Electronic Pressure Measurement

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Basics, applications and instrument selection

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Introduction

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 (Fig. 1), measurement and control of the system pressure is the most important prerequisite for safe and economic operation.

Variety of applications and instruments

During the past 20 years, electronic pressure measurement has been introduced in a multitude of applications, and new applications are added every day. 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.

Instrument selection

This selection is a classic optimisation process, including the comparison of numerous parameters and weighing of requirements relative to each other. This is needed in order to achieve diverse objectives in the application, to ensure maximum safety of operation, to reach or increase the planned performance of the plant and machinery and to reduce the total costs. Incorrect decisions not only have economic consequences, but can also bear a potential safety risk.

Suitability

In order to be able to make a proper selection of the suitable electronic pressure measuring instrument, the users or engineers should have

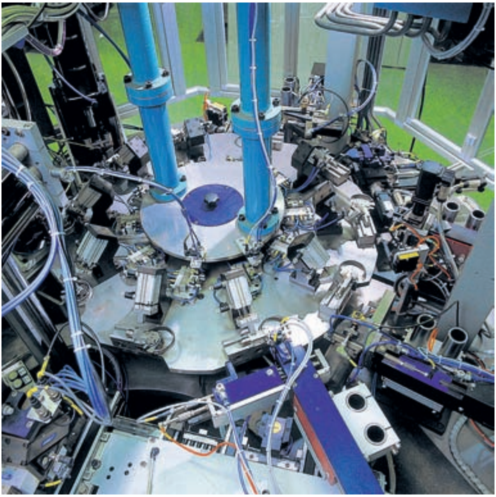


Fig. 1:
Typical application of pressure measurement: pneumatic and hydraulic applications in factory automation

knowledge about the physical principles of pressure measurement, the advantages and disadvantages of different sensor technologies in relation to the particular application, and also about the key basics of instrument technology. The selection of the suitable pressure measuring instrument is based, among other things, on such criteria as the pressure range, the pressure or process connection, the electrical connection, the output signal and the measuring accuracy. This book presents the background knowledge required to understand and compare data in the data sheets in an easy-to-understand and clear way.

Pressure and pressure measurement

In process systems two of the most important process variables to measure are temperature and pressure. The common pressures measured are the hydrostatic pressure of a liquid column and the atmospheric pressure.

Definition of pressure

In general, pressure is defined as follows: if a force per unit area is applied in a direction perpendicular to a surface, then the ratio of the force value F to the surface area A is called pressure p:

$$p = \frac{F}{A} \tag{1}$$

To transmit pressure, incompressible media such as liquids are suitable. To store energy in the form of pressure work, compressible media such as gases are used.

International pressure units

SI unit

The derived SI unit for pressure is Pascal (unit symbol Pa), which can also be represented, according to the equation above, in the SI units Newton (unit symbol N) and metre:

$$1 \text{ Pa} = 1 \ \frac{\text{N}}{\text{m}^2} = 10^{-5} \text{ bar} \tag{2}$$

Europe

North America

The bar is the most common unit of pressure in Europe. This legitimate, SI-compliant unit enables large pressure values, common in daily life and in technology, to be expressed using small numerical values. In North America, on the other hand, the pressure unit “pound (-force) per square inch” (psi) is common. Specifically in Asia, the common units are

Table 1: International pressure units

Pressure unit	Conversion	
1 bar	10^5 Pa	1000 mbar
1 psi	6895 Pa	68.95 mbar
1 MPa	10^6 Pa	10 bar
1 kg/cm2	0.0981 MPa	0.981 bar

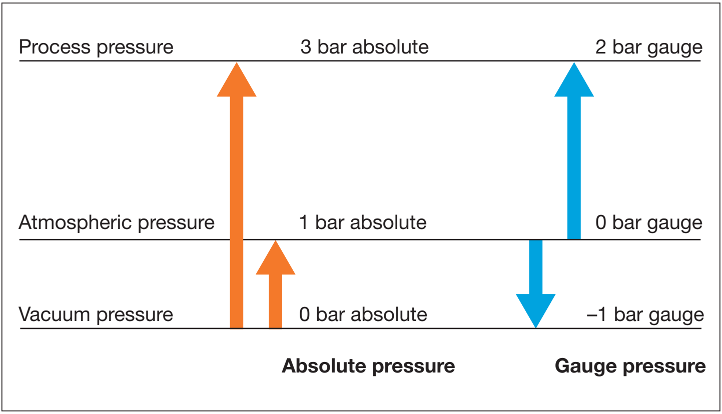
Asia

Megapascal (MPa) and "kilogram(-force) per square centimetre" (kg/cm^2). Table 1 displays the correlation of these pressure units.

Absolute, gauge and differential pressure

Absolute, gauge and differential pressure are three measurement parameters that differ in their reference points, i.e. in the corresponding zero point of the pressure scale. The zero point of absolute pressure is always the pressure in an evacuated space, i.e. in a vacuum (Fig. 2). The zero point of gauge pressure, on the other hand, is provided by the prevailing local atmospheric pressure. This atmospheric pressure equals approximately 1 bar at sea level and decreases continuously with increasing height. In addition, it depends on the weather conditions.

Fig. 2: Pressure types



For some applications, the difference between two variable system pressures is the actual measurement value. This is known as the measurement of differential pressure. A practical example of this is differential pressure monitoring upstream and downstream of a filter element (see *Critical value monitoring*, p. 39 f.).

Principles of electronic pressure measurement

From pressure to electrical signal

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:

$$R = \rho \cdot \frac{l}{A} \qquad (3)$$

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. 3). Since the resistivity of a

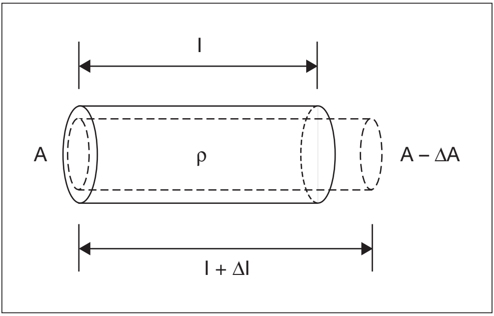


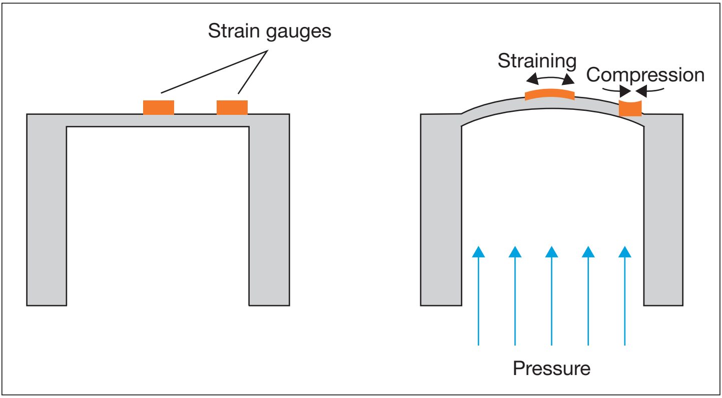
Fig. 3:
Change of the dimensions of a cylindrical conductor by elongation

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.

Diaphragm …

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.

Fig. 4:
Deflection of the sensor diaphragm under pressure



… with 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. 4). 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.

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 (see page 8), 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.

Silicon diaphragm with integrated strain gauges

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.

Encapsulation of the sensor element

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:

$$C = \varepsilon \cdot \frac{A}{d} \tag{4}$$

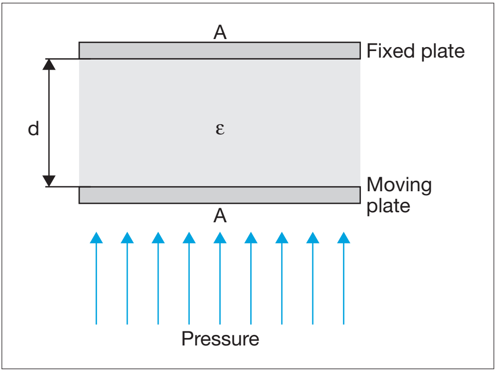
C	Capacitance of the dual-plate capacitor
ε	Permittivity
A	Area of the capacitor plate
d	Plate separation

Diaphragm as a moving capacitor plate

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. 5).

In this way, the pressure can be measured with high sensitivity. Therefore, capacitive pressure measurement is also suitable for very low pres-

Fig. 5: Capacitive measuring principle



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

Piezo-electric pressure measurement

Piezo-crystalline diaphragm

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. 6). 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.

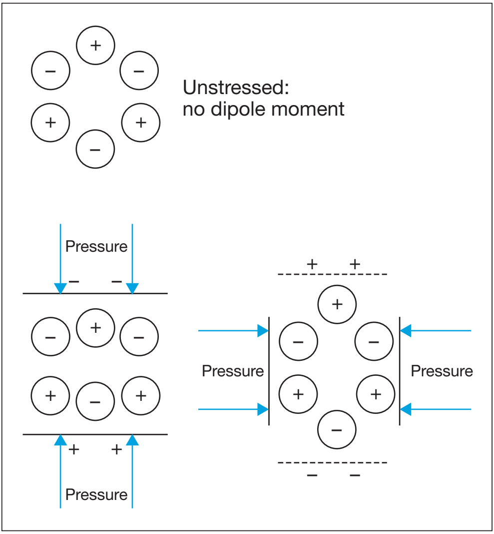


Fig. 6:
Piezo-electric effect

Measurement of changes in pressure

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.

Sensor technology

The three most common sensor principles are described below (Fig. 7). 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.

