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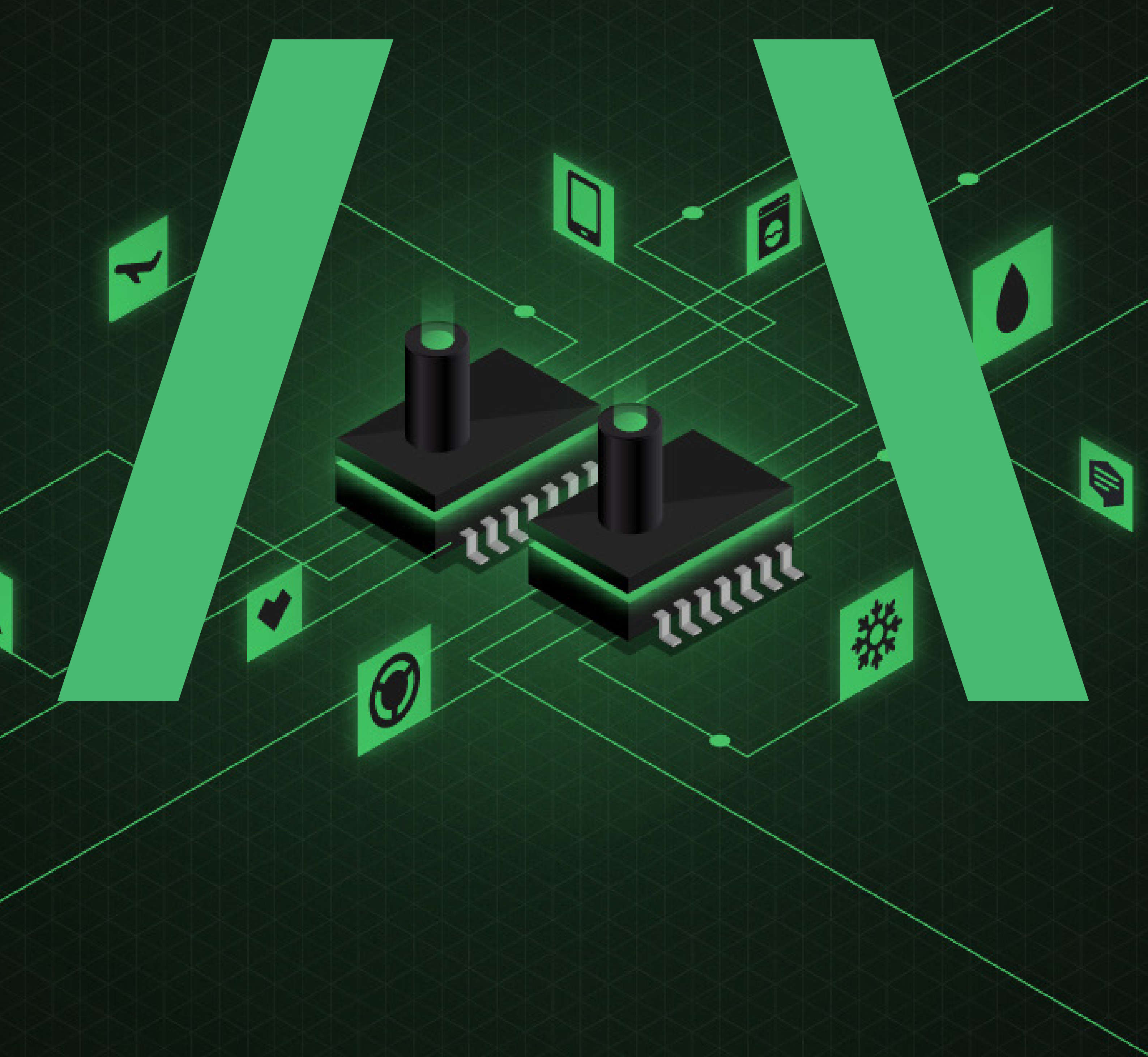

Pressure sensors:
The design engineer's guide

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THE EXPANDING APPLICATIONS OF PRESSURE SENSORS (WHY WE MADE THIS GUIDE)

The worldwide pressure sensor market was worth $13.6 billion USD in 2020 and is estimated to be worth $20.8 billion by 2025. That's 52% growth over 5 years or a compound annual growth rate of 8.9%.

And while analysts are busy predicting the future, engineers are busy creating it.

In recent years, pressure sensors have become digital, miniaturised, lower-cost and lower-powered. These changes have increased sensor efficiency and performance, generating a new wave of innovation.

The applications are vast across many industries - aerospace, automotive, medical, consumer, wearables, industrial, HVAC, home automation, and more.

In a fast-moving area of technology, it can be difficult to keep up. And if you're researching a new product, you might want to know the latest lay of the land and what developments are over the horizon.

The Design Engineer's Guide to Pressure Sensors is intended to help you navigate this fast-changing terrain, as you set out to create the applications of tomorrow.

WHAT'S IN THE GUIDE?

In this 9-chapter guide, we'll cover:

- An introduction to how pressure sensors work and pressure sensing elements
- Detailed insight into various applications, including specific spotlights on automotive, medical, building and home automation (including HVAC), consumer and wearables, and industrial.
- An overview of the different types of pressure sensors
- A quick clarification on terminology: transducers vs transmitter vs sensors
- An exploration of the different types of pressure measurement - absolute, gauge and differential and a comparison between the three: absolute vs gauge vs differential.
- A comparison of capacitive vs piezoresitive vs piezoelectric
- The different technologies - MEMS, capacitive, piezoresistive strain gauge, piezoelectric, optical - including the working principle, function and construction, design considerations, applications, and the advantages and disadvantages of each technology.
- Measuring pressure in different media - air, the atmosphere, gas, water, liquid, pneumatic and hydraulic systems, and corrosive liquids and gases.
- Measuring pressure in harsh environments, including high temperature, high pressure, underwater, salt water and dynamic environments.
- Demystifying the specification sheet

HOW TO USE THE GUIDE

Whether you've designed with pressure sensors before or not, we've created this guide to provide a handy reference and overview of the technology.

It isn't necessarily intended to be read from start to finish as a complete story; it's more of a field guide. You can pick and choose the parts most relevant to you, and consume them in whichever order you like.

All of this is designed to give a greater understanding of the available options, insight into the various possible applications, and help you determine which sensor is right for your intended application.

If you need any further assistance, our technical specialists are on hand to help. Feel free to get in touch at avnet-abacus.eu/ask-an-expert.

We wish you well in your exploration.

How pressure sensors work

Pressure sensors vary widely in their construction, due to the range of applications for the components. Just one example is their use in consumer equipment such as smartphones, often to aid navigation or other more specialised measurement apps.

Typically, these are barometric pressure sensors, designed to detect changes in atmospheric pressure.

Throughout industrial and commercial scenarios, there are multiple demands for accurate pressure measurement, such as:

- Gas pressure inside a tank, such as an industrial-compressor reservoir
- Measuring level or volume of liquid contained by sensing the pressure at the bottom of a vessel
- Measuring pressure differences between two points in a system, as a means of monitoring or quantifying the flow of liquids or gases
- Barometric pressure: change in atmospheric pressure with weather conditions or with altitude. Useful in weather stations, environmental monitoring, or to assist navigation dead reckoning alongside GPS or cell triangulation.

WHAT IS PRESSURE?

Pressure = Force/Area

In SI (MKS) units, a force of one Newton, applied to an area of one square meter, exerts a pressure of one Newton per square meter, or one Pascal.

Any kind of pressure sensor contains a mechanism or structure that reacts proportionately to a force applied. The area over which the force is applied is constant, for a given sensor structure.

WORKING PRINCIPLE

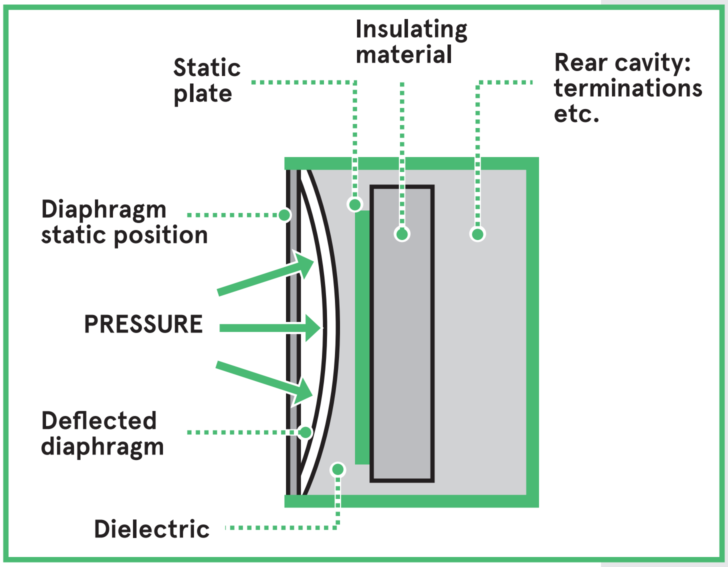
An electronic pressure sensor relies on a physical reaction to applied pressure, and then measuring the resulting proportional change electronically. Commonly used phenomena include changes in capacitance, or changes in ohmic resistance of a strain gauge or piezoelectric element, which are proportional to the magnitude of the deflection when pressure is applied.

Important criteria such as measurement range, environmental suitability, physical size, and power requirements will have a significant guiding influence on engineers looking for an application specific solution.

CAPACITIVE PRESSURE SENSORS

A capacitive pressure sensor contains a capacitor with one rigid plate and one flexible membrane as electrodes. The area of these electrodes being fixed, the capacitance is proportional to the distance between the electrodes. The pressure to be measured is applied to the flexible-membrane side, and the resulting deflection causes a change in capacitance that can be measured using an electrical circuit.

The diagram below illustrates the operating principle behind capacitive pressure sensing.

