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Electronic Pressure Measurement – Measuring Principles and Pressure Measuring Instruments PART I

Electronic pressure measurement contributes to the safe, accurate and energy-saving control of processes. Alongside temperature measurement, it is the most important and most commonly-used technology for monitoring and controlling plants and machinery. Particularly in pneumatics and hydraulics, measurement and control of the system pressure is the most important prerequisite for safe and economic operation.
During the past 20 years, electronic pressure measurement has been introduced in a multitude of applications, and new applications are added every day. Among other things they assist in various applications such as the extraction of clean potable water from wells or desalination plants, in the safe control of the landing flaps of aircraft, in the economical operation of air conditioning and refrigeration plants, in the production of high-performance materials, in the chemical industry, in environmentally-friendly power generation within fuel cells and in the efficient control of heat pumps. They ensure the safe operation of cranes and elevators, trouble-free operation of machine-tools and automated machinery, environmentally sound combustion in engines and the stable and energy-saving running of power units and drives.
However, the demands on the instruments are as diverse as the applications. This fact is also reflected in the very large number of products. In the early days of electronic pressure measurement the user could only choose from a small number of variants, manufactured by a handful of providers. Today the user is confronted with a multitude of technical solutions by numerous providers, and must therefore rely on competent help with the selection.

Principles of electronic pressure measurement

For electronic pressure measurement a sensor is required to detect the pressure and/or its change, and to convert it accurately and repeatably into an electrical signal utilising a physical operating principle. The electrical signal is then a measure of the magnitude of the applied pressure or change in pressure. Four key measuring principles and their technical realisation are shown below.

Resistive pressure measurement

The principle of resistive pressure measurement is based on the measurement of the change in resistance of electric conductors caused by a pressure-dependent deflection. The following equation applies for the resistance of an electric conductor:

$$R = \rho \cdot \frac{l}{A}$$

R Electrical resistance
ρ Resistivity
l Length
A Cross-sectional area

If a tensile force is applied to the conductor, its length increases and its cross-sectional area decreases (Fig. 1). Since the resistivity of a metallic conductor is a (temperature-dependent) constant for a particular material and, therefore, independent of the geometry, the electrical resistance increases as a result of the elongation. In the case of compression, the opposite applies.
The principle of resistive pressure measurement is realised using a main body which exhibits a controlled deflection under pressure. This main body frequently has a (thin) area referred to as the diaphragm, which is weakened intentionally. The degree of deflection caused by the pressure is measured using metallic strain gauges.
Usually four strain gauges are applied to a diaphragm. Some of them are located on elongated and others on compressed areas of the diaphragm. If the diaphragm deflects under the action of a pressure, the strain gauges are deflected correspondingly (Fig. 2). The electrical resistance increases or decreases proportionally to the deflection (elongation or compression). To accurately measure the resistance change, the strain gauges are wired to a Wheatstone measuring bridge.

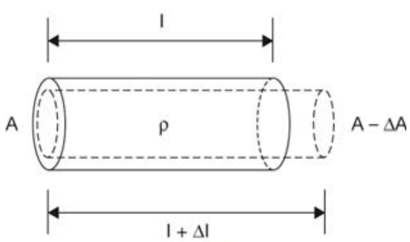

Figure 1: Change of the diemsions of a cylindrical conductor by elongation

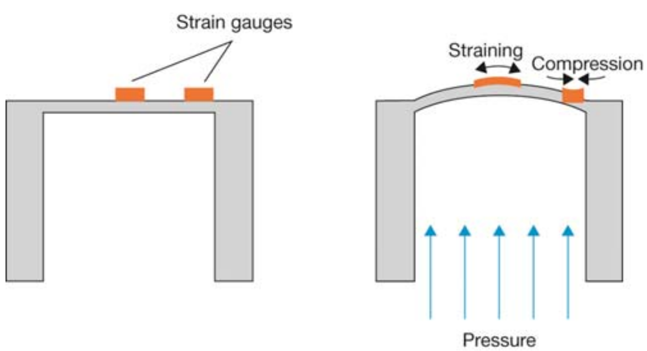

Figure 2: Deflection of the sensor disphragm under pressure

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Piezo-resistive pressure measurement

