# 1. Introduction to Pressure Measurement

## 1.1 Pressure Sensor Classification

Pressure measurements are a key part of many fluid (gas or liquid) systems description. Fluid pressure can be defined as the measure of force per unit area exerted by a fluid, acting perpendicularly to any surface it is in contact with. The standard SI unit for pressure measurement is one Pascal (Pa) which is equivalent to one Newton per square meter ($N/m^2$). In the English measure system, pressure is usually expressed in pounds per square inch (psi). Pressure can be expressed in many different units including in terms of a height of a column of liquid. The table below lists commonly used units of pressure measurement and the conversion between the units.

| | kPa | mm Hg | mbar | in $H_2O$ | psi |
|---|---|---|---|---|---|
| 1 atm | 101.325 | 760 | 1013.25 | 406.795 | 14.696 |
| 1 kPa | 1 | 750062 | 10 | 4.01475 | 0.145038 |
| 1 mm Hg (Torr) | 0.133322 | 1 | 1.33322 | 0.535257 | 0.0193368 |
| 1 cm $H_2O$ (bar) | 0.1 | 0.750062 | 1 | 0.401475 | 0.0145038 |
| 1 in $H_2O$ | 0.249081 | 1.86826 | 2.49081 | 1 | 0.0361 |
| 1 psi | 6.89473 | 51.7148 | 68.9473 | 27.6807 | 1 |
| 1 mm H2O | 0.009806 | 0.07355 | 9.8E-8 | 0.03937 | 0.0014223 |

Pressure measurements can be divided into three categories: absolute pressure, gage pressure and differential (relative) pressure. **Absolute pressure** refers to the absolute value of the force per–unit–area exerted on a surface by a fluid. Therefore the absolute pressure is the difference between the pressure at a given point in a fluid and the absolute zero of pressure or a perfect vacuum. **Gage pressure** measurement is the measurement of the difference between the absolute pressure and the local atmospheric pressure. Local atmospheric pressure can vary depending on ambient temperature, altitude and local weather conditions. The standard atmospheric pressure at the sea level and the temperature of 20°C is 101.325 kPa absolute (abs). When referring to pressure measurement, it is critical to specify what reference the pressure is related to. **Differential pressure** measurement is simply the measurement of one pressure with reference to another pressure. The pressure measured is the difference between these two pressures. This type of pressure measurement is commonly used to measure the pressure drop in a fluid system. Since a differential pressure is a measure of one pressure referenced to another one, it is not necessary to specify the pressure reference.

In addition to these three types of pressure measurement, there are different types of fluid systems and fluid pressures. There are two types of fluid systems: static systems and dynamic systems. As the names imply, a static system is a one in which the fluid is at rest and a dynamic system is one in which the fluid is moving. The pressure measured in a static system is called **static pressure**. In static systems, the pressure increases with depth in the fluid and acts equally in all directions. The pressure in a static liquid can be easily calculated if the density of the liquid is known. The absolute pressure at a depth H in a liquid is defined as:

$$P_{abs} = P + \rho g H$$

where:

$P_{abs}$ is the absolute pressure at a depth H.
P is the external pressure on the top of the liquid.
(For most open systems this will be an atmospheric pressure.)
$\rho$ is the density of the fluid.
g is the acceleration due to gravity ($g = 9.81 m/sec^2$).
H is the depth at which the pressure is desired.

Dynamic pressure systems are more complex than static systems and pressure in this case is usually more difficult to measure. In a dynamic system, pressure is typically defined using the term **total pressure** that is the sum of the **static pressure** and the **dynamic pressure**. The static pressure is the same as the one measured in a static system. The static pressure is independent of the fluid movement or flow. As in a static system, the static pressure acts equally in all directions. The dynamic pressure is associated with the velocity or the flow of the fluid. When measuring dynamic system pressures, care must be taken to ensure accuracy. For static pressure measurements, the pressure tap location should be chosen so that the measurement is not influenced by the fluid flow. Typically, taps are located perpendicular to the flow field. The total pressure at a given point in the system can be measured by means of impact tube (called a Pitot tube) inserted into the flow. It is important that the Pitot tube be aligned parallel to the flow field with the tip of the tube pointing directly into the flow.