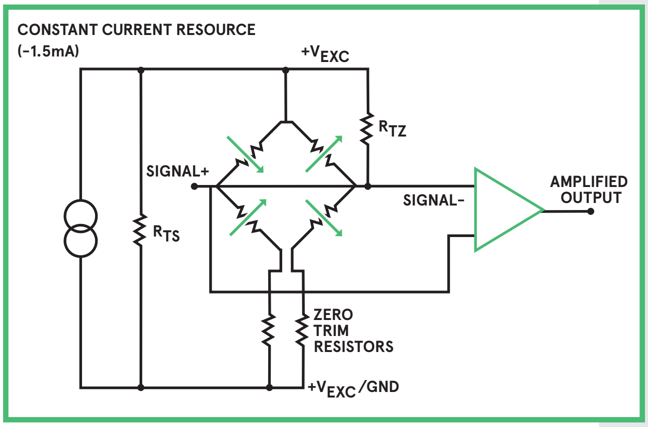


▲ The capacitive pressure transducer relies on capacitance change produced by deflection of the membrane, which alters the capacitor geometry.

How pressure sensors work

STRAIN GAUGE PRESSURE SENSORS

In a strain gauge type pressure sensor, foil or silicon strain gauges are arranged as a Wheatstone bridge. The resulting signal is then amplified and conditioned to provide a suitable transducer-voltage or transmitter-current output representative of the applied pressure (see right).

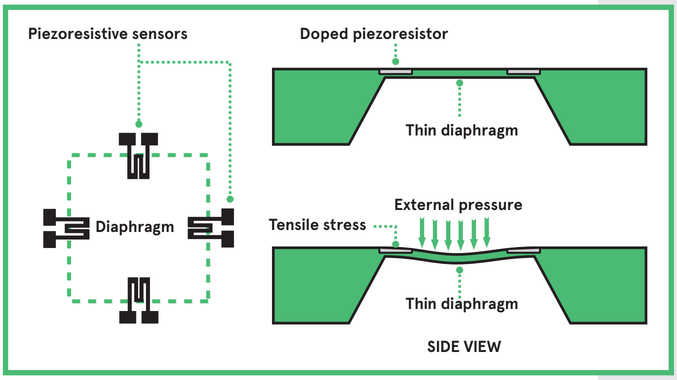


▲ Bridge-sensor circuit diagram

PIEZORESISTIVE PRESSURE SENSORS

Piezoresistive sensing elements can also be arranged in a similar bridge formation. The diagram to the right illustrates how the sensing elements of a bridge-type pressure sensor are attached to a flexible diaphragm, so that resistance changes according to the magnitude of the diaphragm deflection. The overall linearity of the sensor is dependent on the stability of the diaphragm, over the stated measurement range, as well as the linearity of the strain gauges or piezoresistive elements.

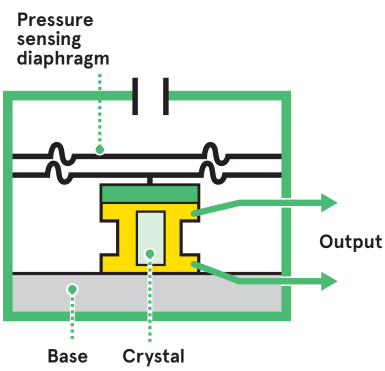
Note that, in practice, piezoresistive elements may be arranged in several ways to sense pressure, such as in the diagram.



▲ Piezo resistive pressure sensor operating principle

PIEZOELECTRIC PRESSURE SENSORS

Piezoelectric sensors use an element made of a material which generates electrical energy when they are under strain, such as quartz or tourmaline (see right). Crucially, they only produce energy when the pressure changes, and are therefore suitable only for dynamic pressure measurements (not static pressure). They are also susceptible to shock and vibration.



▲ The piezo electric effect can be exploited in multiple ways to sense pressure

MEMS SENSORS

It's easy to imagine a piezoresistive or capacitive pressure sensor as a large device like a through-hole electronic component or a module ready to screw into the side of a tank – but that's not always the case.

A piezo or capacitive pressure-sensing mechanism can also be fabricated on silicon as a MEMS (Micro Electro Mechanical System) device and packaged as a compact surface-mount unit typically measuring only about 2-3mm per side.

MEMS devices, which include not only pressure sensors but also motion or position sensors, and silicon microphones, are extremely small, stable, and cost-effective, bringing advanced functionality to space- and cost-constrained equipment like mobiles and IoT endpoints.

MEMS devices are fabricated in silicon using doping and etching processes. These processes are performed at chip scale, resulting in a tiny device that can be co-packaged with signal-conditioning electronics. The electronic circuitry may comprise simple amplification to produce an analogue output, and may also include analogue-to-digital conversion to generate a digital output.

An analogue output may be advantageous if the sensor signal is to be handled entirely in the analogue domain, or if the designer wants to use an ADC of particularly high resolution or accuracy, or if the system-host microcontroller contains a suitable integrated ADC on-chip. A digital sensor can be designed-in with no need for external conversion components, thereby saving overall component count.

Perhaps the easiest type of sensor to visualise is a barometric pressure sensor. These can be used for measuring ordinary atmospheric pressure, and are used in a range of applications including context sensing or indoor navigation in smartphones. Typically, this is a tiny MEMS sensor.

Detecting changes in atmospheric pressure enables the device to theoretically be able to calculate its height above sea level – for example on a road (to assist satellite navigation and aid dead reckoning in the event of loss of satellite signal), or to detect what level of building the user is situated on, such as in a multi-storey car park, office block, apartment block, or shopping mall.

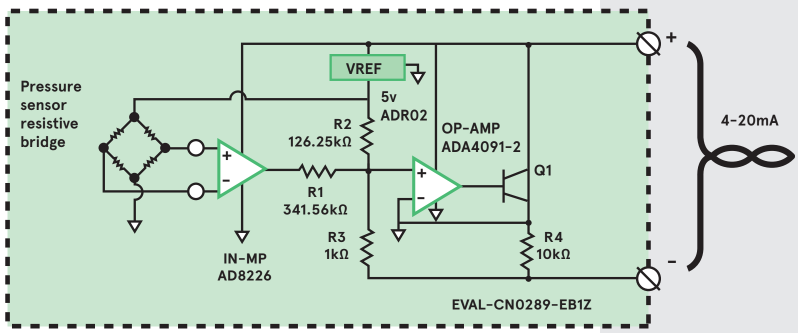
PRESSURE SENSOR: TRANSDUCER OR TRANSMITTER?

It is worth noting that "pressure sensor" is a generic term to describe a pressure-sensing device that may be a transducer or a transmitter, depending on the design of associated electrical circuitry.

The sensing element responsible for detecting and quantifying the effects of applied pressure produces an output that cannot be used directly in an electronic circuit – like a microcontroller-based system. The physical response needs to be translated into an electrical signal, and then signal conditioning is required to create a suitable, usable signal.

A transducer converts the physical change caused by applied pressure into a voltage signal across a high-impedance load.

A transmitter, on the other hand, generates a current signal across a low-impedance load. Hence the output may be a 4-20mA standard industrial output. The diagram below shows an example of the circuitry needed to produce a 4-20mA output signal from a bridge-type sensor.



▲ A bridge-type sensor with transmitter output circuitry for an industrial 4-20mA application

A pressure sensor can also be designed to perform as a pressure switch, which generates a simple on/off signal that will change state when a preset threshold is reached.

How pressure sensors work

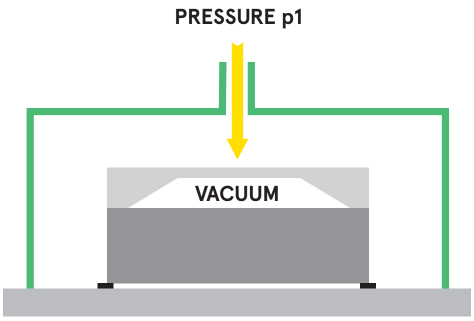
NEED SOME ADVICE?
Our pressure sensor experts are on hand to help you make the right choice for your application.
Get in touch at **avnet-abacus.eu/ask-an-expert**

FUNCTION

Broadly, pressure sensors operate in one of three modes, absolute, gauge, or differential measurement.

- **Absolute pressure sensors**

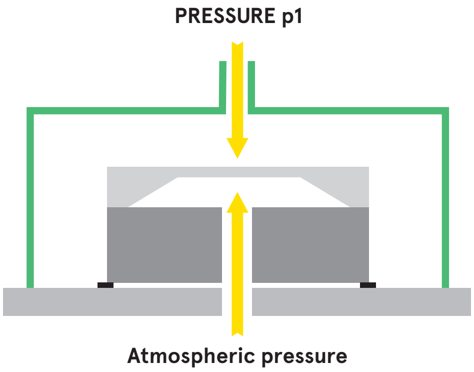
Absolute pressure is detected relative to 0 Pa, i.e. the static pressure of a vacuum. The sensor is designed with one port for the fluid to enter and exert pressure on the sensing element. The pressure applied produces a positive change in output, of magnitude proportional to the pressure applied.



▲ Absolute pressure measurement principle

- **Gauge pressure sensors**

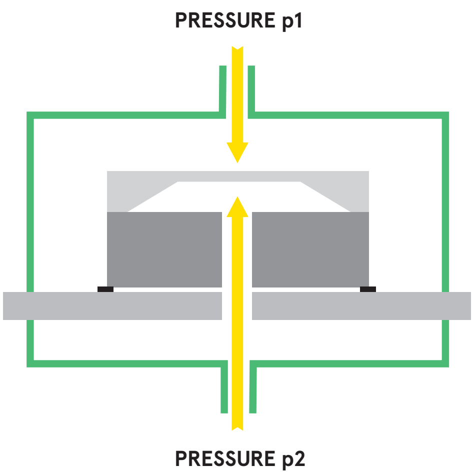
Measures pressure relative to a reference pressure, which is usually the local atmospheric pressure. The sensor has two ports, allowing entry of the fluid at the reference pressure, and at the pressure to be measured.



▲ Gauge pressure measurement principle

- **Differential pressure sensors**

Similar to gauge pressure – although in this case, the reference pressure is the pressure experienced at a different point in the system, as determined by the system designer. The change in differential output is positive or negative, depending on which is greater. The magnitude of the change is proportional to the pressure difference between the two domains.

