Introduction

A cluster of 72 helium-filled balloons over Temecula, California in April of 2003. The helium balloons displace approximately 230 m$^3$ of air, providing the necessary buoyant force. Go ahead – try it!
Practical Application

In many structures of practical application, the submerged surfaces are not flat, but curved as here at Glen Canyon Dam in Utah and Arizona.

What Is Pressure?

Pressure is defined as force per unit area that a fluid exerts on its surroundings. Pressure, $P$, is a function of force, $F$, and area, $A$:

$$ P = \frac{F}{A} $$

The SI unit for pressure is the pascal (N/m$^2$), but other common units of pressure include pounds per square inch (psi), atmospheres (atm), bars, inches of mercury (in. Hg), millimeters of mercury (mm Hg), and torr.
**Pressure Measurement**

- Absolute pressure is the pressure measured w.r.t. a vacuum (unit = psia).
- Gauge pressure is the pressure measured w.r.t. atmospheric pressure (unit = psig).
- Atmospheric pressure is the pressure on the earth’s surface due to the weight of gases in the earth’s atmosphere (14.7psi).

**Definitions**

**Absolute Pressure**

The absolute measurement method is relative to 0 Pa, the static pressure in a vacuum. The pressure being measured is acted upon by atmospheric pressure in addition to the pressure of interest. Therefore, absolute pressure measurement includes the effects of atmospheric pressure. This type of measurement is well-suited for atmospheric pressures such as those used in altimeters or vacuum pressures.

**Gauge Pressure**

Gauge pressure is measured relative to ambient atmospheric pressure. This means that both the reference and the pressure of interest are acted upon by atmospheric pressures. Therefore, gauge pressure measurement excludes the effects of atmospheric pressure. These types of measurements include tire pressure and blood pressure measurements.

**Differential Pressure**

Differential pressure is similar to gauge pressure; however, the reference is another pressure point in the system rather than the ambient atmospheric pressure. You can use this method to maintain relative pressure between two vessels such as a compressor tank and an associated feed line.
Pressure Measuring Instruments

The techniques used for pressure measurement depend on the level of pressure (low, moderate, high).

- Low Pressure Measurement (below 133 Pa or 1 torr)
  - McLeod gauge, Pirani gauge, or Ionization gauge.
- Moderate Pressure Measurement
  - Manometer and elastic elements (diaphragm, bellows, capsules, bourdon tubes, spiral, helix).
- High Pressure Measurement (> 1000 atm)
  - Electrical resistance pressure gauge.

Static Pressure of Atmosphere

- Gases differ from liquids in two respects: they are very compressible, and they completely fill any closed vessel in which they are placed.
- The nonlinear air pressure variation with altitude shown in the figure is an example of the effect of the compressibility of gases.
Dynamic Effects

- Static pressure is measured under steady-state or equilibrium conditions, but most real-life applications deal with dynamic or changing pressure.
- For example, the measurement of blood pressure usually gives the two steady-state values of systolic and diastolic pressure.
- There is much additional information in the shape of the blood pressure signal which is the reason for the monitors used in critical-care situations.
- To measure changing pressures, the frequency response of the sensor must be considered. As a rough approximation, the sensor frequency response should be $5-10 \times$ the highest frequency component in the pressure signal.
- Another issue is the remote measurement of pressure where a liquid coupling medium is used. Care must be taken to purge all air because its compressibility will corrupt the waveform.

Pressure Sensing

- Pressure is sensed by mechanical elements such as plates, shells, and tubes that are designed and constructed to deflect when pressure is applied.
- This is the basic mechanism converting pressure to physical movement.
- Next, this movement must be transduced to obtain an electrical or other output.
- Finally, signal conditioning may be needed, depending on the type of sensor and the application.
Sensing Elements

- The main types of sensing elements are Bourdon tubes, diaphragms, capsules, and bellows.
- All except diaphragms provide a fairly large displacement that is useful in mechanical gauges and for electrical sensors that require a significant movement.