Measurements in **transient systems** with changing conditions such as pressures, flow rates, etc. are the most difficult to obtain accurately. In a pressure measurement system, there are two factors that determine the overall measurement response. Firstly, it is the response of the transducer element that senses the pressure, and secondly the response of the interface between the transducer and the pressure system such as the pressure transmitting fluid and the connecting tube, etc. As the demands to the measurement system become more precise, the frequency response of the measurement system must be considered.

Solid-state pressure sensors have been designed using different techniques to convert mechanical deformations to electrical signals. These techniques are: piezoresistive effect, piezoelectric effect, stress effect on a P-N junction, optical deflection or optical fibre, and capacitive effect. Among these types of pressure measurement systems, silicon–based pressure transducers and sensors are becoming the most important. At present, pressure sensors represent the largest market segment of mechanical MEMS devices. Silicon micromachined sensors offer a very high accuracy at a very low cost and provide an interface between the mechanical world and the electrical system. For the optimal application of these sensors, the user needs to understand their structure, properties and how they are made.

Silicon micromachined sensors can be divided into two general classes, piezoresistive and capacitive. In the following chapters, we will present design approaches used in the development of these two classes of pressure sensors.

## 1.2 Pressure Sensor Characteristics

Pressure sensors are characterized by parameters that depend on the target application. Sometimes it is difficult to compare some of these characteristics because manufacturers are currently using different terminologies for the same sensor performance parameters. The most relevant parameters are the following:

- Sensitivity
- Nominal pressure range
- Maximum pressure range
- Full-scale output (FSO)
- Linearity
- Offset
- Resolution
- Temperature coefficient of sensitivity (TCS)

- Temperature coefficient of offset (TCO)
- Temperature coefficient of resistance
- Temperature coefficient of bridge resistance
- Overall bridge resistance

Usually pressure sensor provides information about static pressure and its slow variations. Frequency range specification can be found in some pressure sensors datasheets. If the sensor covers at least a part of audio frequency range and if it has a sensitivity permitting to detect pressure variations lower than one Pascal, it can be considered as an acoustic sensor (microphone). The development of an acoustic pressure sensor is much more complex because of the requirements on its behaviour in large frequency range.

The sensor characteristics depend on the device geometry, the mechanical and thermal properties of the structural and packaging materials, and the selected sensing scheme. In the following paragraphs we will discuss some of pressure sensor characteristics. **Sensitivity** is defined as a normalized sensor output signal change per unit pressure change to reference signal:

$$S = \frac{1}{\theta}\frac{\partial\theta}{\partial P} \tag{1}$$

where θ is the output signal and ∂θ is the change in it due to the applied pressure ∂P. Figure 2.3 illustrates the definition. The most sensitive sensors are used for pressure measurements in the range from 0 to 10 kPa but there exist sensors for measurements up to 200 kPa.

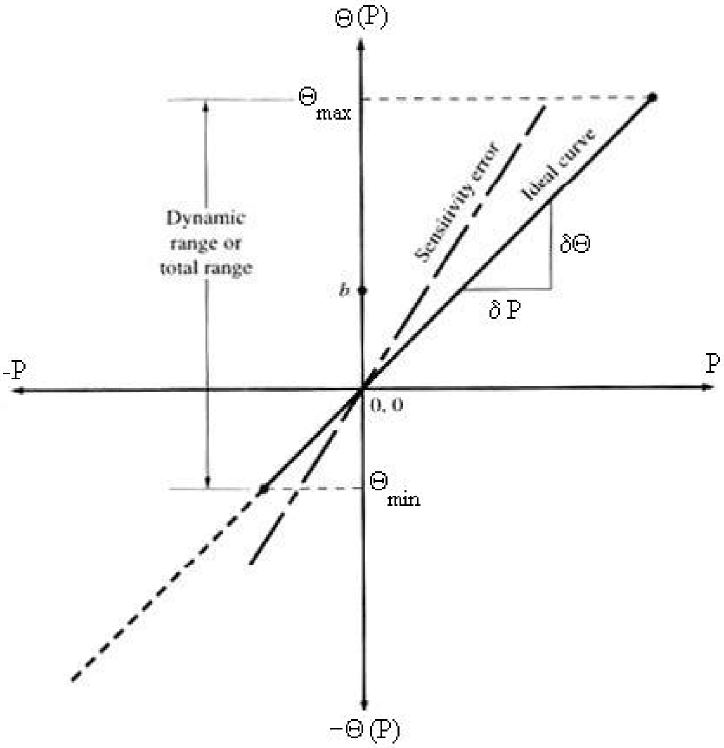

**Figure 1.1.** Ideal Sensitivity Curve and Sensitivity Error.

The sensitivity error is a departure from the ideal slope of the characteristic curve (shown as a dotted curve in Figure 1.1).