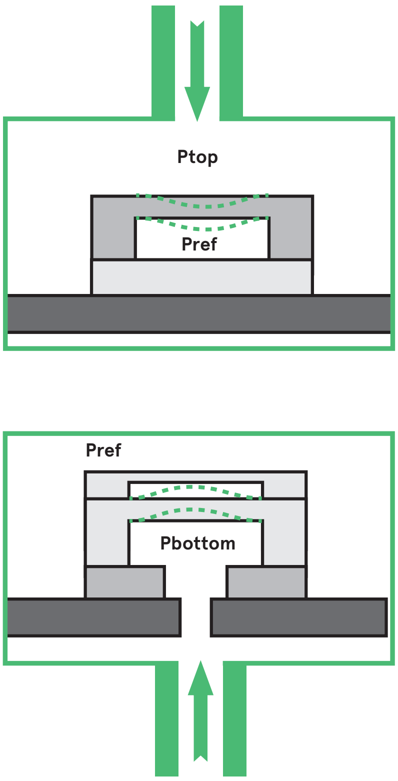


▲ Differential pressure measurement principle

How pressure sensors work

CONSTRUCTION

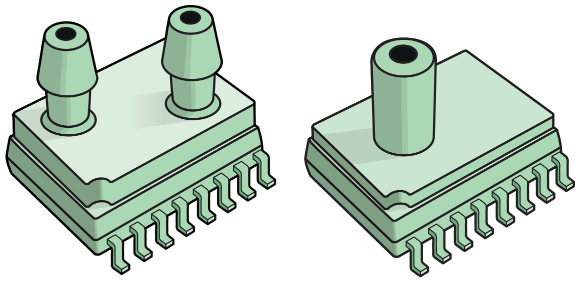
To an extent, the operating principle – absolute, gauge or differential – determines the sensor's construction. An absolute pressure sensor may be designed to respond to pressure applied at the top side or the back side, when mounted on a circuit board or a panel, for example. Creating a port for the measured media to enter through the top side may leave the sensor vulnerable to hazards such as physical damage or contamination with dirt or moisture. A bottom-side entry sensor may be chosen to overcome this. The diagrams below compare the layout of both types.



▲ Top-side or bottom-side entry absolute pressure sensors

A gauge sensor is typically designed to allow atmospheric pressure to apply to one port, while permitting the measured pressure to be applied to the other.

Similarly, a differential sensor will feature two ports, through which each of the measured media is designed to come into contact with the sensing element. The diagram below compares the construction of gauge and differential sensors.



▲ Gauge pressure and two-port differential pressure sensor packages

DESIGN CHOICES

Understanding the types of sensors in common use, their operating principles, and modes of use (absolute, gauge, or differential) can help engineers make initial selection decisions when identifying the most suitable sensor to choose for a given application.

The materials used and type of construction can have an important influence over aspects such as the measurement range, limiting factors like the maximum survivable pressure to which a sensor can be exposed, its stabilising time after soldering, and long-term stability in the intended application.

An understanding of the electrical output properties, and the circuitry needed to interact properly with the host electronic system – typically a microcontroller- or microprocessor-based control system — can help assess how the choice of pressure sensor will influence the likely electronic integration challenges.

What are the different pressure sensing elements?

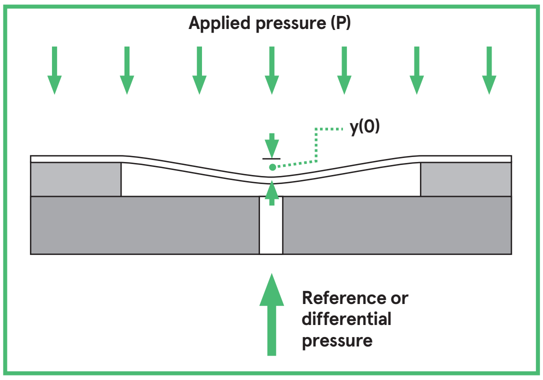
Sensing pressure usually begins with converting the force exerted by the pressure media – gas or liquid – into a physical displacement. This can be used to move a pointer relative to a calibrated scale, or to cause an electrically measurable response such as resistance or capacitance change proportional to the pressure.

The pressure sensing diaphragm, capsule, Bourdon tube, and expanding bellows are proven mechanisms for converting pressure to displacement.

PRESSURE SENSING DIAPHRAGMS

How they work

The pressure sensing diaphragm is a circular plate, fixed around the edge, and exposed to the pressure media on one side (see diagram below). On the opposite side may be a sealed chamber, in the case of an absolute pressure sensor, or it may be vented in the case of a gauge or differential sensor.



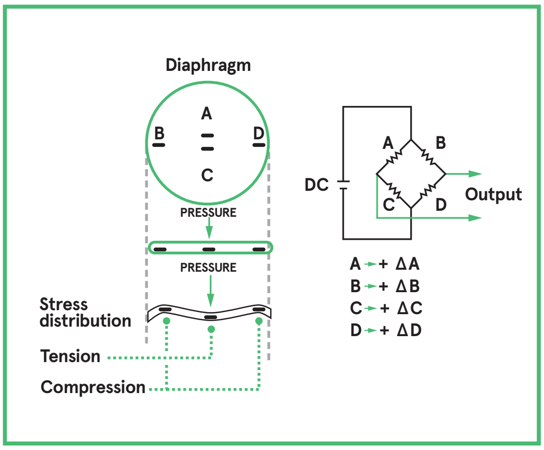
▲ Diaphragm deflection under applied pressure.

When pressure is applied, through the media, the diaphragm deflects to an extent proportional to the magnitude of the pressure. This deflection can be used to create a change in capacitance or resistance.

In a capacitive sensor, the diaphragm represents one electrode of a capacitor that has a fixed plate as the second electrode. Pressure-related deflection of the diaphragm reduces the separation of the electrodes, causing a capacitance change proportional to the applied pressure.

Alternatively, a network of resistive elements is attached to the surface of the diaphragm. These may be foil strain gauges bonded to the surface, or metal resistors deposited using a thin-film sputtering or thick-film process depending on the diaphragm material. Deflection of the diaphragm, under pressure, causes these elements to stretch and changes their resistance.

The resistors are placed in locations subject to both compressive and tensile force (see diagram below) to maximise the resistance change and so enhance resolution. A Wheatstone bridge connection eliminates drifts and offsets from the measurements.



▲ Wheatstone bridge connection to measure resistance change.

The diaphragm may be metal or ceramic. A metal diaphragm is often made from stainless steel or titanium, which allows compatibility with a variety of pressure media. These types of diaphragms can withstand a wide range of applied pressures, and high proof-pressure and burst-pressure ratings.

Ceramic diaphragms offer broad compatibility with various types of pressure media, and good corrosion immunity at a relatively low cost. On the other hand, the measurement range, proof-pressure and burst-pressure ratings are usually lower.

What are the different pressure sensing elements?

Another type of so-called slack-diaphragm sensor can be used for measuring very small pressures. The diaphragm material is typically a synthetic non-elastic material, such as polythene, or a natural material like silk. The non-elastic nature of the material requires external springs to oppose the diaphragm, to enable calibration and ensure precise operation.

Diaphragm-type sensors are used throughout various industries. Care must be taken in applications such as food preparation or pharmaceuticals manufacturing, to allow proper cleaning of equipment and prevent contamination by germs or bacteria.

Oil-filled sensors may be used, which feature an oil-filled cavity between the sensor diaphragm and an outer diaphragm that is installed flush with the wall of the vessel containing the pressure media to permit thorough cleaning.

This diaphragm must be extremely compliant, to fully transfer the applied pressure to the internal sensing diaphragm. The temperature characteristics of the oil may affect the sensing accuracy, and the potential for leakage risks contaminating the pressure media. Alternatively, the sensor may be designed with a fully flush sensing diaphragm, which is designed to come into direct contact with the pressure media.

Piezoresistive and MEMS pressure sensors typically feature a silicon diaphragm and resistors fabricated as part of the same structure. The diaphragm for a standard piezoresistive sensor is machined from silicon. For a MEMS sensor, the diaphragm/resistor structure is produced by selective doping and etching as part of the standard MEMS fabrication process.

Advantages and disadvantages

Pressure sensing diaphragms have a simple construction and are easy to miniaturise. Precision resistors require only small deflection, minimising diaphragm fatigue. Media-isolated sensors maintain high accuracy. And diaphragm-based sensors can measure lower pressures than a Bourdon tube.

The choice of materials for the construction of the diaphragm enables broad media compatibility. Metal diaphragms can measure high pressures. And piezoelectric sensors allow a wide range of measurement.

One potential downside is that conventional, i.e non-MEMS, diaphragms have limited low-pressure measurement capability.

What are the different pressure sensing elements?

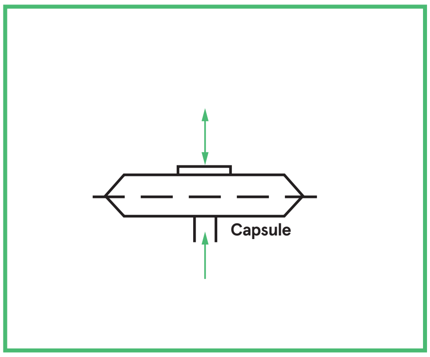
PRESSURE SENSING CAPSULES

How they work

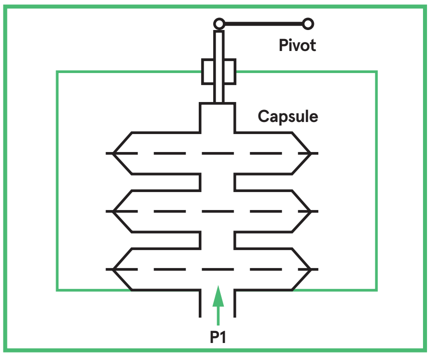
The pressure-sensing capsule adapts the diaphragm sensing principle to allow measurement of low pressures that would otherwise require an impractically large and thin diaphragm.

The capsule comprises two diaphragms, welded at the edge, to allow the pressure media to act on both simultaneously. The resulting structure displays twice the displacement, relative to the pressure applied, compared to a single-diaphragm.