Fig. 7: Metal thin-film sensor (left), ceramic thick-film sensor (centre) and open piezo-resistive sensor (right)

Metal thin-film sensor

Production

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. 8). 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

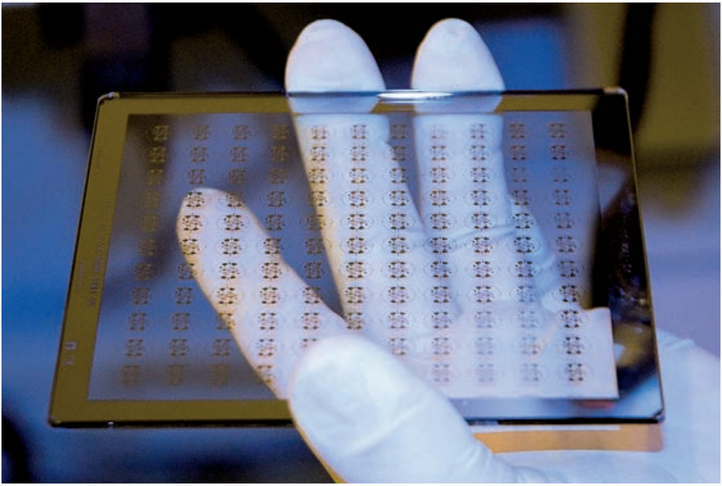


*Fig. 8:
Photomask in order to produce resistor structures on the sensor diaphragms*

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.

Special features

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.

Ceramic thick-film sensor

The main body and the diaphragm of the ceramic thick-film sensor are made of ceramic. Aluminium oxide (Al_2O_3) is widely used due to its stability and good processability. The

Production processes

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. 9). 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.

Fig. 9: Sensor production in cleanroom

Special features

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.

Piezo-resistive sensor

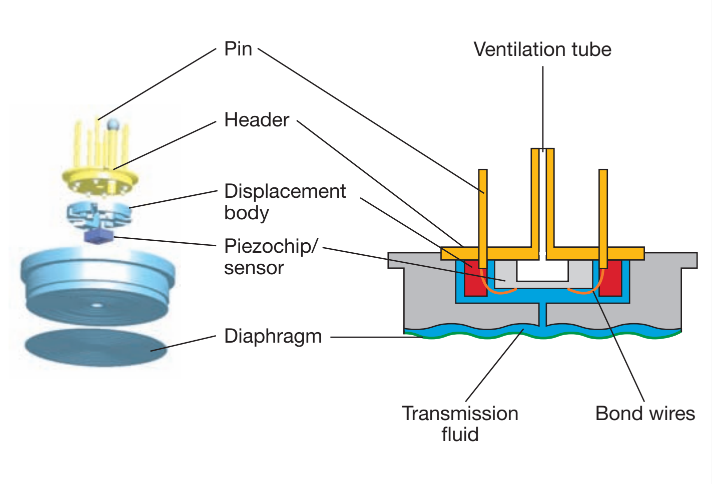
Structure

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.

Encapsulation

The piezo chip is very susceptible to environmental influences and, therefore, must be hermetically encapsulated in most cases (Fig. 10). 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-

Fig. 10:
Design of an encapsulated piezo-resistive sensor



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.

Electrical connection

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. 11) 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,

Fig. 11: Bonding of the silicon chip and the header

Measurement of absolute or gauge pressure

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. 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.

Sensor principles by comparison

There is no ideal sensor principle since each of them has certain advantages and disadvantages (Table 2). The sensor type that is most suitable for an application is primarily determined by

Table 2: Sensor principles by comparison

Requirement	Sensor principle		
	Metal thin-film sensor	Ceramic thick-film sensor	Piezo-resistive 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 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.

Selection of a suitable sensor

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.

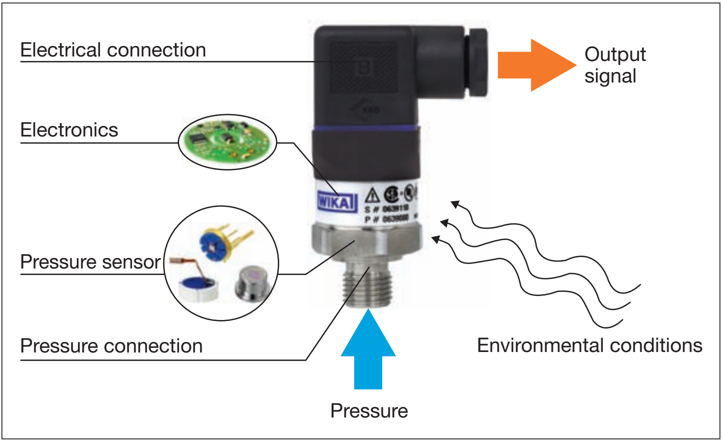
Pressure measuring instruments

This chapter presents the most common types of electronic pressure measuring instruments and gives an overview of their design in respect of a long service life. Subsequently, functional safety under environmental influences will be addressed, and how it can be ensured through product testing.

Instrument types at a glance

Common instrument types are pressure transmitters, level probes, pressure switches and process transmitters. Basically, these electronic pressure measuring instruments consist of a pressure connection, a pressure sensor, electronics, an electrical connection and the case (Fig. 12).
In addition to those mentioned above, there are also simpler instrument types known as pressure sensor modules; often consisting of no

Fig. 12: Structure of a pressure measuring instrument



more than a pressure sensor and simple mechanical and electrical interfaces. These types are particularly suitable for complete integration into users' systems.

Pressure transmitter

Standard instrument and functionality

A pressure transmitter (Fig. 13) has standardised interfaces, both on the process side and on the electrical output signal side, and converts the physical pressure value to a standard industrial signal. The pressure connection is used to lead the pressure directly onto the sensor. It has a (standardised) thread and an integrated sealing system to enable easy connection of the pressure transmitter simply by screwing it in at the relevant measuring point. A suitable case protects the sensor and the electronics against environmental influences. The electronics transform a weak sensor signal into a standardised and temperature-compensated signal; e.g. the common industrial signal of 4 … 20 mA. The output signal is transmitted via a (standardised) plug or cable for subsequent signal evaluation.

Fig. 13:
Pressure transmitter

Level probe

The level probe (Fig. 14), sometimes also referred to as a submersible transmitter, is a special type of pressure transmitter used for level measurements in tanks, wells, shafts and bore holes. For this purpose the level probe measures the hydrostatic pressure at the bottom of the vessel or well. Particularly important is the choice of material for the case and cables, and also the seals at connection points, due to complete and permanent submersion into the medium. Venting of the sensor system, required for the gauge pressure measurement, is achieved via a ventilation tube passed through the cable.

Fig. 14:
Level probe

Pressure switch

In many applications electronic pressure switches replace the mechanical pressure switches that used to be very common, since they offer, as a result of their design principle, additional functions such as digital display, adjustable switch points and considerably higher reliability. They are most frequently used in machine building.
An electronic pressure switch is based on an electronic pressure transmitter and therefore offers the entire functionality of a transmitter. With the integrated electronic switch, which can close or open an electrical circuit, it is able to perform simple control tasks. The switch point and the reset point can be set individually.
By default, a pressure switch only outputs binary signals such as switch point or reset point “reached” or “not reached” but it does not output how far the measured pressure is from the switch or reset point. That is why many pressure switches have a display and additionally an analogue output signal. The set parameters and measured pressure can be read

Fig. 15:
Pressure switch with display

off the display. In addition, the measured pressure can be transmitted by the analogue output signal to a downstream control unit. Thus, this widely adopted type of electronic pressure switch includes a switch, a pressure transmitter and a digital indicator − all in one instrument (Fig. 15).

Process transmitter

User-configurable

The process transmitter (Fig. 16) is a pressure transmitter with a pressure range that can be set within a predefined pressure range (turndown). It is mainly used in process engineering, since in this application area it is necessary to adjust every single measuring point to a multitude of specific requirements that must be individually set by the operator on site. The process transmitters have a very high measurement accuracy within the entire pressure range. In addition, the pressure range, the zero point and further parameters

Fig. 16:
Process transmitter with display

can usually be set individually. For this purpose many process transmitters have both digital display and additional operating elements and extensive operating software directly within the instrument.

Pressure transducer

Application-specific features

Providers of pressure transducers usually offer a multitude of sensor modules that can be directly matched to the requirements of the user. They have, for example, a user-specific pressure connection and/or a user-specific electric interface (Fig. 17). Only very few manufacturers of electronic pressure measurement technology even offer the so-called “bare” pressure sensor as a module. For these, the users must develop their own design solu-

Fig. 17:
Pressure transducers

tions in order to get the pressure to the sensor and evaluate the sensor signal.
For pressure transducers it is generally the case that their correct function must be ensured by the user's design-related measures. Therefore, this option is usually only suitable for mass-produced equipment.

Instrument qualification and reliability

Mean time to failure: MTTF

A whole series of examinations is required for electronic pressure measuring instruments to be qualified for a particular application. Of fundamental importance here is the required reliability with respect to the service life of the instrument under the expected operating conditions. The (mean) service life is the mean time to failure (MTTF). It mainly depends on the operating conditions. As a result of the operating conditions, the failure probability of the individual components of an electronic pressure measuring instrument can vary considerably.

Pressure connection
Pressure connections are standardised to a great extent, easy to dimension and easy to

handle. For pressure values up to 1000 bar, most are considered to be failure-proof, i.e. they offer practically unlimited service life. At most for seals, in particular seals made of organic materials, certain ageing effects are to be expected. As long as the pressure medium is compatible with the material and the operating temperature range is not exceeded, almost no serious problems occur. Detailed information on media resistance is given in the relevant technical literature and manufacturer's specifications.

Resistance to media

Sensor system

When assessing the service life of the sensor system, a differentiation must be made between the different sensor principles. Since these sensor types are exposed to completely different loadings and the materials or material combinations used respond completely differently, a highly differentiated approach is absolutely essential.