The principle of piezo-resistive pressure measurement is similar to the principle of resistive pressure measurement. However, since the strain gauges used for this measuring principle are made of a semiconductor material, their deflection due to elongation or compression results primarily in a change in resistivity. According to equation 3, the electrical resistance is proportional to the resistivity. While the piezo-resistive effect in metals is negligible and thus effectively insignificant within resistive pressure measurement, in semiconductors such as silicon it exceeds the effect of the variation of length and cross-section by a factor between 10 and 100.
Unlike metallic strain gauges, which can be attached to nearly any material, the semiconductor strain gauges are integrated into the diaphragm as microstructures. Thus, the strain gauges and the deflection body are based on the same semiconductor material. Usually four strain gauges are integrated into a diaphragm made of silicon and wired to a Wheatstone measuring bridge.
Since the microstructures are not resistant to many pressure media, for most applications the sensor chip must be encapsulated. The pressure must then be transmitted indirectly to the semiconductor sensor element, e.g. using a metallic diaphragm and oil as a transmission medium.
Due to the magnitude of the piezo-resistive effect, piezo-resistive sensors can also be used in very low pressure ranges. However, due to strong temperature dependency and manufacturing process-related variation, individual temperature compensation of every single sensor is required.

Capacitive pressure measurement

The principle of capacitive pressure measurement is based on the measurement of the capacitance of a capacitor, which is dependent upon the plate separation. The capacitance of a dual-plate capacitor is determined using the following equation:

$$C = \varepsilon \frac{A}{d}$$

C	Capacitance of the dual-plate capacitor
ε	Permittivity
A	Area of the capacitor plate
d	Plate separation

The principle of capacitive pressure measurement is realised using a main body with a metallic diaphragm, or one coated with a conductive material, which forms one of the two plates of a dual-plate capacitor. If the diaphragm is deflected under pressure, the plate separation of the capacitor decreases, which results in an increase in its capacitance while the plates' surface area and permittivity remain constant (Fig. 3).
In this way, the pressure can be measured with high sensitivity. Therefore, capacitive pressure measurement is also suitable for very low pressure values, even down in the one-digit millibar range. The fact that the moving diaphragm can be deflected until it reaches the fixed plate of the capacitor ensures a high overload safety for these pressure sensors.

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Practical restrictions on these sensors arise from the diaphragm material and its characteristics, and also from the required joining and sealing techniques.

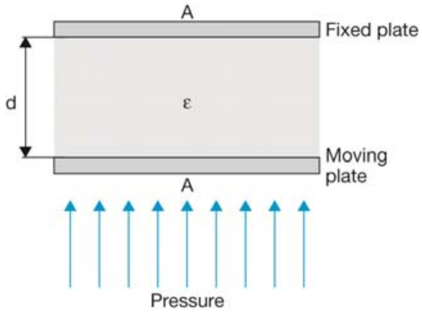

Figure 3: Capacitive measuring principle

Piezo-electric pressure measurement

The principle of piezo-electric pressure measurement is based on the physical effect of the same name, only found in some non-conductive crystals, e.g. monocrystalline quartz. If such a crystal is exposed to pressure or tensile force in a defined direction, certain opposed surfaces of the crystal are charged, positive and negative, respectively. Due to a displacement in the electrically charged lattice elements, an electric dipole moment results which is indicated by the (measurable) surface charges (Fig. 4). The charge quantity is proportional to the value of the force, its polarity depends on the force direction. Electrical voltage created by the surface charges can be measured and amplified.
The piezo-electric effect is only suitable for the measurement of dynamic pressures. In practice, piezo-electric pressure measurement is therefore restricted to specialised applications.