Bridge-Based Pressure Sensors

- Wheatstone bridge (strain-based) sensors are the most common because they offer solutions that meet varying accuracy, size, ruggedness, and cost constraints. Bridge-based sensors can measure absolute, gauge, or differential pressure in both high- and low-pressure applications. They use a strain gage to detect the deformity of a diaphragm subjected to the applied pressure. You can bond foil strain gages directly to a diaphragm or to an element that is connected mechanically to the diaphragm. Silicon strain gages are sometimes used as well.
Signal Conditioning for Bridge-Based Pressure Sensors

- Bridge-based pressure sensors are by far the most common pressure sensors. You need to consider several signal conditioning elements to make an effective bridge-based pressure measurement system:
  - Excitation to power the Wheatstone bridge circuitry.
  - Remote sensing to compensate for errors in excitation voltage from long lead wires.
  - Amplification to increase measurement resolution and improve signal-to-noise ratio.
  - Filtering to remove external, high-frequency noise.
  - Offset nulling to balance the bridge to output 0 V when no strain is applied.
  - Calibration to verify the output of the bridge to a known value.

Capacitive Pressure Sensors

A variable capacitance pressure transducer measures the change in capacitance between a metal diaphragm and a fixed metal plate. The capacitance between two metal plates changes if the distance between these two plates changes due to applied pressure.
Capacitive Pressure Sensors

• Capacitive pressure sensors typically use a thin diaphragm as one plate of a capacitor.
• Applied pressure causes the diaphragm to deflect and the capacitance to change.
• This change may or may not be linear and is typically on the order of several picofarads out of a total capacitance of 50 - 100 pF.
• This change in capacitance may be used to control the frequency of an oscillator or to vary the coupling of an AC signal through a network.

Piezoelectric Pressure Sensors

Piezoelectric sensors rely on the electrical properties of quartz crystals rather than a resistive bridge transducer. These crystals generate an electrical charge when they are strained. Electrodes transfer the charge from the crystals to an amplifier built into the sensor. These sensors do not require an external excitation source, but they are susceptible to shock and vibration.
Piezoelectric Pressure Sensors

- Piezoelectric elements are bi-directional transducers capable of converting stress into an electric potential and vice versa.
- One important factor to remember is that this is a dynamic effect, providing an output only when the input is changing.
- This means that these sensors can be used only for varying pressures.
- The piezoelectric element has a high-impedance output and care must be taken to avoid loading the output by the interface electronics. Some piezoelectric pressure sensors include an internal amplifier to provide an easy electrical interface.

Conditioned and Optical Pressure Sensors

Sensors that include integrated circuitry, such as amplifiers, are referred to as amplified sensors. These types of sensors may be constructed using bridge-based, capacitive, or piezoelectric transducers. In the case of a bridge-based amplified sensor, the unit itself provides completion resistors and the amplification necessary to measure the pressure directly with a data acquisition system. Though excitation must still be provided, the accuracy of the excitation is less important.

Optical Pressure Sensors

Pressure measurement using optical sensing has many benefits including noise immunity and isolation. Read Fundamentals of FBG Optical Sensing for more information about this method of measurement.
Choosing the Right Pressure Sensor

- Bridge-based or piezoresistive sensors are the most common types of sensor because of their simple construction and durability. This translates to lower cost. In general, foil strain gages are used in high-pressure (up to 700M Pa) applications. They also have a higher operating temperature than silicon strain gages, but silicon strain gages offer the benefit of larger overload capability. Because they are more sensitive, silicon strain gages are often preferred in low-pressure applications (~2k Pa).

- Capacitive and piezoelectric pressure transducers are generally stable and linear, but they are sensitive to high temperatures and are more complicated to set up than most pressure sensors. Piezoelectric sensors respond quickly to pressure changes. For this reason, they are used to make rapid pressure measurements from events such as explosions. Because of their superior dynamic performance, piezoelectric sensors are the least cost-effective, and you must be careful to protect their sensitive crystal core.