Metal thin-film sensors

The classic metal thin-film sensor represents a clearly-defined system. The main body, including the weld seam, is usually over-dimensioned in order to ensure permanent stable conditions at the diaphragm and thus a long service life. Dimensioning of the diaphragm geometry and positioning of the strain gauges are optimised using the Finite Elements Method (FEM). This helps to achieve a linear deflection of the diaphragm under pressure in the case of radial and tangential tension over a large load range, which enables accurate measurement of the pressure values. Since the materials used are mostly ductile steels or special alloys, the FEM simulations can also ensure that the deflection of the diaphragm material across the entire pressure range re-

FEM simulation

mains far below the yield point (Fig. 18). Thus, local overloads with corresponding plastic deformation are avoided.

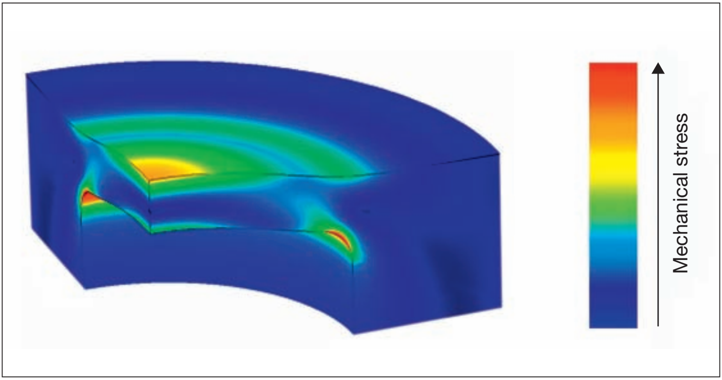


Fig. 18: FEM simulation of the equivalent stress intensity on the deflected diaphragm of a metal thin-film sensor

Fatigue life test

The fatigue life can be determined using standard procedures such as fatigue testing, its results are represented by the S-N curve (Wöhler curve). The known and trusted manufacturers consider 10^8 load cycles to be a safe design criteria. Particularly for new developments, geometrical variations or material replacements, despite this high value, manufacturers will not do without the validation of their design through empirical data based on fatigue tests conducted over weeks, or even months, on test benches. One of the reasons for this is that, besides mechanical stress distribution, manufacturing procedures such as heat treatment of steel and forming processes, as well as production-related surface defects, for example striations, may also have significant influences.

Ceramic thick-film sensors

The main body of the ceramic thick-film sensor is also overdimensioned. However, two material-related differences must be considered: on the one hand, the ceramic of the main body, unlike steel, does not suffer fatigue (ageing) so long as it is neither overloaded nor suffers additional stress due to mechanical or thermal shock. However, imperfections such as slight impurities or microscopic mechanical defects on the surface may result in dramatic changes to the burst pressure and must therefore be monitored carefully during the manufacturing process. On the other hand, the ceramic main bodies require carefully dimensioned mounting or seating and an additional seal in the transition to the pressure port. Usually the ageing of this seal, under the influence of load and temperature changes and under the influence of the application's pressure media, represents the limiting factor. Therefore, there is often no other choice than to determine the service life and thus the suitability individually through load cycle tests, especially under the influence of the medium and ambient temperatures.

Load cycle tests under temperature influence

Piezo-resistive sensors

To some degree, the same applies for the piezo-resistive sensors as for the ceramic thick-film sensors. While the sensor material itself is almost unaffected by fatigue, the rest of the sensor system must be designed carefully and evaluated for potential risks using, for example, failure mode and effects analysis (FMEA). This applies both to the design and construction of the diaphragm seal (consisting of a diaphragm, capsule housing with diaphragm bed and pressure port as well as a displacement body) and the design and bonding methods used for the header and support for the piezo chip. Load cycle tests, in particular for high-pressure ranges, are also absolutely essential for piezo-resistive sensors. However,

FMEA

Specific load cycle tests

the systems are so complex that individual tests are usually required.

Electronics

The dimensioning guidelines common in standard industrial electronics also apply to the circuitry and electronic components used in electronic pressure measurement technology. Of course, attention must be paid to the correlation between the number of components used and the number of required soldering points as well as the strong correlation between the service life of electronic components and the temperature. The approved standard methods can be used for the calculation of service life. Since the MTTF values usually obtained in this way can be several

Fig. 19: Machine to perform the Highly Accelerated Life Test (HALT)

hundreds of years, they cannot be verified experimentally, so accelerated ageing methods must be used (Fig. 19).

Instrument tests

To ensure the functionality of electronic pressure measuring instruments under all environmental conditions, the research laboratories of major manufacturers regularly perform long series of different tests. Some testing, e.g. that for electromagnetic compatibility (EMC), is stipulated by law. The instruments cannot be placed on the market if they have not passed these tests. Other tests are carried out to meet particular market requirements and/or to specific operating conditions. If standards or directives for certain tests exist, then they are implemented. If the standards do not provide adequate test procedures, market-specific and application-oriented tests are often developed.

EMC tests

Application-specific tests

For market-specific test procedures the application conditions are simulated as accurately as possible. The test objects are often not only exposed to one test, but must pass a whole series of tests. They are exposed, for example, first to strong vibrations (Fig. 20) and must

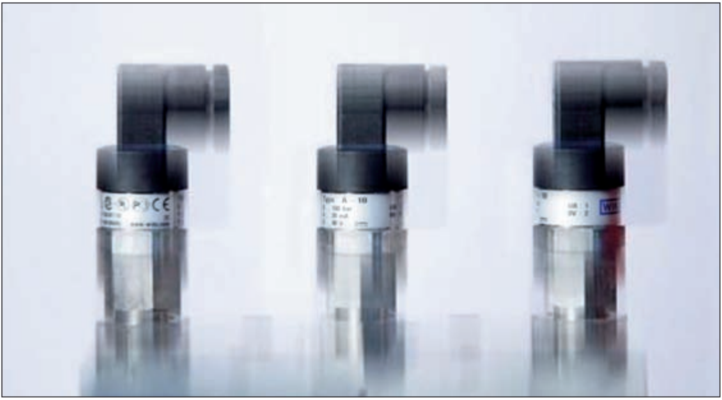


Fig. 20: Vibration test

then resist severe shocks. Alternatively they will be successively heated, cooled, immersed in water, exposed to salt spray and daubed with solvents or lubricants and additives. An instrument will have passed the test series only if it measures with its original accuracy both during and after the tests. This type of extended product testing is usually known as “application-specific standard testing procedure”. Since the test contents and procedures are specified by each manufacturer individually, they must generally be requested by the end-user and evaluated accordingly.

Environmental influences and special requirements

Temperature influence

Since temperature influences many properties of a material, it also affects the proper operation of measuring instruments. Very high or very low temperatures can damage or even destroy parts of the measuring instrument. In particular, plastic parts and sealing materials age much faster under the influence of constant high or low temperatures. For example, if the temperature is too low, they lose their elasticity.

Manufacturer specifications

To ensure proper function of the pressure measuring instruments, some manufacturers specify temperature ranges in their data sheets for the pressure medium, ambient conditions and during storage. Other manufacturers define an operating temperature range which includes both the medium and ambient temperature range. The measuring instrument will not be damaged provided these specifications are adhered to. The data specified in the data sheets regarding the measuring accuracy (see page 58 ff.), on the other hand, are only valid for the temperature-compensated range which is significantly smaller and will also be specified in the data sheets.

Compatibility with the pressure medium

The pressure media are as many and diverse as the applications of pressure measurement technology. In pneumatics it is mostly air mixed with residues of compressor oil and condensed water; in level measurement it is mostly fuel, oils or chemicals. In hydraulics the pressure of the hydraulic oil must be measured; in refrigeration technology, the pressure of the refrigerant must be measured.

All physical and chemical characteristics of the pressure medium must be considered when selecting the material and other properties of those parts of the pressure measuring instrument in contact with the pressure medium. Special attention must be paid to the fact that the diaphragms are only a few microns thick. Material abrasion due to corrosion cannot be accepted; not only because it would erode the diaphragm, but also since the measurement characteristics would change continuously. Due to the small material thickness there is a risk of pressure medium diffusing through the diaphragm and reacting with the materials behind it, for example filling media and adhesives.

Diaphragm

To prevent chemical reactions initiated by aggressive media, measures such as having a flush stainless-steel diaphragm with a highly-resistant coating made of special plastic, ceramic materials or noble metals are often taken. As an alternative, the wetted parts can be made of titanium or other special materials such as alloys based on nickel, molybdenum or cobalt.

Pressure connection

The reactivity of the pressure medium is, however, just one aspect from a whole range. If, for example, the water used as a pressure medium does not drain completely and subsequently freezes, it may damage the internal sensor diaphragm as a result of expansion. Lime deposits can also clog the pressure port. Some media, such as those with high viscosity or high solids content, require a pressure connection without a pressure port. For this purpose a flush variant of the sensor diaphragm is used (see page 52 f.).

Protection against soiling and water

IP rating

The electronic components and electrical connections must be protected against the ingress of any foreign objects or water in order to ensure they continue to operate. The IP ratings defined in the DIN EN 60529 standard specify what level of protection is provided by an electrical or electronic instrument at room temperature against contact with, and intrusion of, foreign objects (first digit) as well as against ingress of water (second digit). A higher IP rating does not automatically imply an improvement in protection. For example, IP67 (total dust ingress protection, protection against temporary immersion) does not necessarily cover IP65 (total dust ingress protection, spray water protected), since the load due to spray water can be significantly higher than the load during temporary immersion. For the IP68 rating (total dust ingress protection, protection against permanent submersion), the manufacturer must always specify additionally the duration and depth of immersion. These conditions are not specified in the standard.

Sealing problems can also be caused through temperature variations. Therefore, some manufacturers utilise different testing procedures to verify that their measuring instruments remain functional and measure within the specified accuracy limits even after temperature variations.

