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

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. 9).
In addition to those mentioned above, there are also simpler instrument types known as pressure sensor modules; often consisting of no more than a pressure sensor and simple mechanical and electrical interfaces. These types are particularly suitable for complete integration into users' systems.

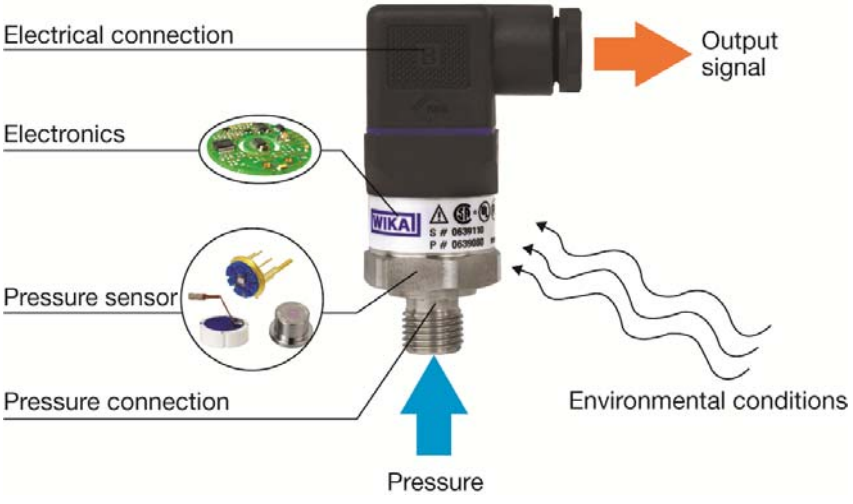

Figure 9: Structure of a pressure measuring instrument

Pressure transmitter

A pressure transmitter (Fig. 10) 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.

Figure 10: Pressure transmitter

Level probe

The level probe (Fig. 11), 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.

Figure 11: 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 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. 12).

Figure 12: Pressure switch with display

Process transmitter

The process transmitter (Fig. 13) 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 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.

Figure 13: Process transmitter with display

Pressure transducer

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. 14). 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 solutions 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.

Figure 14: Pressure transducers

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. 15) and whether it is absolute or gauge pressure. The accuracy data specified in the data sheet applies within the pressure range.
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 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.
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.

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.

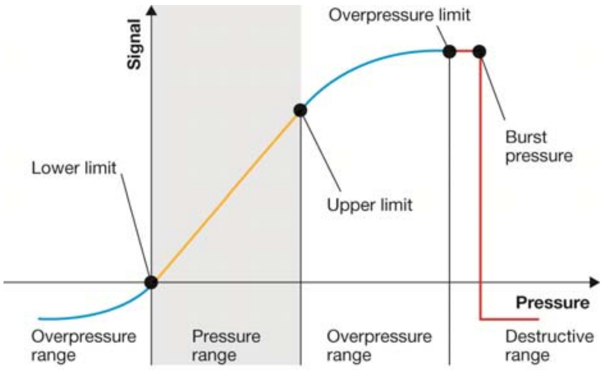

Figure 15: Measuring range, overpressure ranges and destructive range

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 process connections with an internal diaphragm the pressure medium directly contacts the sensor diaphragm through the pressure port (Fig. 16 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. 16 bottom).

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.

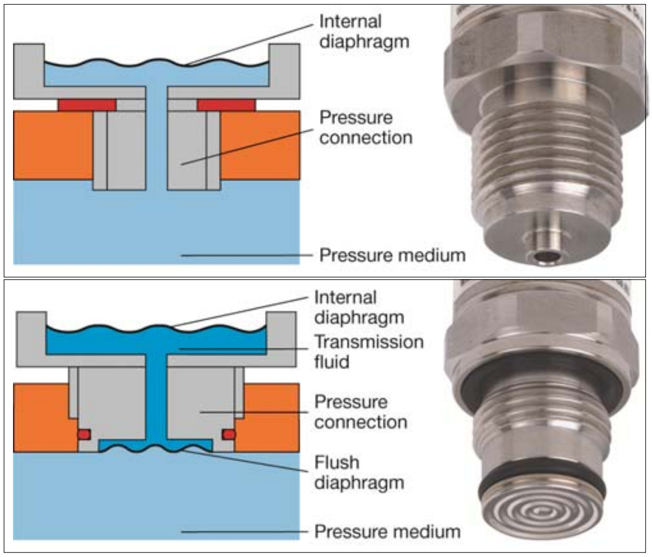

Figure 16: Internal (top) and flush (bottom) diaphragm

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 2). Generally, both male and female threads are common.

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

Table 2: Overview of threads

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. 17).

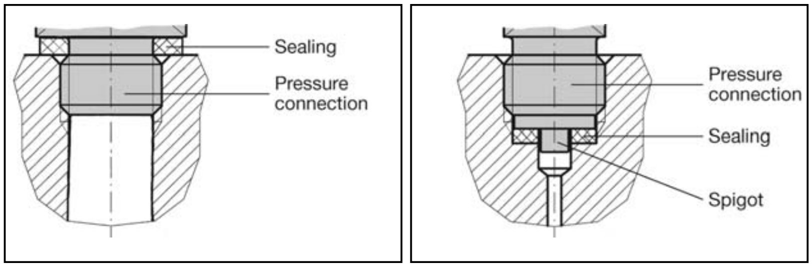

Figure 17: Sealing between thread and housing (left); sealing with metal spigot (right)

Electrical connection

The electrical connection of an electronic pressure measuring instrument is implemented using either a standard plug-in connector or using a cable output (Fig. 18). The nature of the connection has a considerable influence on the IP rating of the instrument 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.