Pressure sensing can be done using a single capsule, as shown in the first diagram below, or using a stack of capsules as shown in the second diagram.

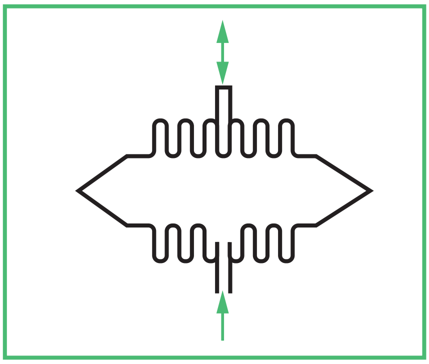


▲ Single capsule



▲ Stacked capsule

Some capsules feature profiling (such as the corrugations shown below) to optimise linearity and mechanical strength.



▲ Profiled capsule.

Advantages and disadvantages

Stability, simplicity and its small size are the main advantages of the pressure sensing capsule - as well as its ability to measure lower pressures, compared with a diaphragm sensor of a similar size.

However, the capsule does not self-drain so it is not suitable for measuring pressure in liquid media.

BOURDON TUBES

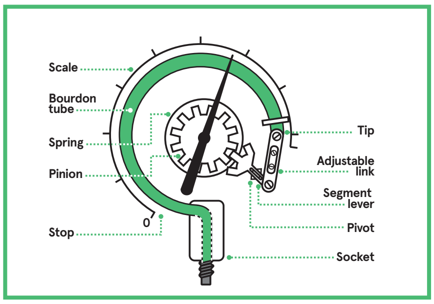
How they work

A Bourdon tube can be either c-shaped or helical, with an oval cross section. When the pressure media enters the tube, the pressure acts to change the oval towards a circular cross section. The effect of this distortion causes the tube to move – opening the c-shape, or extending the helix. The closed end of the tube is attached to a movement, so that displacement causes an indicator needle to deflect. The deflection can be measured on a scale, calibrated to represent the pressure exerted by the media.

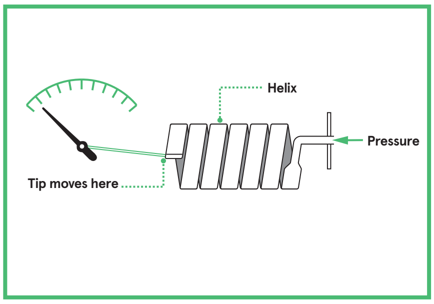
What are the different pressure sensing elements?

The diagrams **below** illustrate the operating principle of the c-shaped and helical Bourdon tube, respectively. Alternatively, the movement mechanism can be attached to a potentiometer to provide an electrical representation of the pressure.

Depending on application requirements, such as corrosion resistance, cost, size, measurement range, proof pressure, and burst pressure, the tube may be made from a metal such as copper, brass, aluminium, or a nickel alloy such as monel.



▲ C-shaped Bourdon tube



▲ Helical Bourdon tube

Advantages and disadvantages

The operating principle of the Bourdon tube is well understood, and tube-production techniques are mature.

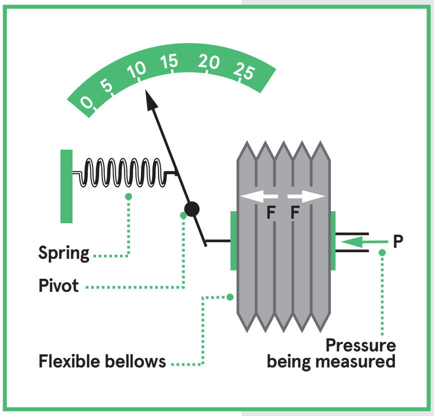
However, the minimum measurable pressure is about 600mbar. In addition, miniaturisation can be difficult, and liquid pressure media cannot drain fully from the tube. Drainage may not be a problem if the media is inert. However, other types of media may decompose or solidify, impairing function or accuracy, and possibly contaminating fresh media.

BELLOWS SENSING ELEMENTS

How they work

The bellows sensing element is a container that expands in response to the force applied by the pressure medium within. The bellows is typically made from a metal such as phosphor bronze, brass, beryllium copper, or stainless steel. It can be machined from solid stock, rolled from tube, or fabricated with a series of welded annular rings.

An internally mounted - or external - spring enhances the bellows' response to positive- and negative-going pressure changes. As a result, the deflection characteristics are a combination of the mechanical properties of the bellows, and those of the spring. An attached mechanical movement converts the expansion and contraction of the bellows due to changing media pressure into a proportional deflection of the pointer to indicate the pressure on a calibrated scale (see diagram **right**). In this sense the bellows is quite similar to the Bourdon tube. Alternatively, the movement may be attached to a potentiometer to provide an electrical analogue of the applied pressure.



▲ The bellows operating principle

Advantages and disadvantages

Advantages of the bellows sensor include simplicity, low cost, and the ability to connect directly to a pointer. The movement and pointer can be designed to give a large change in indication relative to the change in unit pressure, resulting in high resolution.

The bellows must operate within the elastic limit defined by the material and construction. And the mechanism can fatigue over time. As with capsules, drainage can be a challenge that may complicate use with liquid media. However, the bellows can be filled with an inert liquid, such as oil, and the open end sealed with a diaphragm to create an element suitable for monitoring liquid pressure.

The varying applications of pressure sensors

Pressure sensors are used for many automotive, medical, industrial, consumer and building devices, which depend on accurate and stable pressure measurements in order to operate reliably. As more industries rely on pressure sensors to monitor and control their applications, demand for these technologies has greatly increased, putting estimations of the worldwide pressure sensor market at $11.4 billion by 2024.

Here's how recent innovations in sensor technology are enabling smarter, safer, and more environmentally friendly electronics for businesses and consumers alike.

AUTOMOTIVE APPLICATIONS

In automobiles, hydraulic brakes are a crucial component in passenger safety. The ability to control a vehicle using brakes is down to a complex blend of components, including pressure sensors. These can be used to monitor pressure within the chambers of the braking system, alerting drivers and engine management systems alike if pressures are too low to be effective. If pressure inside chambers is not measured, systems can fail without the driver knowing and lead to a sudden loss of braking efficacy and accidents.

Until recently, airbags were solely designed to inflate inside of vehicles for the front two passenger seats in the event of a collision. Now, car manufacturers have created airbag innovations inside and outside of vehicles that release faster, resulting in safer outcomes for passengers in any seat and pedestrians too. They have also found ways of making the driving experience safer for the planet; bringing down engine emissions, by re-circulating exhaust gases.

Learn more about the life-altering and eco-friendly applications of pressure sensors for automotives on page **15**.

LIFE-SAVING MEDICAL APPLICATIONS

Raising the air pressure in a sealed chamber containing a patient is known as hyperbaric therapy. It can be effective for treating a number of medical conditions, from skin grafts, burn injuries, and carbon monoxide poisoning to decompression sickness experienced by divers.

Measuring blood pressure correctly is crucial to patient care, as errors in readings can lead to a misdiagnosis. Thanks to recent innovations, tiny pressure sensors can even be implanted into the body, known as In Vivo Blood Pressure Sensing for more accurate monitoring.

Learn more about the medical advances being made with pressure sensors on page **19**.

INDUSTRIAL APPLICATIONS

Submersible pressure sensors can be used to measure liquid pressures (up to 30 PSI) with either a voltage or current (4-20mA) output in liquid tanks. By positioning these sensors at the bottom of a tank, you can get an accurate reading of the contents in order to alert workers or the process control system when levels in the tank fall below safe limits.

Learn more about how pressure sensors empower smart factories on page **22**.

AUTOMATED BUILDING APPLICATIONS

As building and home automation technologies become increasingly popular, pressure sensors continue to play a central role in controlling the environments we live in. Refrigeration systems are one such example. Common coolants in HVACs like ammonia can cause significant danger to people in the event of a leak. Using relative pressure sensors to monitor the pressure of the ammonia as it passes through the system ensures it stays within safe limits.

Controlling large building environments is a challenge for designers and operations staff alike.

Learn more about how pressure sensors are improving building control interfaces and monitoring systems on page **24**.

LIFE-ENHANCING CONSUMER APPLICATIONS

The things we use, carry and wear on a daily basis are growing in intelligence. Adding a pressure sensor to a consumer device can provide new information for an improved user experience.

Take vacuum cleaners, or example. By measuring suction changes, they can detect what kind of flooring is being cleaned and adjust settings accordingly, or notify their owners when a filter needs replacing.

Learn more about consumer devices that are becoming smarter with the use of pressure sensors on page **27**.

Pressure sensors are a fast-moving area of technology, and advances are transforming products across a number of industries, with safer outcomes for both people and planet.

Pressure sensors: 10 innovative automotive applications

Driving would be an entirely different experience without all the pressure sensors used throughout the modern vehicle, helping to manage everything from braking to electric windows, exhaust emissions to power steering.

In fact, most of the critical systems in a vehicle rely on pressure sensors to measure and monitor key parameters, which has become central factor in making our roads safer, lowering pollution and improving our driving experience.

But how exactly do pressure sensors enable better vehicles, and what do manufacturers need to know in order to do that?

1. DETECTING EARLY FAULTS IN HYDRAULIC BRAKES

That easy braking sensation you're used to and the responsiveness of the pedal beneath your foot is down to a complex blend of components, including pressure sensors. In-car systems detect the pressure you're applying to the pedal then amplify it to make your efforts more effective.