The use of pressure measuring instruments outdoors places especially high demands on them. A combination of high ambient humidity and low temperature can lead to condensation or even icing. Large cyclic climatic fluctuations can lead to the accumulation of water within the instrument if the instrument is not sealed (pumping effect).

Case design

Intensive moisture accumulation (continuous condensation) on the measuring instrument, and partially inside it, occurs regularly if the ambient humidity is high and the temperature of the pressure medium is much lower than the ambient temperature. In this case, a special case design is needed, which can only be realised for certain instruments optimised for such operating conditions.

Mechanical load capacity

In many applications the pressure measuring instruments are sometimes exposed to significant shock and vibration loadings. Vibration loads are oscillating mechanical loads of longer duration. In contrast, shock is considered as an impulse wave which abates quickly compared to vibration. Strong vibrations, for example, have an effect when using pressure measuring instruments on test benches and engines. Shocks occur, for example, during mobile use in a vehicle driving on a rough road, or during stationary application in machines with high accelerations during operation, such as solid forming presses or drop forges.

Typical vibration and shock resistance

For the pressure measuring instrument to be used safely in applications with strong vibrations and/or shocks, it must withstand these loads. The vibration resistance of industrial pressure transmitters is usually in the range of 10 to 20 times the acceleration due to gravity (10 g to 20 g). Nowadays, the shock resistance of industrial pressure transmitters is at several hundred g.

Electromagnetic radiation

Interference emission and immunity

Every electrically operated device can potentially emit electromagnetic radiation. However, since an electronic circuit can also be influenced by electromagnetic radiation, such instruments can also influence (interfere with) each other. The requirements for electromagnetic compatibility (EMC) cover both interference emission and immunity.

EMC problems frequently occur if many electronic devices are located within a small space. With increasing automation this is also the case in many applications of electronic pressure measurement technology. EMC problems occur more and more frequently, because of the increasing operating frequency and electrical power of electronic devices, plants or systems.

Legal requirements

In the European Union (EU) protection requirements are stipulated by the EMC directive and its implementations in national laws, which refer to the corresponding harmonised standards. Mandatory limit values for the interference immunity and emitted interference are specified in the standards. Only instruments developed and manufactured in accordance with these standards may be labelled with the CE mark and placed on the Single European Market.

Increased requirements

However, for the reasons mentioned above, in certain applications the end-users will place much higher demands on the electromagnetic compatibility and, in particular, on the interference immunity, in order to ensure safe operation even under unfavourable conditions. These are summarised in factory standards or special specifications and must be individually checked for a particular prototype.

Explosion protection

Types of explosion protection

For electronic measuring instruments used in hazardous areas it is necessary to ensure through technical measures that, in accordance with the classification of the hazardous area, no ignition source can have an effect. There are several technical approaches to achieve explosion protection for an electrical instrument. The corresponding design concepts are referred to as explosion protection types. In electronic measurement technology the most frequently used is the concept of limitation of the ignition energy − referred to as intrinsic safety (abbreviation i). For this, the current and voltage of the electrical power supply are limited in such a way that neither the minimum ignition energy nor the ignition temperature of an explosive mixture are ever reached. Another explosion protection type is enclosing the measuring instrument in a flameproof enclosure (abbreviation d), where all components that are likely to cause ignition are installed within an enclosure that can withstand the internal explosion pressure. The escaping ignition energy is reduced by means of gaps between the enclosure parts to the extent that no ignition or external transmission of it is possible.

The operator of a plant or equipment is generally responsible for compliance with the requirements for the equipment and facilities. Requirements for equipment that can present an ignition hazard have been harmonised across Europe. They are listed in the ATEX product directive, 94/9/EC. The directive describes the conformity assessment procedure for electrical and non-electrical instruments used in hazardous areas. The manufacturer can or must obtain an EC-type examination certificate in accordance with the conformity assessment procedure and mark it correspondingly

Fig. 21:
Symbol for explosion protection valid for Europe

on the instrument (Fig. 21). Within the scope of the quality assurance system, the manufacturer bears the responsibility of ensuring that every single instrument is manufactured in accordance with this EC-type examination certificate.

Standard applications and requirements

Trend-setting applications

Electronic pressure measuring instruments take on a multitude of tasks in the industrial environment. Among other things they assist in 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.

Three fields of application

Despite this diversity, the application of electronic pressure measurement technology can generally be assigned to one of three areas: to the monitoring of critical system pressure, to the control of pressure or to the indirect measurement of process values. The following description of standard applications from all three areas gives an overview of the demands placed on electronic pressure measuring instruments.

Critical value monitoring

In applications within the field of critical value monitoring, the pressure measuring instrument has the task of reporting that a certain critical pressure level has been exceeded or has not been achieved. For pure monitoring, pressure switches are most suitable. A pressure transducer, in addition, enables the continuous measurement of the system pressure.

Leak detection

For instance, leak detection in systems with elevated pressure: if there is a leak in a system, the system pressure drops. As soon as the pressure drops below the specified critical value, the electronic pressure switch or pressure transmitter reports this. To detect the leaks as soon as possible, very high measurement accuracy is usually required.

Another example is the monitoring of the degree of clogging of filters (Fig. 22). With the increasing degree of clogging, the pressure conditions upstream and downstream of the filter also change. If an electronic pressure measuring instrument is installed upstream or downstream of the filter, it can report clogging of the filter or indicate the optimum time for filter replacement.

Fig. 22:
Filter monitoring

Pressure control

In the case of pressure control using an electronic pressure measuring instrument, a differentiation must be made between the control of a constant pressure or the control of a pressure profile.

Control of constant pressure

When supplying media via pumps it is often advisable to keep the delivery pressure constant. This can be achieved with an electronic pressure measuring instrument and an electronic controller. The pressure measuring instrument sends the measured pressure value to the controller. The controller checks whether and to what extent the current pressure (actual value) deviates from the nominal pressure (nominal value) and reports this to the pump controller. Depending on the pressure deviation, the controller adjusts the drive power in such a way that the actual pressure value once more approximates the nominal pressure value. This offers not only efficient control of the process, but also enables energy-efficient operation since the drive power of the pump is continually adjusted to the actual demand.

Control of a defined pressure profile

Autofrettage

An electronic pressure measuring instrument and an electronic controller can also be used to ensure operation corresponding to a defined pressure profile, its monitoring and, if necessary, recording. A typical example is autofrettage, during which the pipes are pressurised to a defined multiple of their permitted operating pressure. This intentional overpressure leads to a partial plasticity and thus to an intentional compression of the pipeline material, thus allowing the pipelines to withstand pressure spikes better. In this application the pressure profile must be controlled accurately and the achievement of the defined pressure values must be reliably documented. Since very high pressure values (of up to several thousand bar) must be measured repeatedly with constant accuracy, especially high demands are placed on the pressure measuring instruments used in such applications.

Indirect measurement of process values

Indirect force measurement

Lifting hydraulics

According to equation 1 (see page 6) it is possible to determine the force generating the pressure by measuring this pressure, provided the geometry is known. An example is given in figure 23 which shows lifting hydraulics with two movable pistons, each with different surface areas in contact with the hydraulic oil. If the smaller piston moves downwards with a

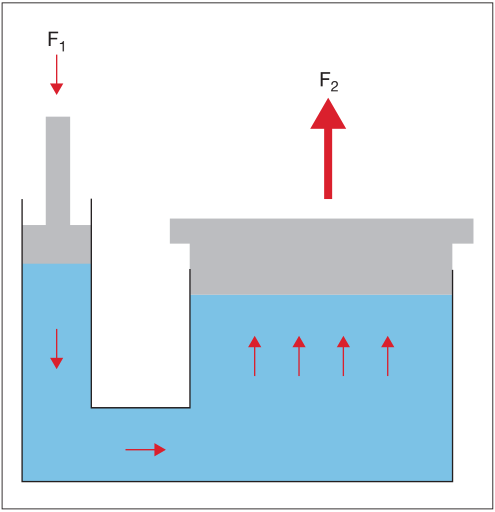


Fig. 23: Hydraulic principle

force F_1, the larger piston pushes upwards with a greater force F_2 since the pressure in the liquid remains constant.

Load torque monitoring

One of the most typical pressure measurement tasks in hydraulic systems is overload monitoring on lifting gear, clamping devices or tools. If, for example, a crane lifts a load, the pressure required to generate the counteracting force in the hydraulic liquid increases. If the maximum permitted load is exceeded, the pressure will also consequently exceed the set upper limit value. In this way it is possible to detect the load torque limit on the basis of the measured pressure in the hydraulic fluid.

Many hydraulic applications are present in mobile hydraulics (Fig. 24), for example, in construction machinery, agricultural vehicles, lifting platforms or forklifts. Pressure measuring instruments used in such applications must often withstand very high operational shock and vibration loads; they must also have especially high electromagnetic interference immunity.

Fig. 24: Pressure measuring instruments in the mobile hydraulics industry must be suitable even for harsh operating conditions.

Furthermore, they must withstand extreme climatic conditions during outdoor operation. Since such machines often need cleaning using high-pressure steam cleaners, they must remain leak-tight from all sides, even under high jet pressures. In addition, they must be resistant not only to hydraulic oil, but also against many other media, such as dust, mud and fuel.

Control of a hydraulic press

Especially high demands are placed on the control of a hydraulic press via indirect force measurement of the hydraulics. A predefined force profile must be maintained for every pressing cycle. An electronic pressure measuring instrument can be used to monitor and control this profile.

Indirect level measurement

The hydrostatic pressure under a static liquid column increases proportionally with the height of the column. Thus, for example, the pressure in a water tank becomes 100 mbar higher, compared to the effective atmospheric pressure on the water surface, with every metre of water depth (Fig. 25).