The **dynamic range** is the pressure range over which the sensor can provide a meaningful output. It may be limited by the saturation of the transducer output signal or by yield and failure of the pressure diaphragm. The **full-scale output** (FSO) of a pressure sensor is simply the algebraic difference of the end points of the output. The **nominal pressure range** is the pressure range for which the sensor complies with given data. The **maximum pressure range** is the maximum pressure the sensor can withstand without damage.

The **linearity** refers to the proximity of the device response to a specified straight line. It is the maximum separation between the actual measured or calibration curve and the ideal line, expressed as a percentage of full-scale output. Linearity is often specified in terms of *percentage of nonlinearity (NL)*, which is defined as:

$$\mathrm{NL} = \frac{\Delta P_{\mathrm{max}}}{P_{\mathrm{FS}}} \times 100 \ [\%] \tag{2}$$

where $DP_{max}$ is the maximum input deviation, $P_{FS}$ is the maximum full-scale input. In most cases, the static curve is used to determine linearity, and this may deviate somewhat from a dynamic linearity. The static nonlinearity defined by Equation 2 is often subject to environmental factors, including temperature, vibration, acoustic noise level, and humidity. It is important to know under what conditions the specification is valid and departures from those conditions may not yield linear changes of linearity. Generally, capacitive pressure sensors provide highly nonlinear outputs, and piezoresistive pressure sensors provide fairly linear output.

The **offset error** of a transducer is defined as the output that will exist when it should be zero or, alternatively, the difference between the actual output value and the specified output value under some particular set of conditions. An example of the first situation in terms of Figure 2.3 would exist if the characteristic curve had the same sensitivity slope as the ideal one but crossed the Y-axis (output) at *b* instead of zero.

The **resolution** is the smallest incremental change of pressure that can be detected. Resolution can be expressed either as a proportion of the reading (or the full-scale reading) or in absolute terms.

The temperature sensitivity of a pressure sensor is an important performance factor. The definition of **temperature coefficient of sensitivity** (TCS) is:

$$\mathrm{TCS} = \frac{1}{S}\frac{\partial S}{\partial T} \tag{3}$$

where $S$ is the sensitivity at the reference temperature, and $T$ is the temperature.

Another important parameter is the **temperature coefficient of offset** (TCO). The offset of a pressure sensor is the value of the output signal at a reference pressure, such as when ?P = 0. Consequently, the TCO is:

$$\mathrm{TCO} = \frac{1}{\theta_0}\frac{\partial \theta_0}{\partial T} \tag{4}$$

where $?_0$ is the offset at the reference temperature, and $T$ is the temperature.

The **temperature coefficient of bridge resistance** (TCR) concerns piezoresistive pressure sensors that use a Wheatstone bridge for the output signal measurement and is defined in a similar manner as the previous characteristics:

$$\mathrm{TCR} = \frac{1}{R}\frac{\partial R}{\partial T} \tag{5}$$

where $R$ is the bridge resistance at the reference temperature, and $T$ is the temperature.

Thermal stresses caused by differences in expansion coefficients between the diaphragm and the substrate or packaging materials are some of the many possible contributors to these temperature coefficients. In many cases, the temperature coefficient of sensitivity has a significant value. The temperature coefficient of offset can be neglected in the main field of applications.

There are many other parameters that can be regarded in the pressure sensors. Often they are more significant in some specific applications or in some specific environmental conditions. The parameter called **g-sensitivity** is the effect of the gravity on the sensor output. To determine the g-sensitivity, the simplest approach is just to place the device in one orientation, measuring the offset and then rotating to another position and measuring the offset again. The change in offset is the effect of a 2-g change in acceleration. The hysteresis, and the response time are other parameters that may have importance in some special kinds of measurements.

## 1.3 Related Reading

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