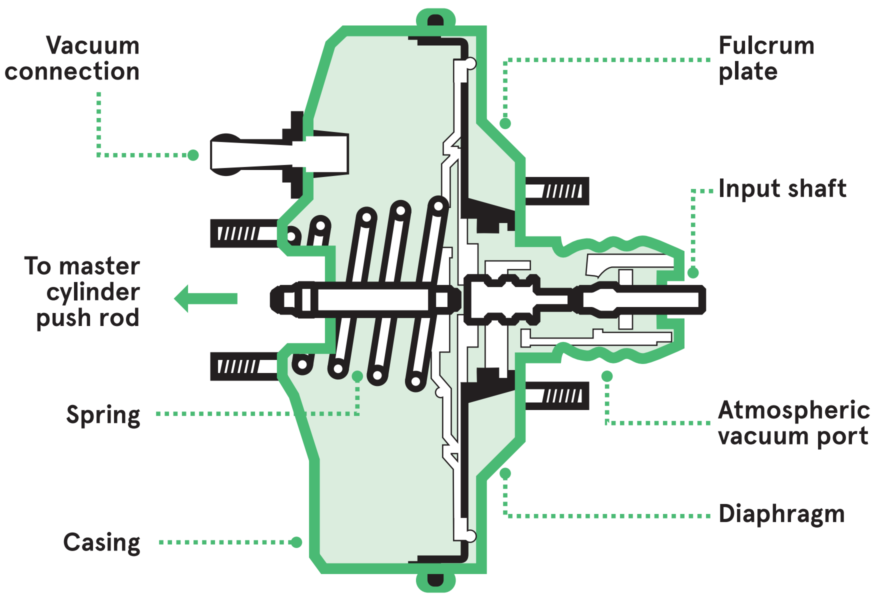
These systems use an absolute pressure sensor to monitor the vacuum maintained in two separate chambers inside the brake servo (see diagram below).

Under normal operating conditions, when the brake pedal is depressed it allows atmospheric pressure to flow into one of the chambers. This increases the pressure on a diaphragm, which, in turn, increases the effort applied to the master cylinder. When the brake pedal is released the vacuum is restored using a vacuum source, which may be via a dedicated pump or drawn from the manifold.

A fault condition arises if the vacuum in one or both chambers cannot be maintained or restored. An absolute pressure sensor is used to monitor the pressure in the chambers and alert the driver or engine management system if the pressure inside the chambers is not low enough to be effective.

Without a way of measuring the pressure inside the chambers, the system could fail without the driver knowing and result in a sudden loss of braking efficacy, just when it's needed most.

Manufacturers are using Manifold Absolute Pressure (MAP) sensors in this kind of application, which can be supplied in surface-mount packages and are able to measure pressures in the range of 10 to 150 kPa (kilopascal) with an accuracy of 1% across the entire range.



Pressure sensors: 10 innovative automotive applications

2. OPTIMISING THE FUEL MIX TO MATCH THE AIR PRESSURE

Making internal combustion engines as efficient as possible has much to do with getting the fuel mixture just right for the prevailing conditions. This includes the actual and desired speed, of course, but also includes making adjustments for the current engine speed, and the engine and manifold temperature.

It isn't just the air temperature that needs to be measured though; the air pressure is also an important factor when adjusting the fuel mixture and ignition timing. Here, absolute pressure sensors are used to provide the engine management system (EMS) with the information it needs.

The sensors are used to measure the pressure inside the manifold and, because air is drawn in from the surrounding area, the outside air pressure too. Barometric air pressure can have a significant influence on fuel mixture, so by measuring it and compensating for changes, the EMS can tune the engine for optimum efficiency, whether the car is at sea level or 20,000 feet above it.

MAP sensors are used here, too, but in this case they need to be able to measure pressures as high as 400 kPA.

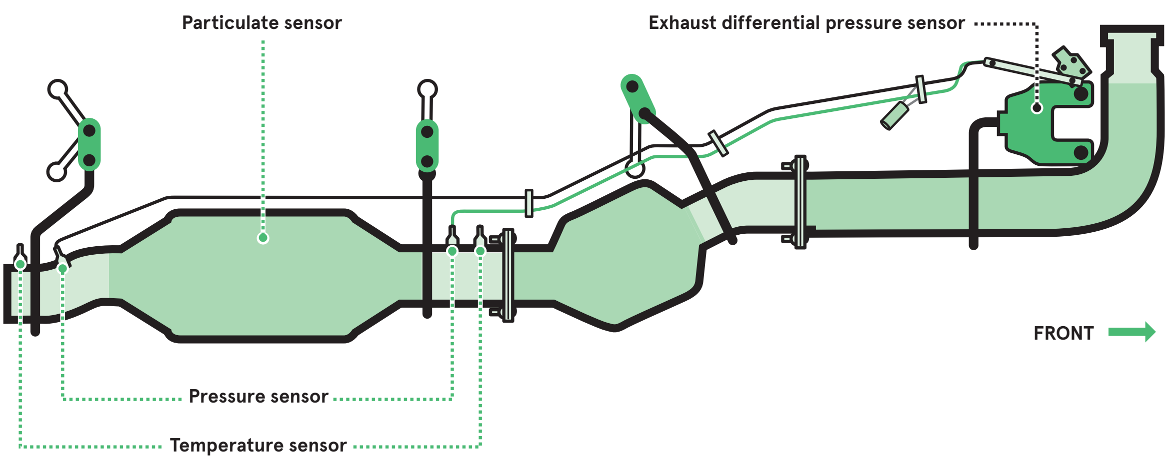
3. CLEANING EXHAUST FILTERS AUTOMATICALLY

Diesel fuel is one of the most common forms of fuel for vehicles, especially large haulage, construction and agricultural vehicles, and pressure sensors are vital in making diesel engines as clean as possible.

Particulate filters inside the engine are used to capture the soot and other particles present in the exhaust gas before it can escape into the atmosphere. The filters then need cleaning, which is done by burning off the particulates.

This can either be achieved using an active system which heats the filter to a temperature where the soot combusts, or a passive system using a catalyst.

In the active system (see diagram below), pressure sensors are used to measure the exhaust gas pressure. The cleaning process is triggered when pressure across the diesel particulate filter (DPF) reaches a threshold. This can be measured by using two absolute pressure sensors or a differential pressure sensor.



Pressure sensors: 10 innovative automotive applications

4. ENSURING THE CATALYTIC CONVERTER IS SEALED

In a passive system, particulates in exhaust gases are destroyed using a catalytic converter. In this case a pressure sensor is used to make sure the system can work efficiently even at low engine temperatures.

The catalytic converter needs to get up to temperature quickly in order to work efficiently. Typically, it needs to reach in excess of 300°C but when the engine is cold so too is the catalytic converter. Feeding air into the exhaust manifold triggers an exothermic process, which helps raise the temperature of the catalytic converter.

Once at temperature, the pump for the secondary air valve is switched off and the system is sealed with a valve. Using an absolute pressure sensor positioned between the pump and the valve provides the necessary assurance that the valve is closed properly and the rest of the system is protected from harmful exhaust gases.

5. MONITORING EXHAUST RECIRCULATION

Automotive manufacturers are under pressure to bring down overall engine emissions, and one tool in the box is to recirculate part of the exhaust gas.

Effective in both gasoline and diesel engines, the technique lowers the temperature in the combustion chamber, which has the effect of reducing the amount of Nitrogen Oxide generated and emitted.

Controlling the engine gas recirculation (EGR) process involves using an absolute pressure sensor to monitor the pressure at the valve. Without that control the system could become unstable and result in too much or too little gas recirculation.

Sensor manufacturers are constantly striving to improve their processes to deliver pressure sensors that are better able to withstand the harsh environments present in this class of application.

6. CHECKING THE PRESSURE OF CRITICAL FLUIDS

Perhaps the most common use for an electronic pressure sensor is to measure the pressure of the vehicle's critical fluids such as engine oil, gearbox and transmission oil, and the hydraulic oil in the braking system, cooling system and fuel systems.

An electronic pressure sensor will have part of its structure exposed to the fluid being measured, so they need to be robust and resilient. Typically, it will use the piezoresistive effect, which detects the change in resistance of a material resulting from deflection caused by the pressure exerted by the fluid.

Pressure sensors targeting this application space will typically be able to withstand extreme environments, and be sealed to IP 6k 9k (dust tight, high-pressure steam/jet cleaning), and be able to measure pressures from 0 bar to as much as 600 bar across an operating temperature range of -40 to +125 °C.

7. STOPPING DOORS FROM CATCHING YOUR FINGERS

Electric door closing on cars is a great innovation but if you (or someone smaller) gets between the door and the frame at the wrong time, trouble can result – but pressure sensors are there to help.

Using relative pressure sensors connected to a sealed hose and mounted around the edge of the doorframe, any obstruction can be detected quickly and reliably.

Any compression of the hose causes the pressure inside to rise, which is instantly picked up by the relative pressure sensor and conveyed to the vehicle's safety system. If the door is electrically activated, it will stop closing; the same technique works for windows too.

Sensors designed for this emerging application are typically compliant with the PSI5 (Peripheral Sensor Interface 5) protocol, which was originally developed as a reliable interface between airbag sensors and ECUs, and uses a twisted-pair that carries both power and data. Pressure sensors designed for this safety-critical application operate over a range of around 50 to 110 kPa.

Pressure sensors: 10 innovative automotive applications

8. DETECTING LEAKING VAPOURS

Part of the responsibility of car manufacturers is to keep the environment free from potentially harmful vapours produced by combustion engines.

New petrol vehicles now include a system that prevents these vapours from escaping the sealed fuel system, normally by routing the vapours to an evaporative system, which contains activated carbon. Air is mixed with the vapours so they can be safely burned up by the engine. Known as evaporative emission control (EVAP) systems, they are strictly tested.

An absolute pressure sensor monitors the integrity of the sealed system at all times, alerting the car (and driver) if a leak occurs. Without the pressure sensor monitoring the system, vapours could escape in the event of a breach, not only releasing harmful vapours into the atmosphere but also putting the manufacturer at risk of prosecution for not complying with regional regulations.

The barometric sensor will likely be located inside the fuel tank, and may provide either an analog or digital output, measuring a pressure range of around 40 to 115 kPa with an accuracy of 1.5 kPa or better.

9. ACTIVATING AIRBAGS FASTER

Car manufacturers are continually innovating to improve passenger safety. Modern cars don't just have the airbags in the dashboard; they have them all around the interior, including airbags in the door to protect occupants in the event of a side impact.