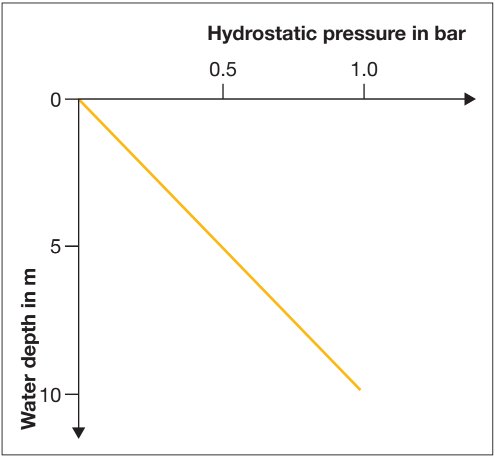
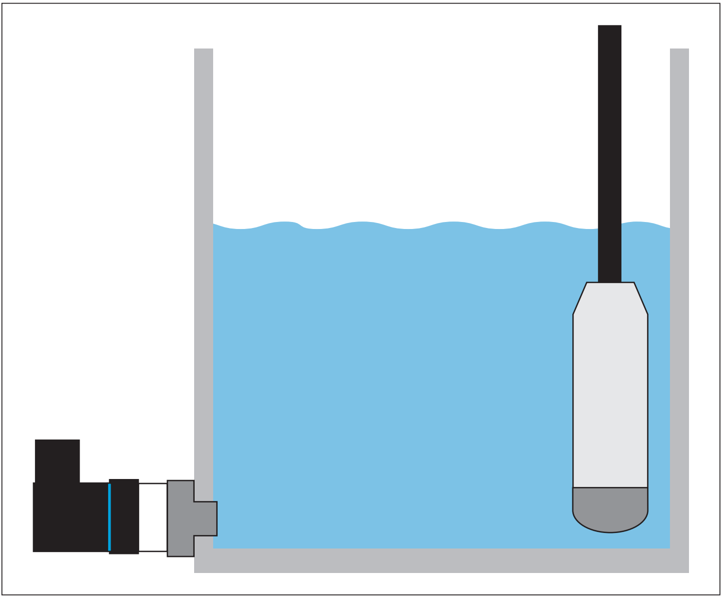


Fig. 25: Functional correlation between water pressure and depth

Electronic pressure measuring instruments are used for indirect level measurement if the level of the tank must be monitored; for example to avoid completely emptying the tank or if it is necessary to continuously monitor the consumption of the tank contents. Depending on the application, either a level probe is submersed into the tank or a pressure measuring instrument is attached to the bottom of the exterior of the tank and exposed to pressure of the tank contents through an opening in the bottom of the tank (Fig. 26). If the tank is not vented, or if it is under higher pressure, it is necessary to measure the pressure prevailing on the surface of the liquid in the tank and to take this into account when determining the hydrostatic pressure. This can be carried out in two ways: either by using two independent pressure measuring instruments and then

Fig. 26: Level measuring options at a tank



generating the pressure differential in the downstream control unit, or by using special differential pressure measuring instruments with two process connections designed for this application.

Automated filling of a tank

(Re-)Filling of the tank can also be carried out automatically by means of an electronic pressure switch. For this purpose it is necessary to define two states – “tank is full” and “tank is empty” – and switch on/off the supply pump using the switch contacts depending on the reported state. Continuous level control using an integrated analogue output or the digital indication on the electronic pressure switch are an additional benefit.

Level probes for special applications

Electronic pressure measuring instruments for level measurement are characterised above all by their resistance to the pressure medium and their mostly relatively small pressure range. A further requirement for level probes (due to their continuous submersion) is that the medium must not enter neither the cable nor the probe itself, even at submersion depths of several hundreds of metres. In explosion-protected applications, for example, in bore holes for oil and gas exploration or in refineries and chemical industry plants, the measuring instrument must above all correspond to the required explosion protection type. For use in wells, shafts and bore holes, the design must be as slim as possible and there are high demands regarding the robustness of the (mostly very long) cable.

Indirect temperature measurement

In air conditioning and refrigeration plants or heat pumps, pressure measurements are used for the indirect measurement and control of temperature. For example, they ensure that food on the refrigerated shelf or freezer remains cool.

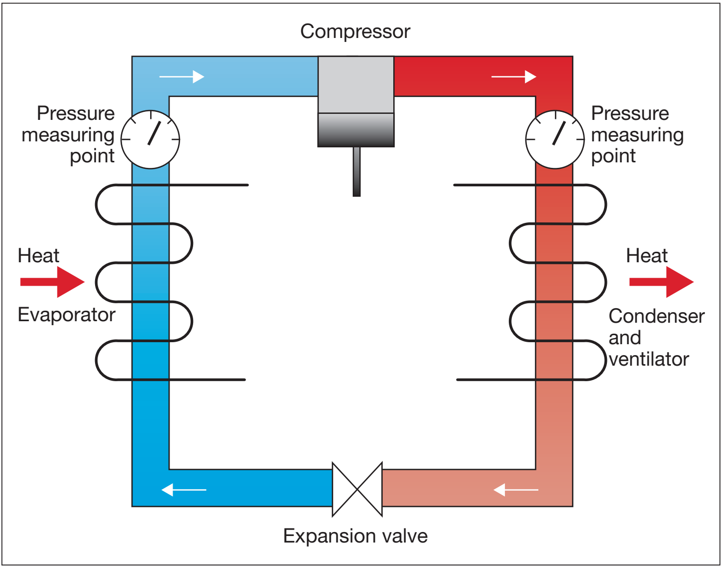


Fig. 27:
Refrigeration circuit

In the evaporator of a refrigeration circuit (Fig. 27), the cold, liquid refrigerant absorbs the heat from the surroundings needing cooling. During the evaporation stage, it absorbs additional thermal energy from the surroundings – the evaporation enthalpy. This phase transition can be controlled very accurately by means of targeted depressurisation of the refrigerant under pressure in the expansion valve. The cooling effect obtained can be controlled very accurately using the measured and controlled pressure. The evaporated and heated refrigerant is compressed again through a compressor which makes its temperature and pressure rise again. With pressure transmitters, it is possible to determine the pressure in the refrigerant circuit exactly, and to control the expansion valve and the compressor systematically. The measured pressure also allows conclusions to be drawn on the phase state of the refrigerant.

Safety function

Since liquid refrigerant can damage the compressor, it is necessary to ensure that it is still gaseous prior to compression. In this instance, pressure measurement also takes on an important safety function. As soon as the compressed and hot refrigerant is in the compressor, it starts releasing thermal energy into the environment and thus becomes liquid again. In large refrigeration systems a ventilator speeds up the condensation. If the pressure, and indirectly the temperature, are measured in the condenser, the ventilator power can be adjusted exactly to the corresponding requirements. This demand-oriented ventilator control leads to significant energy savings. The use of pressure transmitters in the refrigeration circuit allows both better control of the process and significant energy savings.

Process control and energy saving

The measuring instruments used should be, on the one hand, resistant against all common refrigerants and, on the other hand, they must measure with high accuracy despite the extraordinary temperature conditions. Upstream of the compressor the temperature may reach –40°C and downstream of the compressor up to +100°C. This accuracy is needed in order to enable very accurate control of depressurisation of the refrigerant in the evaporator. However, in the future, the use of new refrigerants could lead to much higher demands related to the operating temperatures and the pressure range.

Criteria for the instrument selection

Except for special designs and models which are specifically for particular applications, pressure measuring instruments are generally available in many variants, which differ from each other with regard to their pressure range, pressure connection, electrical connection, output signal and measuring accuracy in particular. The selection of a pressure measuring instrument suitable for a specific application is therefore a complex process. This chapter provides an overview of the most important specifications for pressure measuring instruments.

Pressure range

The pressure range specified in the data sheet of a pressure measuring instrument defines the limits within which the pressure can be measured or monitored. Essential for the specification of the pressure range are the lower and upper limits of the pressure range (Fig. 28) and whether it is absolute or gauge pressure. The accuracy data specified in the data sheet applies within the pressure range.

Adjacent pressure ranges

Pressure ranges specified in the data sheet which are under and over the limits of the pressure range are referred to as overpressure ranges. Pressures within the overpressure range will not cause any permanent damage to the sensor; however, the measuring error limits specified in the data sheet may be exceeded. Only pressure values above the overpressure limit, i.e. known as the destructive range, can

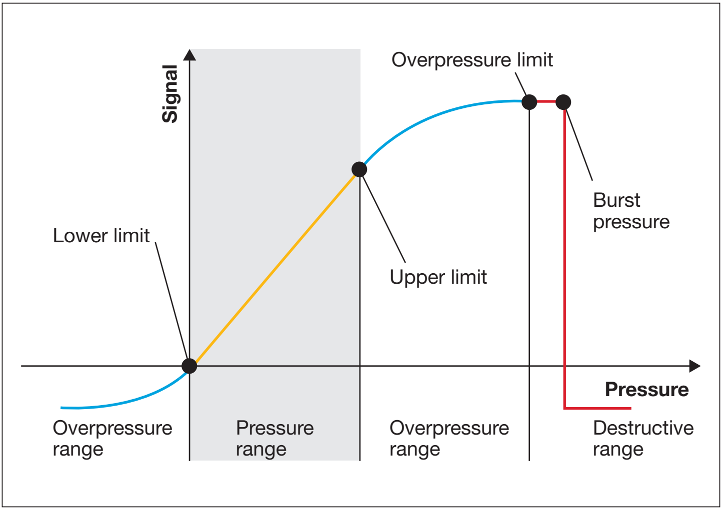


Fig. 28: Measuring range, overpressure ranges and destructive range

lead to irreversible damage of the measuring instrument. It does not matter whether this pressure is present constantly or only for a short period of time. Once the specified burst pressure has been exceeded, the complete destruction of the parts exposed to the pressure and the sudden release of the pressure medium can be expected. Therefore, these operating conditions must always be avoided through careful design.