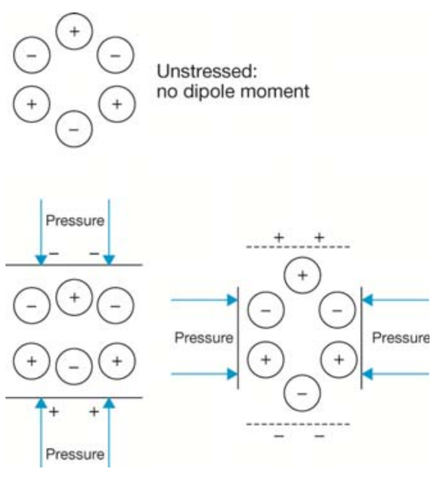

Figure 4: Piezo-electric effect

Sensor technology

The three most common sensor principles are described below. Metal thin-film and ceramic thick-film sensors are the two most common implementations of resistive pressure measurement. The significant differences between them result from the different materials used and their properties. The third sensor principle described is the piezo-resistive pressure sensor.

Metal thin-film sensor

The main body and the diaphragm of a metal thin-film sensor are usually made of stainless steel. They can be manufactured with the required material thickness via machining the diaphragm in automatic precision lathes and then grinding, polishing and lapping it. On the side of the diaphragm not in contact with the medium, insulation layers, strain gauges, compensating resistors and conducting paths are applied using a combination of chemical (CVD) and physical (PVD) processes and are photolithographically structured using etching (Fig. 5). These processes are operated under cleanroom conditions and in special plants, in some parts under vacuum or in an inert atmosphere, in order that structures of high atomic purity can be generated. The resistors and electrical conducting paths manufactured on the sensor are significantly smaller than a micrometre and are thus known as thin-film resistors. The metal thin-film sensor is very stable as a result of the materials used. In addition, it is resistant to shock and vibration loading as well as dynamic pressure elements. Since the materials used are weldable, the sensor can be welded to the pressure connection − hermetically sealed and without any additional sealing materials. As a result of the ductility of the materials, the sensor has a relatively low overpressure range but a very high burst pressure.

Figure 5: Metal thin-film sensor

Ceramic thick-film sensor

The main body and the diaphragm of the ceramic thick-film sensor are made of ceramic. Aluminium oxide (Al2O3) is widely used due to its stability and good processability. The four strain gauges are applied as a thick-film paste in a screen-printing process onto the side of the diaphragm which will not be in contact with the pressure medium, and then burned in at high temperatures and passivated through a protective coating. No impurities are permitted during the screen-printing and the burn-in processes. Therefore, manufacturing is usually performed in a cleanroom (Fig. 6). Only the leading manufacturers are able to operate their plants with the proper segregation in order to avoid any cross-contamination and thus maintain the high process stability.

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The ceramic used for the sensor is very corrosion-resistant. However, installation of the sensor into the pressure measuring instrument case requires an additional seal for the pressure connection, which will not be resistant against all media. In addition, the ceramic is brittle and the burst pressure is therefore lower in comparison to a metal thin-film sensor.

Figure 6: ceramic thick-film sensor

Piezo-resistive sensor

A piezo-resistive sensor has a far more complex structure than the sensors described above. The sensor element is made of a silicon chip. This chip consists of a diaphragm, structured with piezo-resistive resistors, which deflects under pressure. The chip has a surface area of only a few square millimetres and is thus much smaller than, for example, the diaphragms of metal thin-film or ceramic thick-film sensors.

The piezo chip is very susceptible to environmental influences and, therefore, must be hermetically encapsulated in most cases (Fig. 7). For this reason it is installed into a stainless-steel case which is sealed using a thin flush stainless-steel diaphragm. The free volume between the piezo chip and the (external) diaphragm is filled with a transmission fluid. A synthetic oil is usually used for this. In an encapsulated piezo-resistive sensor, the pressure medium is only in contact with the stainless-steel diaphragm, which then transmits the pressure through the oil to the (internal) chip's diaphragm.

To minimise the influence of the thermal expansion of the transmission fluid on the pressure measurement, the sensor design must be optimised in such a way that the free internal volume for the given contour of the stainless-steel diaphragm is minimal. Among other things, special displacement bodies are used for this purpose.