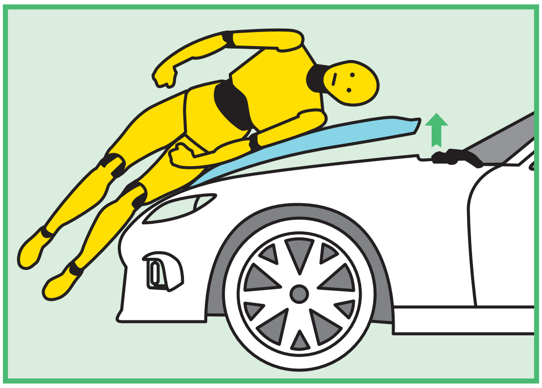
The sudden pressure change that occurs in the door cavity during a side impact can be detected using a relative pressure sensor, often much faster than using other techniques. Using the right kind of sensor in this application tells the car's safety system to deploy the airbag within a few hundredths of a second and normally much quicker than a front airbag system operates. This is necessary because the proximity of the door to the passenger reduces the available reaction time significantly compared to a dashboard airbag system. And in this context, milliseconds count.

10. RELEASING PEDESTRIAN AIRBAGS

In the unfortunate event that a car hits a pedestrian, a recent innovation uses pressure sensors to deploy a safety mechanism (an active bonnet system) which is designed to reduce the impact to the pedestrian if they land on the bonnet.

By putting relative pressure sensors in the front bumper of a car, any deformation to the bumper can be detected immediately. If this happens, the car's safety system can activate a compressed air reserve in the engine bay, which pushes the bonnet up and towards the front of the car.

The elevated bonnet (as shown below) creates a barrier between the pedestrian and the harder components of the engine, thus reducing the potential severity of the impact.



Some cars also deploy an airbag from the engine bay that covers the windscreen to further protect the pedestrian.

Pressure sensors play a crucial role in all of these innovations, making for a cleaner, smoother, and safer ride.

The automotive market is now one of the largest markets for pressure sensors and is likely to remain so due to the huge variety of ways they're used.

From a host of safety features to reducing pollution and optimising engine efficiency, pressure sensors are central to the modern motoring experience. Without them, we could easily still be starting our cars with a crank, changing gears with three sticks and hoping we don't need to stop too quickly!

Pressure sensors: 8 life-saving medical applications

Many medical devices now depend on accurate and stable pressure measurements in order to operate reliably.

What's more, patient care is expanding beyond the hospital and the GP`s surgery and arriving in patients' homes, in the form of home health monitoring.

As a result, developing with pressure sensors has become an integral part of designing medical applications.

Below, we explore 8 different uses of pressure sensors in medical technology.

1. GETTING THE MIX RIGHT IN MEDICAL VENTILATORS

A ventilator works by mixing air with pure oxygen to help the respiratory function of a patient. Differential or gauge pressure sensors are normally sited between valves and regulators to ensure the air and oxygen are mixed in the right quantities. In this kind of application, small surface-mount sensors are ideal; they will typically be specified for a pressure range of 2in or 5in H2O and are available with either analog or digital (I2C) outputs.

Despite being small and low power, these low pressure sensors can often include an integrated DSP (digital signal processor) for compensating for non-linearity, offsets or the effects of temperature.

2. MONITORING OXYGEN THERAPY EFFECTIVENESS

Oxygen therapy comes in a number of forms, as concentrated oxygen can be an effective initial treatment for asthma, bronchitis and oedemas, as well as heart failure.

Oxygen therapy systems use differential pressure sensors at several points in the system to monitor the pressure of the oxygen as it is mixed with atmospheric air. These sites are usually at the outlet of the oxygen tank, inline with the pressure regulator, and next to the flow control valve (see diagram right).

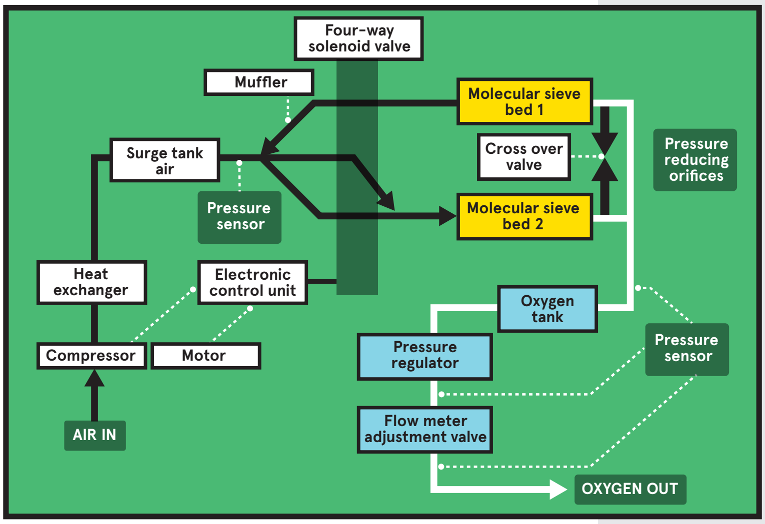
The pressures sensors in this application are likely to be differential pressure sensors with a scale of up to 4 kPa.

3. DELIVERING HYPERBARIC THERAPY

Raising the air pressure in a sealed chamber containing a patient is known as hyperbaric therapy and can be effective for a number of conditions. It's used to treat decompression sickness experienced by divers, and can also help patients with skin grafts or burn injuries. It can also be effective in treating carbon monoxide poisoning and even some necrotizing infections.

Pressure sensors are used to monitor the pressure inside the chamber and control the amount of pressure applied during treatment. This will typically take the form of an absolute pressure sensor capable of measuring pressures up to around 100 kPa.

Even this most industrial of treatments is making inroads into patient's homes, as `soft' chambers become increasingly available - although the pressures these soft chambers can achieve are lower than the professional-grade `hard' chambers. Typically, a soft chamber will require gauge pressure sensors capable of measuring around 0.3 to 0.5 bar, while a hard chamber would employ gauge pressure sensors able to measure as much as 6 bar.



▲ Pressures sensors in an oxygen concentrator (Source: All Sensors)

Pressure sensors: 8 life-saving medical applications

4. PROVIDING POSITIVE PRESSURE MASKS TO TREAT SLEEP APNOEA

Sleep apnoea is a condition that causes the sufferer to stop breathing while asleep. Left untreated it can lead to a number of serious conditions, from chronic fatigue to potential heart failure.

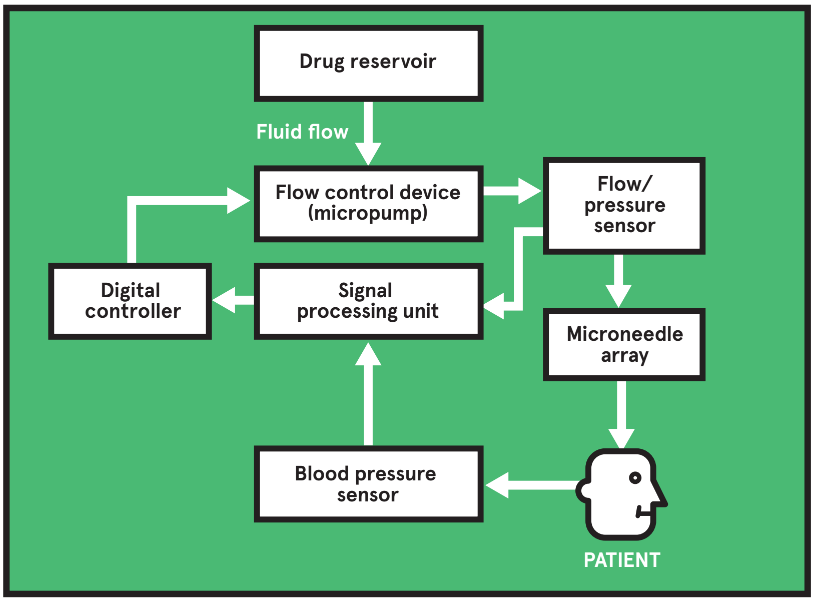
The treatment involves using a device called a continuous positive air pressure machine, or CPAP, which delivers air at a positive pressure to a mask worn over the nose and mouth of the patient. An airflow pressure sensor is used to monitor the air pressure, detecting when the patient is breathing in and immediately turning on a fan to create positive pressure to open the airways. As the patient breathes out the fan is deactivated, allowing the patient to exhale without forcing them to fight against the positive pressure.

Sleep apnea machines will likely employ a differential pressure sensor able to measure pressures up to 4 kPa.

5. AUTOMATING DRUG INFUSION

Drugs delivered in liquid form can be an effective form of treatment, as can other types of fluids. e.g. for rehydration. These fluids can be administered either intravenously, subcutaneously or directly into a vein, and are typically delivered using infusion pumps. In order to ensure the correct volume of fluid is administered at the correct rate, the pumps use a number of sensors including gauge and differential pressure sensors, to closely monitor and control the flow of liquid.

Differential pressure sensors are used in drug delivery systems (see diagram below) to measure and control the flow of liquids into the patient. This ensures the right volume of drugs is delivered at the right time throughout the day and night, without the need for constant medical attention. They are normally differential pressure sensors, calibrated to measure flow rates in the range of 0.5 to 10.0 micro litres/min



◀ How pressure sensors are used to control drug delivery (Source: All Sensors)

Pressure sensors: 8 life-saving medical applications

6-8. MEASURING IN VIVO BLOOD PRESSURE, EX VIVO BLOOD PRESSURE AND INTRAOCULAR PRESSURE

In vivo blood pressure sensing involves implanting a sensor into the body. It can now be achieved using tiny absolute pressure sensors designed for this purpose.

Ex vivo blood pressure sensing, from outside the body, can be implemented using gauge pressure sensors to measure the blood pressure when the heart beats (systolic) and between the heart's beats (diastolic).

Sensors for both in vivo and ex vivo blood pressure sensing need to be able to measure pressures up to 300 mm Hg (maximum), however in vivo applications tend to use absolute pressure sensors, while ex vivo favour gauge pressure sensors.

MEMS-based gauge pressure sensors are now being used to measure the intraocular pressure of a patient's eyes, which is particularly important after an operation to replace the cataract.