Pressure spikes

Special attention is required in the event of pressure spikes in the case of dynamic pressure elements. They are caused, for example, by the switching on and off of a pump, the connection or disconnection of a hydraulic system and, in particular, by the opening and closing of the fast-acting valves in fluid flows. These pressure surges can reach a multiple of the operating pressure. This effect sometimes occurs in households if a tap is turned off quickly. It is known, technically, as *water hammer*. The pressure wave developed propagates through the entire system and leads to extremely high loads, and often to the overload of the sensors. Pressure spikes in the destructive range can even cause the sensor element to burst. Therefore, they represent a safety hazard and must always be considered when designing the plant. Common ways to reduce pressure spikes are to use throttles in the pressure port and EDM drillings. Such restrictions prevent the uninhibited propagation of a pressure wave by reflecting much of it.

Protection against cavitation and micro-diesel effect

Extremely high pressure spikes can be caused by cavitation and the micro-diesel effect. Cavitation is generally described as the formation and implosive dissolution of hollow spaces in liquids due to pressure variations. The resulting short-term pressure and temperature peaks can even lead to material removal on metallic components. If, due to cavitation, small bubbles consisting of a combustible air-hydrocarbon mixture are formed, these can burn due to local spontaneous self-ignition during pressure increase − this is known as the micro-diesel effect. If no special measures are taken, the pressure wave resulting from a micro-explosion can cause serious pressure spikes in the hydraulic system and, as a consequence, lead to the destruction of components. Due to the design-based and the desired sensitivity of the pressure sensors, it is necessary either to effectively prevent these effects or to ensure the sensors are suitably protected from the impacts of these effects. Those electronic pressure measuring instruments designed specifically for hazardous applications have protective mechanisms built-in, e.g. the previously mentioned EDM drillings, specially designed throttle elements or specialised baffle and deflector plates within the pressure port.

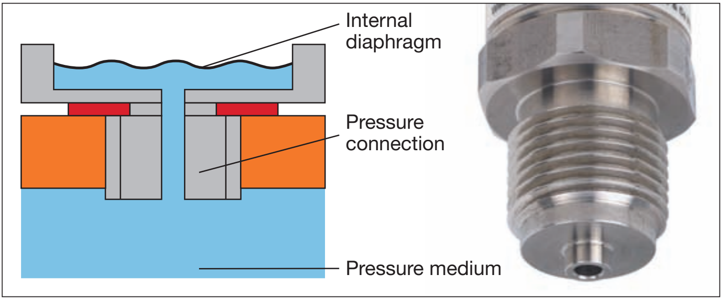
Pressure connection

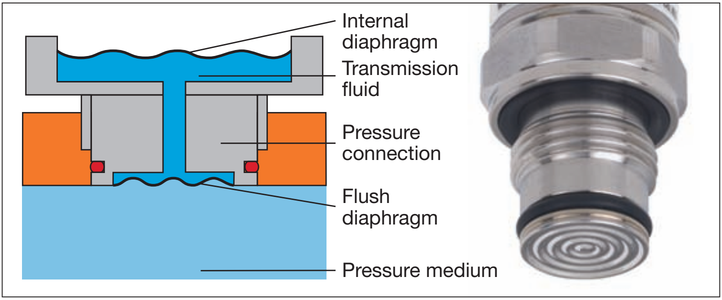
The pressure connection, also frequently referred to as the process connection, is used to channel the pressure medium to the sensor. Almost all pressure connections have a standard thread and can therefore be screwed in at the measuring point without problems.
Leading manufacturers often provide a multitude of different pressure connections for their pressure measuring instruments in order to meet the various requirements of the widest range of industries and applications, as well as regional and national standards.

Internal and flush diaphragms

There is a differentiation between pressure connections with an internal diaphragm and connections with a flush diaphragm. In pro-

Fig. 29:
Internal (top)
and flush (bottom)
diaphragm





cess connections with an internal diaphragm the pressure medium directly contacts the sensor diaphragm through the pressure port (Fig. 29 top). In process connections with a flush diaphragm the pressure port is itself closed flush, using an additional stainless-steel diaphragm. A transmission fluid transmits the pressure up to the internal sensor diaphragm (Fig. 29 bottom).

Selection criteria

Pressure connections with internal diaphragms and a pressure port are easier to handle and cheaper to manufacture than those with a flush diaphragm. They are primarily used with gaseous and liquid pressure media. For all pressure media that can clog or damage the pressure port (for example crystalline, viscous, aggressive, adhesive or abrasive media), use of a flush diaphragm is recommended. Also, if the application requires residue-free cleaning of the pressure connection, the flush diaphragm should be preferred to the internal diaphragm.

Thread

In order to enable the simultaneous screwing in and sealing of the measuring instrument seal at the measuring point, the pressure connections are usually designed with a thread. Different threads are commonly used worldwide (Table 3). Generally, both male and female threads are common.

Table 3:
Overview of threads

Threads	Short symbol	Region/Country
Parallel pipe threads	G	Western Europe
Self-sealing pipe threads	NPT	North America
Fine threads	UNF	North America
Metric threads	M	Eastern Europe and Russia
Conical Whitworth pipe threads	R or PT	Asia

Seal

The sealing concepts are as diverse as the threads. Some threads are self-sealing, for example taper threads. On the other hand, other threads require an additional seal. For this there are different application-specific and regional solutions. The most common for parallel threads are sealing behind the thread (i.e. between the thread and the case) or sealing in front of the thread by means of a metallic spigot (Fig. 30).

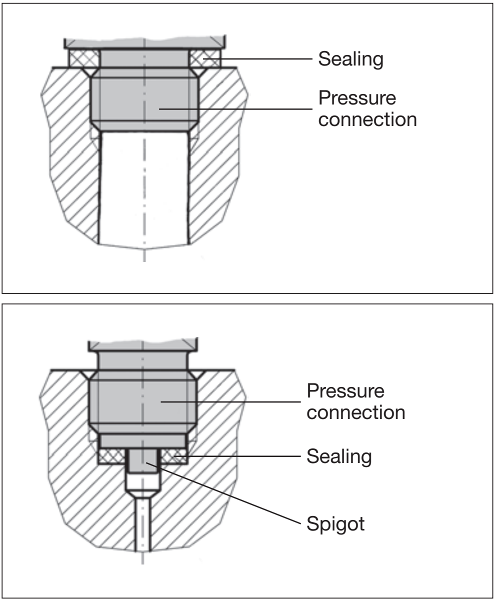


Fig. 30: Sealing between thread and housing (top); sealing with metal spigot (bottom)

Electrical connection

Connector or cable

The electrical connection of an electronic pressure measuring instrument is implemented using either a standard plug-in connector or using a cable output (Fig. 31). The nature of the connection has a considerable

Fig. 31: Various electrical connections

influence on the IP rating of the instrument (see page 34 f.) and often limits the permissible ambient temperature range and the resistance of the instrument to aggressive media or environmental influences (e.g. UV radiation). To ensure the reliability of the electrical connection in the application, it is necessary to know exactly the specific installation conditions and to consider them when selecting the electrical connection. For plug-in systems, one must above all bear in mind that the mating plug (selected by the user) and the entire associated cable entry forms an integral part of the sealing system for the instrument case.

Reliability

Output signals

Analogue or digital

The output signal of an electronic pressure measuring instrument is generally an analogue voltage or current signal. It is transmitted to a control unit connected downstream of the instrument. However, pressure measuring instruments are also available with digital outputs. With the exception of switching output signals, which are, strictly speaking, already a digital signal, the output signal should be as proportional as possible to the pressure.

For this purpose, the sensor must first of all generate a measurable sensor signal proportional to the pressure. To achieve this, the resistors in the measuring instrument with strain gauges on the sensor are wired to a Wheatstone measuring bridge. In pressure transmitters, process transmitters and pressure switches with an analogue output signal, low level sensor signals are amplified, filtered and standardised through the electronic components. The result is a standard industrial signal which is used as an output signal. The most important output signals are described briefly below.

Standard industrial signals

Standard analogue output signal

The most common output signal in pressure measurement technology is the analogue output signal. Commonly used are the current signal 4 … 20 mA and the voltage signals 0 … 5 V, 0 … 10 V and 1 … 5 V. In comparison to voltage signals, the advantages of the current signals are a much lower sensitivity to electromagnetic interference and automatic compensation of conduction losses by the current loop. The elevated zero point of the 4 … 20 mA current signal and likewise with the 1 … 5 V voltage signal also enables cable break detection and instrument fault detection.

4 … 20 mA

The 4 … 20 mA output signal is commonly transmitted using 2-wire technology, which enables the sensor to source its supply energy directly from the current loop. The other analogue signals require a 3-wire connection that uses the third lead for the power supply.

Ratiometric output signals

The analogue output signals which are easiest to generate are those which are proportional to the supply voltage, where the zero point and final value represent a constant percentage of the sensor supply voltage. Thus, for example the 10-90 signal has a zero point which is 10% of the supply voltage and a final value which is 90%. If the supply voltage decreases by 5%, then the absolute analogue signal also decreases by 5%. Thus, the ratio of the output signal to the supply voltage remains the same.

0.5 … 4.5 V ratiometric

These sensors are often operated with a (reduced) supply voltage of 5 V. The 10-90 signal is then specified in the data sheets as “0.5 … 4.5 V ratiometric”. This is the most common ratiometric output signal.

Digital output signal

Bus-compatible signal

Basically, the transmission of digital output signals offers the possibility of communication with the pressure measuring instrument via a fieldbus system, so operating data and parameters can be exchanged. However, both processes are of minor importance in industrial pressure measurement technology. Therefore, electronic pressure measuring instruments with a connection to CANbus or PROFIBUS-DP play a minor role in industrial applications at the moment.