A header is normally used for mounting and electrical connection of the sensor chip. It has integrated glass-to-metal seals for the electrical connection between the inner and outer chambers and can be hermetically welded to the case. The sensor element, glued to the rear side of the header, is connected to the pins using bond wires (Fig. 8) and transmits the electrical signals from the sensor element to the connected electronics in the external chamber of the sensor. A ventilation tube, which leads to the rear side of the sensor diaphragm, is located in the centre of the header. If the chamber behind the sensor element is evacuated and the ventilation tube is closed, it is possible to use such a piezo-resistive sensor to measure absolute pressure, since the vacuum of the hollow space serves as a pressure reference. In sensors designed for gauge pressure measurement, the ventilation tube remains open and ensures continuous venting to the rear side of the diaphragm, so that the measurement is always performed relative to the local atmospheric pressure. The venting is realised either through the outer case or via a ventilated cable to the outside.

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This ventilation tube must be carefully protected against contamination, especially moisture ingress, since the sensor is very susceptible to this and may even become inoperative.

Figure 7: open piezo-resistive sensor

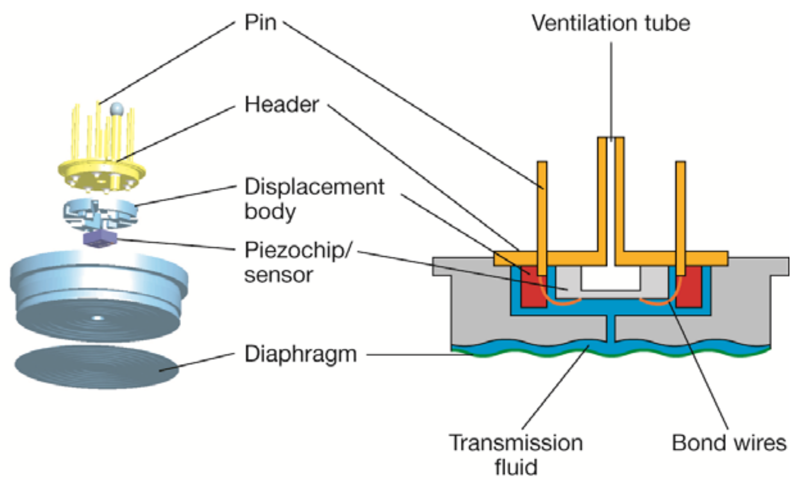

Figure 8: Design of an encapsulated piezo-resistive sensor

Sensor principles by comparison

There is no ideal sensor principle since each of them has certain advantages and disadvantages (Table 1). The sensor type that is most suitable for an application is primarily determined by the demands of the application. It is not only the basic sensor technology that is key for the suitability of the sensor, but above all the practicalities of its implementation. Depending on the application, the sensor principles described may indeed make the implementation either easier or more difficult.

The material in contact with the pressure medium (wetted parts) and its suitability for certain media are of fundamental importance. Thus, one of the disadvantages of the ceramic thick-film sensor in comparison with the metal thin-film sensor is that it requires additional sealing between the non-metallic diaphragm material and the case. This almost always prevents universal applicability.

The product ranges of sensor manufacturers are usually tailored and optimised to different applications dependent upon such considerations. Only universal instruments allow the users themselves to select the suitable sensor principle. The leading manufacturers offer proficient support for this purpose.

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Requirement	Sensor principle		
	Piezo-resistiv sensor	Metal-thin-film sensor	Ceramic thick-film sensor
Measurement of the absolute pressure	●	○	○
Very low pressure ranges	●	○	○
Very high pressure ranges	○	●	○
Shock and vibration resistance	⦿	●	⦿
Long-term stability	●	●	⦿

● Requirement fulfilled, ⦿ Requirement partly fulfilled, ○ Requirement not fulfilled

Table 1: Sensor principles by comparison

Eugen Gaßmann and Anna Gries: Electronic Pressure Measurement, basics, applications and instrument selection; Süddeutscher Verlag onpact GmbH; Munich 2010

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