Manufacturers are now producing an ever-widening range of pressure sensors for medical applications, including disposable pressure sensors based on MEMS technology that can be used inside the body or in-line with fluids entering the body. These are produced in clean rooms and in accordance with industry-accepted guidelines including those generated by the Association for the Advancement of Medical Instrumentation (AAMI).

Pressure sensors have become an essential element of medical care, providing accurate and stable measurement of critical pressure levels in gas and liquids within the body and in treatments being applied to patients.

Future developments will enable more sophisticated, and ever smaller medical equipment to be developed, as well as lowering the price point for home-use devices.

One significant result will be an elevated quality of life for an ageing population.

NEED SOME ADVICE?

Our pressure sensor experts are on hand to help you make the right choice for your application. Get in touch at **avnet-abacus.eu/ask-an-expert**

Pressure sensors: 3 industrial applications enabling the smart factory

Real-time sensor data is enabling factories to better understand their own processes and keep them running. And putting that data into the IIoT also helps optimise how raw materials are ordered, handled and consumed. Knowing what to reorder and when can keep continuous processes at high capacity.

Smart manufacturing is changing the way we make, package and distribute just about everything, but Industry 4.0 is revolutionising the way our factories operate. While the Industrial IoT is dependent on connectivity, fundamentally it's harnessing raw data and turning that into operational intelligence, which means sensors are key to the entire process. While there are many types of sensor at play here, the pressure sensor is probably the most diverse and widely deployed type of sensor in the IIoT.

1. MONITORING PROCESS FLOWS

Differential pressure sensors are used extensively in process flows where a fluid needs to pass through some form of barrier, such as a filter. Under normal conditions the pressure difference between the upstream (often called the line or influent pressure) and the downstream (effluent) pressure should be nil or minimal. As the filter becomes blocked with contaminants, the downstream pressure will decrease, which causes the difference measured to increase.

The sensor's output can be calibrated to show the maximum permissible pressure difference at full scale. For example, a 4-20mA output could be calibrated to show 20mA when the pressure difference reaches the maximum permissible, but read 4mA when the pressure difference is nil.

Differential pressure sensors measure the difference between the influent and effluent pressures of a filter, which should be nil under normal operating conditions but will rise as the filter becomes clogged. ▶

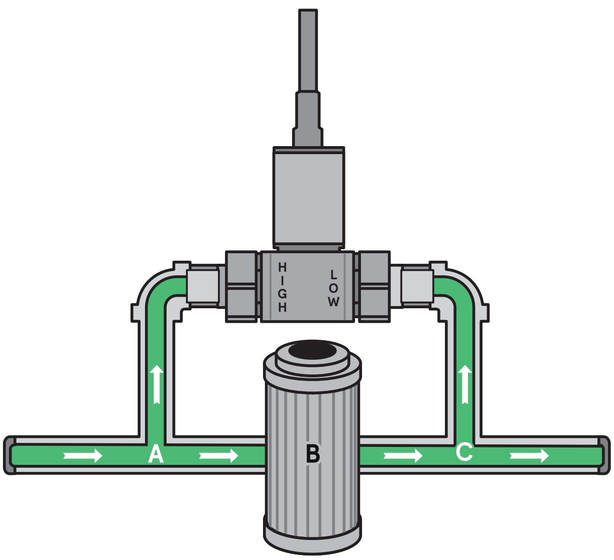
2. MEASURING SAFE LEVELS IN LIQUID TANKS

Submersible pressure sensors that are certified for use in intrinsically safe areas can be used to measure liquid pressures of up to 30 PSI with either a voltage or current (4-20mA) output. Positioning a submersible pressure sensor at the bottom of a tank would provide an accurate reading of the contents of the tank, thereby alerting workers or the process control system when the level in the tank falls below an allowable lower limit.

The pressure at the bottom of a tank – normally called the hydrostatic or head pressure – is measured in units of distance (feet, inches, meters) of water columns. For example, 27.670 inches of water column (WC) is around the same as 1 PSI at 100°F.

The pressure measured is only dependent on the height of the tank (as opposed to its shape) or the volume of the liquid. For this reason it is important that the sensor is placed at the bottom of the tank (instead of half way down).

Process controllers can calculate the level of liquid in a tank by measuring the hydrostatic pressure, which is more accurately measured when the density of the liquid is also known.



How pressure sensors are enabling smart factories in industry 4.0

3.MANAGING CONTROL LOOPS

As well as being used to monitor processes, pressure sensors are often instrumental in the control loop. This is particularly relevant in the use of hydraulics, where pressurised fluids are used to apply effort in presses or lifts for example.

The sensors are often small, particularly those based on MEMS technology. They can measure less than 2mm on each side yet be capable of measuring absolute pressures in the region of 20 Bar or more. This makes them suitable in a range of applications, including medical and automotive.

EVEN SMARTER SENSORS

Smart factories are now employing smarter sensors, such as pressure sensors with built-in Bluetooth connectivity, allowing them to be monitored wirelessly. These sub-systems feature a gauge pressure sensor, Analog to Digital Converter and Bluetooth radio in a single sealed unit that can be mounted in places where adding wires may be difficult. As they are battery-powered they can operate autonomously for as much as two years without any maintenance, providing accurate pressure sensor readings for gases, liquids and even mildly corrosive fluids.

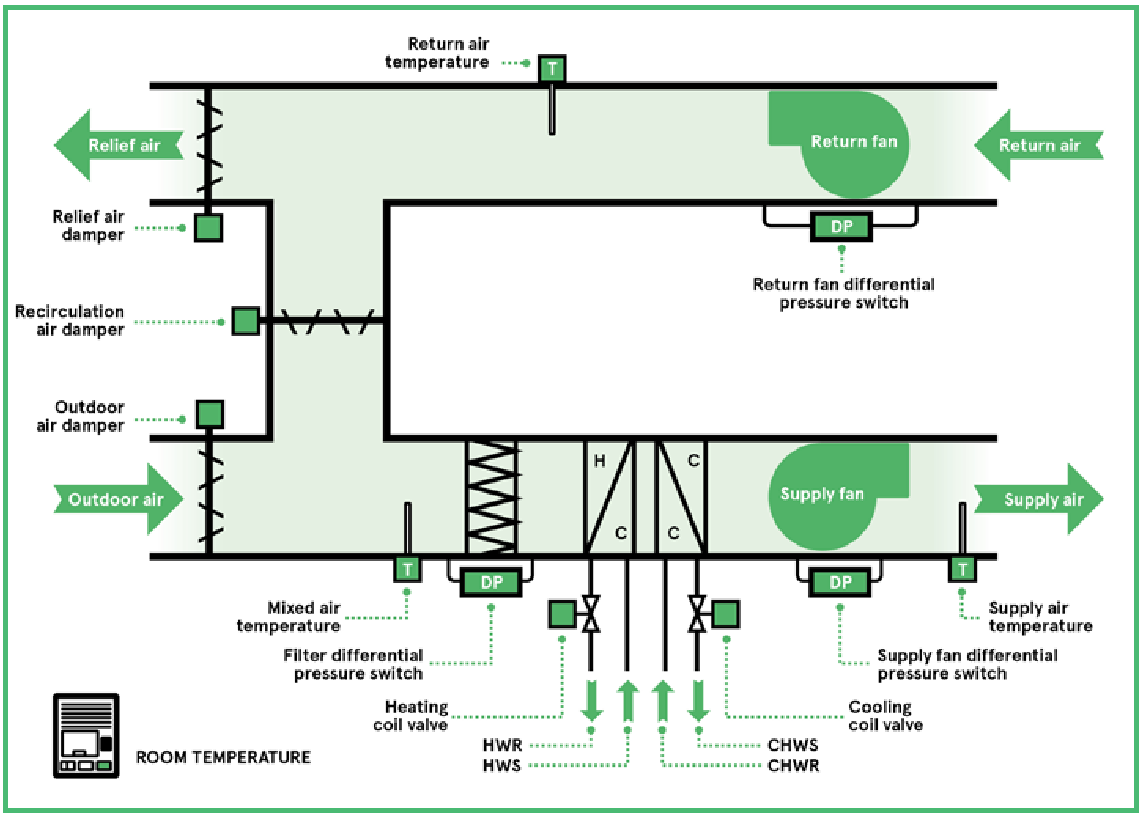
Pressure sensors are fundamental in the smart factory and in enabling Industry 4.0.

Pressure sensors: 8 automated building applications

As urban population density increases, larger buildings are becoming increasingly commonplace, and controlling their internal environment accurately is a challenge for designers and operations staff alike. In addition, rising environmental concerns and tightening regulations have made minimising resources used to heat and cool buildings a serious consideration.

The business of building automation integrates heating, ventilation, air conditioning and refrigeration (HVACR), with control interfaces and monitoring systems – all with the help of pressure sensors.

HVACR involves complex control algorithms that operate using feedback obtained throughout the system from a range of sensors - checking temperatures around the building and pipework, as well as overall air circulation.

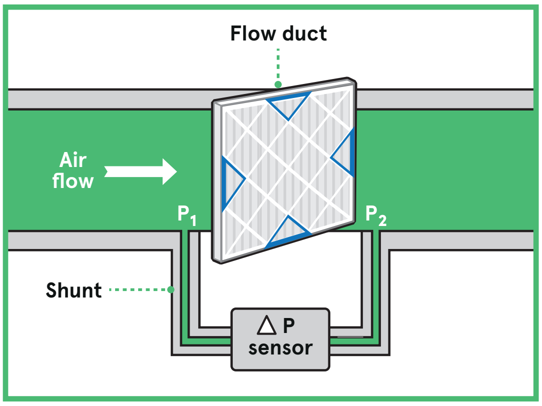


▲ A general representation of an HVAC system

Pressure sensors: 8 automated building applications

1. MONITORING AIR FILTERS

The air filter is a critical part of any HVAC system, and it needs to operate efficiently at all times. By using a differential pressure sensor to measure the pressure on both sides of the filter (see diagram below), the building automation system can monitor the airflow at all times. As the airflow reduces over time it may indicate the filter needs replacing or cleaning. If it isn't replaced, the system may need to use more energy to restore the airflow to required levels, which also places additional wear on other components in the system.



