caused when a small amplitude of periodic input has a frequency approaching one of the natural frequencies of the driven system.

Response time: An output expressed as a function of time, resulting from the application of a specified input under specified operating conditions.

RMS value: The square root of the average of the squares (root-mean-square) of the instantaneous values. It is the square root of the arithmetical mean of the squares.

S

Sample-and-hold (S/H): Circuit that acquires and stores an analog voltage on a capacitor for subsequent conversion.

Sampling period: The time interval between observations.

Scale factor: The factor by which the number of scale divisions indicated or recorded by an instrument should be multiplied in order to compute the value of the measured variable.

SCFM: Standard cubic foot per minute, where the term "standard" usually refers to 14.7 PSIA pressure and 68°F temperature.

Sensing element: The element which is directly responsive to the value of the measured variable.

Sensitivity: The minimum change in a physical variable to which an instrument can respond; the ratio of the change in output magnitude to the change of the input which causes it after steady-state has been reached.

Sensor: An element or device which detects a variable, receiving information in the form of one quantity and converting it to information in the form of that or another quantity.

Servomechanism: An automatic feedback device in which the controlled variable is mechanical position or any of its time derivatives.

Setpoint: A variable, expressed in the same units as the measurement to be taken, which sets either the desired target for a controller or the condition at which alarms or safety interlocks are to be energized.

Settling time: The time required after a stimulus for the output to center and remain within a specified narrow band centered on its steady-state value.

Shielded twisted pair (STP): Cable construction that includes an external grounded shield as well as twisting on a regular basis to minimize noise.

Signal: A variable that carries information about another variable that it represents.

Signal-to-noise ratio: Ratio of signal amplitude to noise amplitude; the ratio of the overall rms signal level to the rms noise level, expressed in dB. For sinusoidal signals, amplitude may be peak or rms.

Single-ended (SE): An analog input that is measured with respect to a common ground.

Span: The algebraic difference between the upper and lower range values, expressed in the same units as the range.

Span shift: Any change in slope of the input-output curve.

Stability: The ability of an instrument or sensor to maintain a consistent output when a constant input is applied.

Steady-state: A characteristic of a condition, such as value, rate, periodicity, or amplitude, exhibiting only negligible change over an arbitrary long period of time.

Stiffness: The ratio of change of force (or torque) to the resulting change in deflection of a spring-like element; the opposite of compliance.

Strain: The ratio of the change in length to the initial unstressed reference length of an element under stress.

Strain gage: Sensor whose resistance varies with applied force. A measuring element for converting force, pressure, tension, weight, etc., into a change in electrical resistance.

Subsidence: The progressive reduction or suppression of oscillation in a device or system.

Suppressed range: The range in which the zero value of a measured variable is greater than the lower-range value (LRV). The terms "elevated zero," "suppression" or "suppressed span" are also used to express the condition that exists when the zero of the measured variable is greater than the LRV.

Suppressed span: The span in which the zero of the measured variable is greater than the LRV.

Suppressed zero: The range in which the zero value of the measured variable is less than the lower range value. The terms "elevation," "elevated range" and "elevated span" are frequently used to express the condition in which the zero of the measured variable is less than the lower range value.

Suppression ratio: The ratio of the lower-range value to the span. If range is 20-100 and therefore span is 80 and LRV is 20, the suppression ratio is 20/80 = 0.25 or 25%.

Synchronous: An event or action that is synchronized to a reference clock.

System noise: The measure of the amount of noise seen by an analog circuit or an ADC when the analog inputs are grounded.

T

Temperature coefficient: The amount of drift, in percent of full scale output, that might result from a 1°C change in ambient temperature.

Thermal shock: An abrupt temperature change applied to a device.

Time constant: The value T in an exponential term $A^{(-t/T)}$. For the output of a first-order system forced by a step or an impulse, T is the time required to complete 63.2% of the total rise or decay. For higher order systems, there is a time constant for each of the first-order components of the process.

Torque tube: A torsion spring used to measure force or pressure.

Transducer: An element or device which receives information in the form of one quantity and converts it to information in the same or another quantity or form. Primary elements and transmitters are also referred to as transducers.

Transfer function: Mathematical, graphical, or tabular statement of the influence which a system or element has on a signal or action compared at input and at output terminals.

Transient: The behavior of a variable during transition between two steady-states.

Transmitter: A transducer which responds to a measured variable by means of a sensing element, and converts it to a standardized transmission signal which is a function only of the values of the measured variable.

U

Upper range limit (URL): The highest value of a measured variable that a device can be adjusted to measure. (This value corresponds to the top of the range.)

Upper range value (URV): The highest value of a measured variable that a device is adjusted to measure. (This value corresponds to the top of the span.)

V

Vapor pressure: The pressure exerted by a vapor which is in equilibrium with its own liquid.

Variable: Any condition which is measured, controlled (directly or indirectly) or manipulated.

Velocity limit: A limit on the rate of change, which a particular variable may not exceed.

Vibration: A periodic motion or oscillation of an element, device, or system.

Volt (V): The electrical potential difference between two points in a circuit. One volt is the potential needed to move one coulomb of charge between two points while using one joule of energy.

W

Warm-up period: The time required after energizing a device before its rated performance characteristics start to apply.

Wet leg: When the low pressure side of a d/p cell is connected to the vapor space of a tank, and the high pressure side is filled with a stable, noncorrosive liquid of known density, the installation is called a "wet leg" arrangement.

Z

Zero offset: The non-zero output of an instrument, expressed in units of measure, under conditions of true zero.

Zero suppression: For a suppressed-zero range, the amount by which a measured variable's zero is below the lower-range value. It can be expressed as a percentage of either the measured variable or of the span.

Zone, neutral: A predetermined range of input values which do not produce a change in the previously existing output value.

Index

List of Figures

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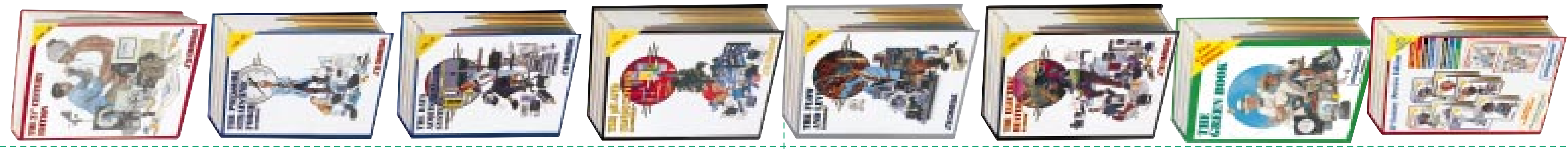

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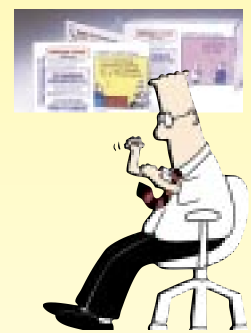

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