Digital communication modulated on an analogue output signal (for example using HART on a standard 4 … 20 mA signal) is also only established for pressure measuring instruments in certain areas. The reasons for this are above all the much higher costs of the pressure measuring instrument and the associated peripherals, the elaborate integration of the instruments as a result of additional control software and the (relatively) low extra benefit. Since, basically, additional configuration of the bus for the pressure measuring instrument is needed, and the diagnosis of a faulty digital connection is much more elaborate than for an analogue connection, for many applications the advantages of a potentially more accurate measured value do not outweigh the additional costs.

Characteristic curve, accuracy and measuring error

The characteristic curve of an instrument reflects the functional dependency of the output signal on the input signal. Ideally, the output signal of an electronic pressure measuring instrument changes with pressure in a linear manner. Thus, the ideal characteristic curve is a straight line. The measured (i.e. the actual) characteristic curve is, however, not an exact straight line. Even at the start and end point of the pressure range the output signal can deviate from the corresponding ideal values (Fig. 32).

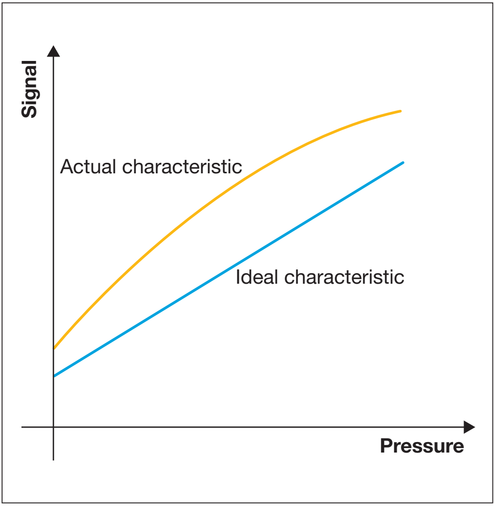


Fig. 32:
Ideal and actual characteristic curves

Accuracy

The deviation of the actual characteristic curve from the ideal one is often referred to as “accuracy”. However, this term is not defined in any standard. Instead, other values are taken to determine the measuring errors. The measuring errors are usually given as a percentage of the span. The span is the difference between the end and start value of the output signal. Thus, for the standard 4 … 20 mA signal, the span is 16 mA.

Span

Maximum measuring error

Error at reference temperature

The measuring error includes all relevant errors at a constant temperature (e.g. reference temperature), such as non-linearity, hysteresis, zero offset and span error. It can be determined directly from the characteristic curve. If the pressure measuring instrument is operated at this temperature, then the maximum measuring error is the maximum error with which the pressure can be measured (Fig. 33).

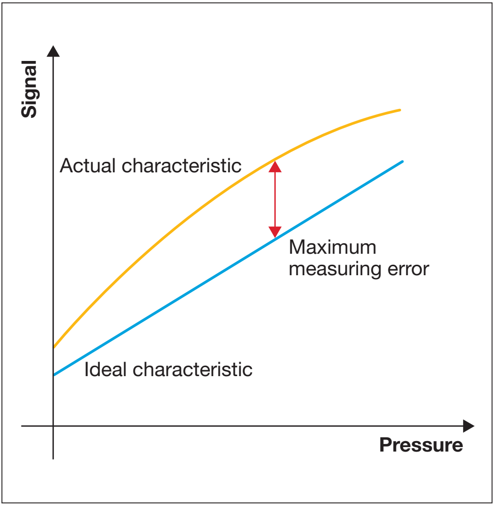


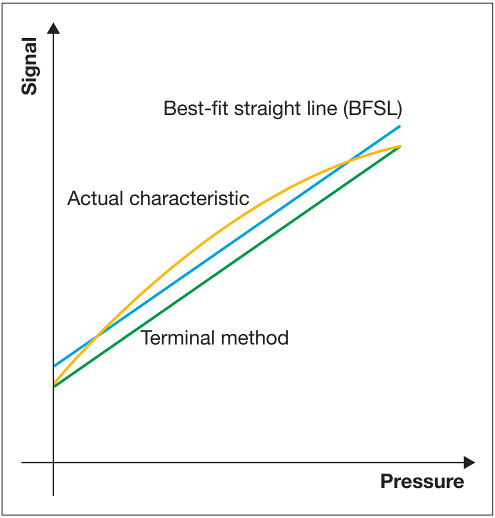
Fig. 33: Measuring error at a defined temperature

Non-linearity

The measuring error, referred to as non-linearity, is defined as the largest possible positive or negative deviation of the actual characteristic curve from the reference straight line. There are different methods to determine the reference straight line. The two most common are the terminal method and the best-fit straight line method (Fig. 34). In the case of the terminal method, the reference straight line passes the start and end point of the measured characteristic curve. In the case of the best-fit straight line method, the reference straight line (in data sheets often referred to as BFSL) is positioned in relation to the measured characteristic curve in such a way that the sum of squares of the deviations is minimal.

Determination of the reference line

Fig. 34: Determination of the non-linearity according to terminal method and best-fit straight line method



BFSL

If one compares both methods with each other, the terminal method usually provides twice as large a deviation as the best-fit straight line method. A comparison of the non-linearity of electronic pressure measuring instruments from different manufacturers is, therefore, only representative provided the non-linearity is determined using the same method.

Electronic linearisation

The non-linearity is a basic characteristic of the sensor system used. If necessary, it can be minimised electronically by the manufacturer.

Hysteresis

If the characteristic curve of a measuring instrument is recorded with steadily increasing pressure and then with steadily decreasing pressure, it can be observed that the output signals for identical pressures do not match exactly. The maximum deviation between the increasing and decreasing characteristic curve is referred to as the hysteresis (Fig. 35).

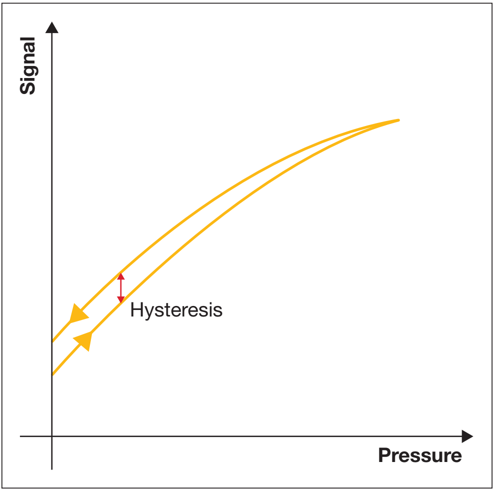


Fig. 35: Hysteresis

No technical compensation

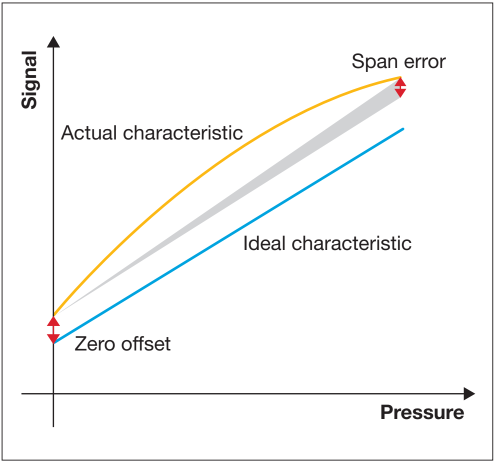
The hysteresis depends on the elastic properties of the sensor material and the design principle of the sensor. It cannot be compensated through any technical measures (e.g. by adjustment).

Zero offset and span error

Two independent errors

The actual zero and end point of the output signal can deviate from the ideal zero point and end point. The zero offset and span errors are the differences in value between the ideal and the actual values of the zero point and end point of the output signal. The zero offset and the span error must always be considered independently when assessing the measuring accuracy (Fig. 36). In extreme cases, both can provide the same preceding sign and produce the maximum permitted error value in the same pressure measuring instrument.

Fig. 36: Zero offset and span error



Non-repeatability

Like other technical systems, electronic pressure measuring instruments are also exposed to stochastic influences, i.e. random influences. Therefore, the output signal for the same pressure values in the case of successive measurements is not always exactly the same, even if the measurements are conducted under identical conditions.

Definition

This measuring error, referred to as non-repeatability, is given as the greatest deviation during three successive pressure measurements under identical conditions and thus is the value of the difference between the largest and the smallest measured output signal. Therefore, a small non-repeatability is a basic requirement of each reliable sensor system with a defined accuracy.

Temperature error

Every change in temperature directly influences the measurement-related properties of the electronic pressure measuring instrument. Thus, with rising temperature the electrical resistance of metals increases and the piezoresistive resistance of the semiconductors decreases. Most materials expand when they are heated. This and other effects cause inevitable measuring errors as a result of temperature changes.

Countermeasures

To prevent these temperature errors, the manufacturers of electronic pressure measuring instruments take a number of measures relating to both the sensor system and the associated electronics. Thus, the sensor design (materials and geometry) is basically optimised to achieve a balanced thermal behaviour in order to be able to minimise the non-linearities and discontinuous behaviour. Remaining errors, inevitable due to residual tolerances, are systematic temperature errors and can be reduced during the manufacturing process or by means of suitable on-board digital processing − the keyword here is “smart sensor”.