Figure 18: Various electrical connections

Output signals

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 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.

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.

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

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. 19).

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.

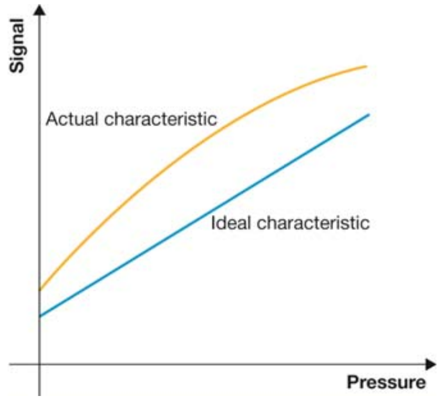

Figure 19: Ideal and actual characteristic curves

Maximum measuring error

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. 20).

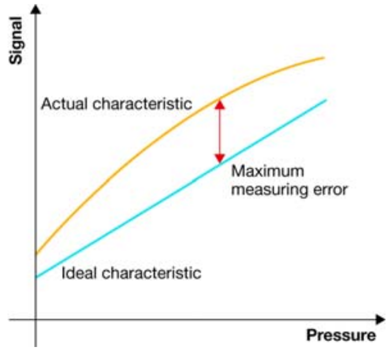

Figure 20: Measuring error at a defined termperature

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. 21). 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.

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

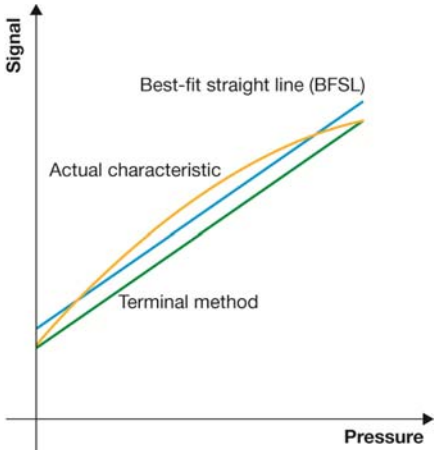

Figure 21: Determination of the non-linearity according to terminal method and best-fit straight line method

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. 22).
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).

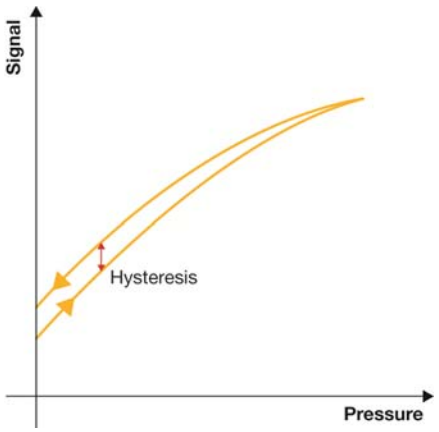

Figure 22: Hystersis

Zero offset and span error

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. 23). In extreme cases, both can provide the same preceding sign and produce the maximum permitted error value in the same pressure measuring instrument.

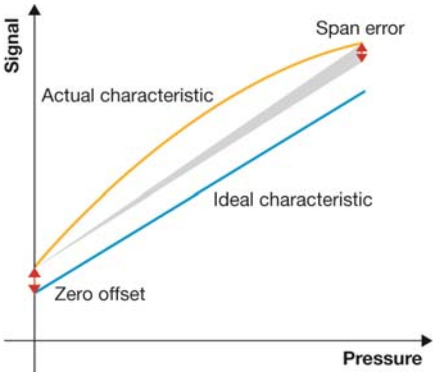

Figure 23: Zero offset and span error

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.

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 piezo-resistive 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.

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”.

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.

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 in a linear manner (Fig. 24). 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.

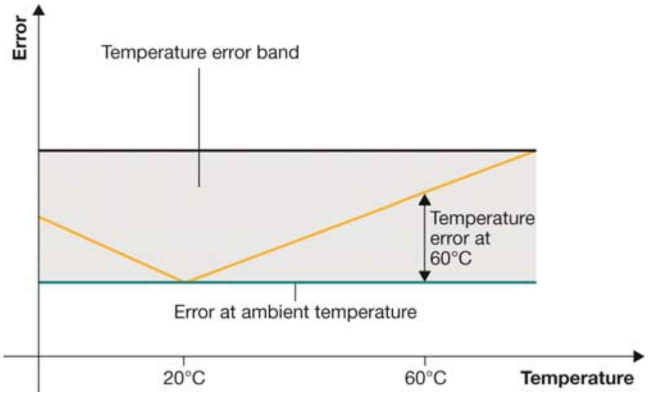

Figure 24: Temperature coefficient and temperature error band

Long-term stability

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

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 product should actually have a considerably smaller error.
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. 25). 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.

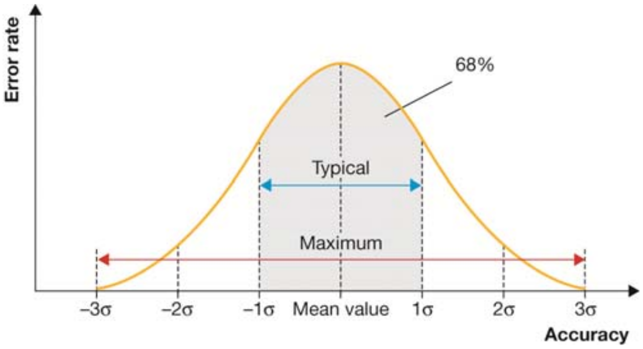

Figure 25: Gaussian distrinbution of accuracies

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.

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.

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.

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