- Conditioned sensors are typically more expensive because they contain components for filtering and signal amplification, excitation leads, and the regular circuitry for measurement. This is helpful for lower cost systems that do not warrant a dedicated signal conditioning system. Because the conditioning is built in, you can connect the sensor directly to a DAQ device as long as you provide power to the sensor in some way.

Pressure Measuring Devices – Barometer

- Atmospheric pressure is measured by a device called a barometer; thus, the atmospheric pressure is often referred to as the barometric pressure.

- A frequently used pressure unit is the standard atmosphere, which is defined as the pressure produced by a column of mercury 760 mm in height at 0°C ($\rho_{Hg} = 13,595$ kg/m$^3$) under standard gravitational acceleration ($g = 9.807$ m/s$^2$).

The basic barometer.
Pressure Measuring Devices – Bourdon Gage

**Principles:** Change in curvature of the tube is proportional to difference of pressure inside from that outside the tube.

**Applications:** Tire pressure, pressure at the top or along the walls of tanks or vessels.

Pressure Measuring Devices – Strain Gage

**Principles:** \( \Delta P \rightarrow \Delta \text{Resistance} \rightarrow \Delta \text{Voltage} \)

**Applications:** Sensors for internal combustion engines, automotive, research etc.
Pressure Measuring Devices – Quartz Gage

**Principles:** \( \Delta \text{Pressure} \rightarrow \Delta \text{Charge} \rightarrow \Delta \text{Voltage} \)

**Applications:** Measurements with high accuracy, good repeatability, high resolution, e.g. Quartz Clock.

Pressures Measuring Devices – Piezo resistive Gage

**Principles:** \( \Delta \text{Pressure} = \Delta \text{Charge} = \Delta \text{Resistance} = \Delta \text{Voltage} \)

**Applications:** Very accurate for small pressure differentials e.g. difference between indoor and outdoor pressure.
Pressure Measuring Devices – U-tube Manometer

**Principles:** Hydrostatic Law

\[ \Delta P = \rho g h \]

![Diagram of U-tube Manometer]

**Applications:** Air pressure, pipe pressure, etc.

Mercury Water Manometer

Air Water Manometer
McLeod Gauge

- It compresses the low pressure gas so that the increased pressure can be measured.
- The change in volume and pressure can then be used to calculate the original gas pressure, providing that the gas not condensed.

![McLeod Gauge Diagram]

Pirani Gauge

- It consists of platinum filament and thermocouple enclosed in a chamber.
- The pressure measurement is based on the relation of heat conduction and radiation from a heating element to the number of gas molecules per unit volume in the low pressure region.

![Pirani Gauge Diagram]
Ionization Gauge

- It can be used to measure pressure down to about 2 torr.
- The gas is ionized with a beam of electrons and the current is measured between two electrodes in the gas.
- The current is proportional to the number of ions per unit volume, which is also proportional to the gas pressure.

![Ionization Gauge Diagram](image)

Piezoresistive Integrated Semiconductor

Integrated Circuit processing is used to form the piezoresistors on the surface of a silicon wafer.

There are four piezoresistors within the diaphragm area on the sensor. Two are subjected to tangential stress and two to radial stress when the diaphragm is deflected.

They are connected in a four-element bridge configuration and provide the following output:

\[ \frac{V_{\text{OUT}}}{V_{\text{CC}}} = \frac{\Delta R}{R} \]
Piezoresistive Integrated Semiconductor

- IC processing is used to form the piezoresistors on the surface of a silicon wafer to fabricate an integrated piezoresistive pressure sensor.

Integrated silicon pressure sensor measures 0.52 in. long by 0.44 in. wide by 0.75 in. high, including the port.

Calibration

**Dead-Weight Tester.** A dead-weight tester uses calibrated weights that exert force on a piston which then acts on a fluid to produce a test pressure.

Oil is the medium typically used for lower pressures. For high pressures (>500 psi), pneumatic bearing testers are available and are more convenient as well as less messy to use.