Compensation during production

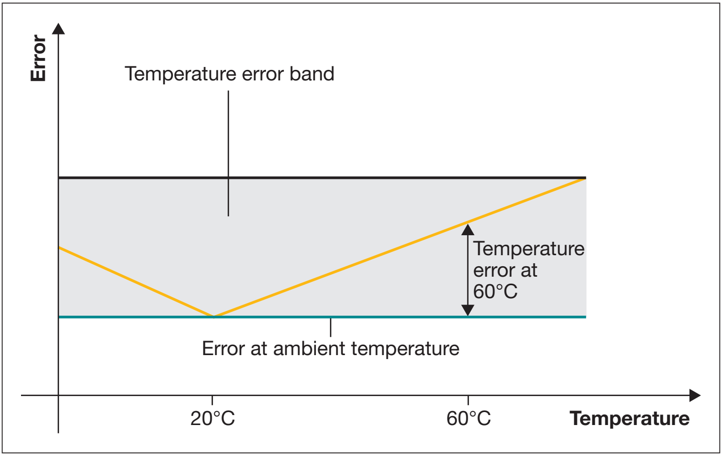
The compensation of temperature-related measuring errors during the manufacturing process is carried out either directly on the sensor and/or in the associated electronics. For example, it is possible to perform laser trimming of the measuring bridge. To perform the compensation of the entire system, consisting of the sensor and electronics, the accuracy of the sensor module (or even of the entire pressure measuring instrument) at different temperatures is compared to reference instruments (calibration). If necessary, it is adjusted electronically or, using a specific PCB assembly, via the corresponding compensation resistors.

Active temperature compensation

Precision measuring instruments often have an additional temperature sensor integrated into the case and related programmed logic that compensates the temperature error directly within the instrument. This procedure is often called “active temperature compensation”.

In spite of all compensation measures a small temperature error will still remain. This error is specified either as a temperature coefficient or as temperature error range. If the manufacturer defines a temperature coefficient, a (linear) error is assumed in relation to a reference point (e.g. room temperature). At this point the temperature error is minimum, and it increases with increasing difference from the reference point with the specified coefficient

Fig. 37: Temperature coefficient and temperature error band



in a linear manner (Fig. 37). The sum of the zero temperature error and the span temperature error gives the maximum total temperature error.

If the temperature error is given in the form of an error band as an alternative, the maximum temperature error present within the temperature compensated pressure range defines the scope of the error band.

Long-term stability

Long-term drift

By design the characteristic curve of a pressure measuring instrument is not constant during its entire service life; it can change slightly over time due to mechanical (pressure change) and, above all, due to thermal influences. This creeping change is referred to as the long-term stability or also as long-term drift.

As a rule the long-term stability is determined by laboratory testing. However, since the testing procedures for different manufacturers can differ significantly, information on long-term stability should not be compared. In addition, simulations always work with reference conditions as a basis. The actual long-term stability under operational conditions can, therefore, differ significantly from the one specified in the data sheet. In spite of the described limitations of its validity, long-term stability is still considered to be an important characteristic for measuring instrument quality.

Accuracy data

Systematic and random parts

The accuracy data are determined statistically since the measuring errors include both a systematic and a random element. It is necessary to distinguish between the measuring errors specified as “maximum” and “typical”. For a maximum error it is to be expected that no single instrument has a greater error than that specified. In fact, the majority of the delivered

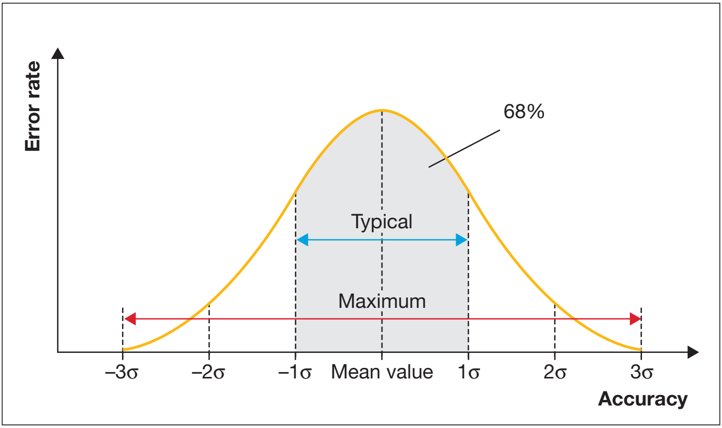
Maximum and typical error

product should actually have a considerably smaller error.

Error rate

If an electronic pressure measuring instrument is developed thoroughly and manufactured soundly with sufficient process control, it can be assumed that the spread of the measuring error adheres to the normal distribution. A “maximum” error in this case corresponds to the expected value of the error plus or minus three times its standard deviation (3σ). This will include more than 99% of all units (Fig. 38). If an error is given with the description “typ.“, which stands for typical, it is to be expected that not every single instrument complies with this accuracy data. Many manufacturers do not specify what share of the supplied instruments has this typical accuracy. However, it can be assumed that the typical accuracy corresponds to the expected value of the error plus or minus the simple standard deviation (1σ). This then includes approx. 68% of all units. In the extreme case, this may mean that an individual instrument has a measuring error three times the specified typical error.

Fig. 38: Gaussian distribution of accuracies



Error minimisation during operation

With the exception of the hysteresis and the non-repeatability, the measuring errors of individual units can be minimised or even eliminated during operation by the corresponding measures.

Zero offset

The zero offset can be compensated by the user as an offset in the evaluation instrument and thus almost completely eliminated. For a pressure range starting at 0 bar relative, this can easily be determined and “tared” in the depressurised state.

Detection of the span error is complicated for the user since for this, it is necessary to achieve the exact full-scale pressure for the pressure range or even the exact pressure at the desired working point. In practice, problems usually occur due to the absence of a sufficient reference.

Non-linearity

The non-linearity of an individual unit can also be minimised by calculating the deviation in the downstream electronics at several reference points. For this purpose it is also necessary to use a high-accuracy standard.

In some applications, the measured value can be compared to the expected value using other process parameters or the vapour pressure curve of the pressure medium and corrected correspondingly.

Prospects

The accurate measurement of pressure forms the basis of the safe and economical performance of many processes. Development of modern and reliable pressure measuring instruments and pressure sensors manufactured in large numbers has made many new production processes possible, for example special forming processes (hydroforming) for exhaust gas purification systems, high-pressure pasteurisation of food, energy-saving control of compressors and pumps, control of system pressures in electronic brake force control or accurate control of fuel injection.

New applications

Nevertheless, there are still many processes nowadays where far too often pressure is generated that significantly exceeds the required value for the optimum operation. The experts estimate that over 90% of the compressors in air conditioning and refrigerating plants worldwide are operated without accurate pressure measurement, i.e. uneconomically. The majority of compressors for compressed air production and pumps for water supply are equipped with simple pressure switches instead of pressure control systems oriented to the requirements. There are more and more attempts to achieve higher energy efficiency and therefore every day more and more applications for electronic pressure measurement technology.

Continuous improvement

The leading manufacturers of pressure measuring instruments and pressure sensors invest constantly in development to make the technology safer, more reliable and more economical. They do this in the belief that this technology will make a significant contribution to safety and resource savings.

Glossary

BFSL Abbr. for *Best-Fit Straight Line*: reference line to determine the non-linearity of the characteristic curve.

CAN Abbr. for *Controller Area Network:* asynchronous serial fieldbus system.

CE Abbr. for French *Conformité Européenne*: with this mark the manufacturer declares conformity of a product with the EU directives.

CVD Abbr. for *Chemical Vapour Deposition*: chemical deposition technique.

EDM Abbr. for *Electrical Discharge Machining*: a thermal gouging machining process for conductive materials.

EMC Abbr. for *Electromagnetic Compatibility*: the desired state in which technical devices do not influence each other mutually with undesired electrical or electromagnetic effects.

Equivalent stress Also known as *von Mises yield criterion*: notional uniaxial yielding, that represents the same material tensile stress as a real multiaxial tensile stress.

FEM Abbr. for *Finite Elements Method*: numerical calculation technique.

FMEA Abbr. for *Failure Mode and Effects Analysis*: analysis of potential failures and effects analysis; analytical method within reliability engineering.

HART Abbr. for *Highway Addressable Remote Transducer*: standardised communication system for engineering of industrial fieldbuses.

IP Abbr. for *Ingress Protection* or *International Protection* (according to DIN): IP ratings in accordance with DIN EN 60529 specify the suitability of the electric equipment for different ambient conditions.

MTTF Abbr. for *Mean Time To Failure*: statistical parameter for electronic components.

PCB Abbr. for *Printed Circuit Board*: used to mechanically support and electrically connect electronic components.

Piezo-resistive effect Change of the material-specific resistivity due to elongation or compression.

PVD Abbr. for *Physical Vapour Deposition*: physical deposition technique.

SI Abbr. for French *Système international d'unités*: worldwide the most common system of units for physical values.

S-N curve Also known as *Wöhler curve*: graph recorded during material fatigue tests.

Wheatstone bridge Measuring bridge designed to measure electrical resistances or small resistance changes.

The company behind this book

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Over the past 60 years WIKA Alexander Wiegand SE & Co. KG has built a reputation as a renowned partner and competent specialist for any task in the field of pressure and temperature measurement. On the basis of steadily growing efficiency, innovative technologies are applied when developing new products and system solutions. The reliability of the products and the readiness to face all challenges of the market have been the key factors for WIKA to achieve a leading position in the global market.

Within the WIKA Group, 6000 employees are dedicated to maintain and improve technology in pressure and temperature measurement. Over 500 experienced employees of the sales department consult the customers and users competently on a partnership basis.

More than 300 engineers and technicians are searching continually on behalf of WIKA to provide innovative product solutions, improved materials and profitable production methods. In close cooperation with recognised universities, institutions and companies, solutions for specific applications are developed and designed.

The WIKA quality assurance management system has been certified in accordance with ISO 9001 since 1994. In 2003, WIKA Tronic's development and manufacturing of pressure sensors and pressure transmitters for the automotive industry were certified in accordance with the globally accepted ISO/TS-16949 standard. The quality and safety standards of our company meet the standard systems of several countries.

Alongside high product quality and efficient health and safety at work, comprehensive environmental protection has equal standing as a company goal. In addition to compliance with national and international environmental laws and regulations, the WIKA environmental management system is certified to ISO 14001.

Thinking global and acting local: WIKA has numerous subsidiaries and agencies around the world and therefore we are familiar with the respective country-specific requirements, standards and applications. This is how we ensure the individual assistance of our customers.

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