▲ A differential pressure sensor measuring the airflow through a filter

2. MINIMISING FAN POWER USE

The flow of air in an HVAC system needs to be kept within specific parameters in order to maintain a safe and comfortable living or working environment. Fans force the air through ducts in the system to keep it circulating. A network of differential pressure sensors fitted across the air ducts monitors how the air is flowing throughout and allows the system to regulate each fan's speed and keep energy costs to a minimum.

3. MAINTAINING RELATIVE DUCT PRESSURE LEVELS

Differential pressure sensors are also used to measure the relative pressure differences between duct air and room air. Air pressure differences can cause various issues in a building, normally attributed to either a positive or negative air pressure difference. For example, a negative air pressure in one part of a building will cause air currents, as the relatively higher pressures find their way into the low pressure areas. An imbalance can lead to doors or windows being difficult to open or close, or a loss of heated/cooled air which leads to higher energy costs. By measuring the relative air pressure differences around a building's HVAC system these issues can be avoided. Measuring the pressure inside a duct, relative to a room or open space, can be achieved using a differential pressure sensor with one side open to the ambient air in the room. Typically, the pressures being measured are relatively low, so the sensor would be specified to operate over a range of around ±50 Pascals.

4. IMPROVING HEAT EXCHANGE EFFICIENCY

Building management, control and automation systems are able to control the temperature and humidity of a room thanks to the feedback their sensors provide. Of particular importance are pressure sensors that measure the relative air pressure in a room, which is generally normalised to 1 atmosphere (ATM). Using a pressure sensor to monitor the air pressure in a room over time can determine whether there are sealant leaks around doors and windows, which would lead to heat (energy) losses.

In addition, the heating and cooling systems use pumps to compress fluids for heat exchange, and these have pressure sensors positioned on the high side and low side of the compressor to ensure the pressure difference is maintained for optimum performance. The type of sensor used here might include a differential pressure sensor with a scale of 0 to 25 bar.

Pressure sensors: 8 automated building applications

5. MONITORING VARIABLE AIR VOLUME HEATING SYSTEMS

Ventilation is an important aspect of HVAC systems, which involves closely monitoring and controlling the volume of air flowing into a room. If the heating system uses a Variable Air Volume (VAV) configuration (as opposed to a Constant Air Volume, or CAV system) the temperature is maintained by varying the volume of air flowing into the room, rather than the temperature of the air. In this case, differential pressure sensors are used to measure the volume of air, and would be specified with a range of around 0 to 360 Pascals. The feedback provided by the sensor allows the building control system to open or close dampers, allowing more or less air to flow into a room.

6. AUTOMATED SAFETY SYSTEMS

Building management controllers can use pressure sensors to directly control aspects of the HVAC system, often in the form of a differential pressure sensor that operates as a switch. This allows the system to automatically turn devices off or on when it measures a pressure difference that is under or over set limits, potentially preventing wider damage to the system or sudden environmental changes within the building.

These sensors will typically be specified to operate over a range of 0.1 to 4.00 InH2O, and they feature a spring-loaded diaphragm that actuates two switches, one to detect over-pressure and one to detect under-pressure. The limits on each state will span a small excursion of the full-scale range and be relative to the sensor's total span. Contacts can be rated up to 240VAC, with in excess of 1 million switching operations.

7. MAINTAINING GAS PRESSURE IN PNEUMATICS

Relative pressure sensors are used to measure the pressure of sub-systems based on hydraulic or pneumatic operating principles in HVAC systems. These can take the form of gases or liquids used in the heating or cooling process, and ensure the sub-systems are ready for immediate use if required.

Pneumatic pressure sensors can operate over a wide range of pressures, up to 600 bar if necessary, and are capable of operating while fully submerged in depths of 100 meters or more.

8. MONITORING DANGEROUS CHEMICALS

Ammonia is used as a coolant in HVAC and refrigeration systems, but could cause significant damage and danger to people in the event of a leak. However, relative pressure sensors can be used to monitor the pressure of the ammonia as it passes through the system, ensuring it stays within acceptable limits.

This is a task where differential pressure sensors able to measure differences from 6.0 psi on the low pressure side to 175 psi on the high pressure side are used.

Building monitoring, control and automation systems harness the power and benefits of HVACR equipment, which in turn relies heavily on pressure sensors to function efficiently.

As building and home automation technologies and concepts become increasingly applicable to all homes, not just large business structures, pressure sensors will continue to play a central role in controlling the environments we live in.

Pressure sensors: 11 life-enhancing consumer applications

The things we use, carry and wear on a daily basis are growing in intelligence. More and more, our appliances are able to detect changes in their environment and modify their behaviour based on those changes. Pressure sensors are one of the technologies enabling smarter consumer electronics.

Adding a pressure sensor to a consumer device gives you an entirely new dimension to explore, and the information this provides can create an improved user experience, making your next product stand out from the crowd.

1. KEEPING FOOD FRESHER FOR LONGER WITH A PARTIAL VACUUM

A recent innovation in refrigeration takes a step beyond cooling, and actually seals the inside of the fridge using a partial vacuum. By lowering the oxygen levels inside the fridge, food remains fresh for longer. Pressure sensors are essential in this application, as they provide the feedback needed by the pump used to reduce the pressure in the compartment.

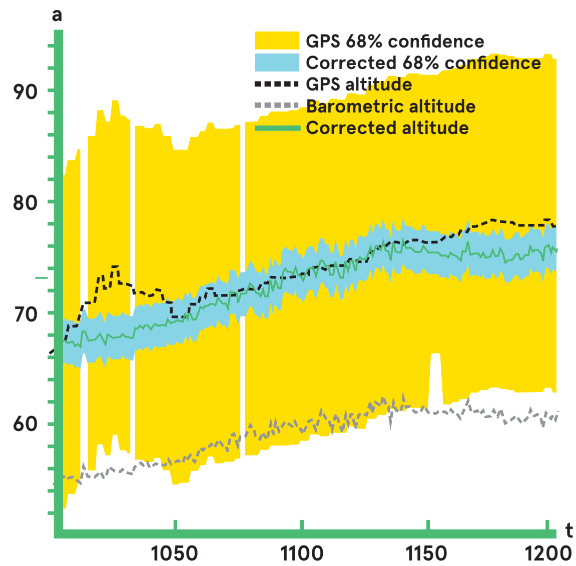
2. MAKING VACUUM CLEANERS MORE EFFECTIVE AND EASIER TO MAINTAIN

Vacuum cleaners are becoming smarter, frequently by using pressure sensors. For example, by measuring minute changes in suction pressure they are able to detect the kind of flooring being cleaned and adjust settings such as power and brush height to suit. Pressure sensors also enable owners to be notified when a dust receptacle is full and when the filter needs to be replaced.

3. AUGMENTING GPS IN BUILT-UP AREAS

Many small devices now integrate GPS receivers that tell the device its position in three dimensions; latitude, longitude and elevation. Mapping software uses these coordinates to plot the device's position on a rendered map. In urban areas, GPS signals can be obscured or degraded by large structures, covered areas and tunnels.

Technology is being used to restore at least one of the three datum points; elevation. In absolute terms a barometric pressure sensor can be used to determine elevation and therefore augment the GPS signal. The argument is that by using the confidence level of both a barometric pressure sensor and GPS signal, a more accurate altitude measurement can be obtained. This can help the device to better determine its position in a mapped building based on its altitude, which in turn can deliver a more accurate location. In the chart below, the research data shows that an increased accuracy confidence level of 85% can be obtained using this sensor fusion technique versus GPS alone. Other sensors can provide an indication of direction and speed, allowing the device to estimate, with reasonable certainty, its position. This technology is now being used to provide consumers with indoor navigation for shopping malls, airports and other large public spaces.



▲ An example of how combining barometric pressure sensing with GPS can deliver more accurate altitude measurement than GPS alone

Pressure sensors: 11 life-enhancing consumer applications

4. FORECASTING HYPER-LOCALISED WEATHER

The use of home weather stations is increasing, as are online services that provide weather information, both of which are contributing to a trend in highly-localised weather forecasting. Inside each weather station sits a barometer; a pressure sensor detecting the smallest variations in atmospheric pressure.

Atmospheric pressure changes can be interpreted by the weather station or its cloud-based algorithm, to determine the presence and movement of storm fronts, and thus predict the likelihood of rain.

5. PURIFYING THE AIR AND WATER

As the population density in metropolitan areas continues to rise, the level of air quality is becoming a greater concern. Many people now choose to use an air purifier, which uses high efficiency particulate air (HEPA) filters to trap airborne contaminants.

Over time, the filters become laden with contaminants and need to be cleaned or replaced. A gauge or differential pressure sensor capable of measuring ultra-low pressure differences can detect when this becomes the case and alert the user.

Pressure sensors can be used in a similar way to monitor filters in water purifying systems, and indicate when they need to be replaced.

6. WASHING CLOTHES MORE EFFICIENTLY

Washing machines are a major home energy consumer, so making their use more efficient is a key focus for consumers and manufacturers alike. As more homes in Europe move onto metered water connections, reducing overall water use per load is also of significant interest.

By using pressure sensors to precisely regulate the amount of water required, significant environmental savings can be made.

7. MAKING BETTER COFFEE

From simple coffee 'pod' machines to more complex bean-to-cup systems, there are two key principles in achieving the perfect brew: temperature and pressure. In fact, pressure is so key to the process, the word 'espresso' literally means 'pressed out'.

Absolute pressure sensors designed for harsh environments are used in these machines during the brewing stage, and in the cleaning process that follows it in higher-end coffee makers.

8. MAKING COOKER EXTRACTION MORE EFFECTIVE

Extraction fans are now a common feature in most kitchens, and pressure sensors help keep them working. To work most efficiently the right amount of negative pressure needs to be produced at the hood, achieved by driving the fan at the correct speed. A pressure sensor is used to measure the negative pressure produced, and in turn control the fan.

9. MEASURING ALTITUDE IN EXTREME SPORTS

For sports enthusiasts, barometric pressure sensors can be used to measure the height above ground or below sea level, in both air and water. These sensors are used by the likes of skydivers and scuba divers. Piezoresistive MEMS sensors are a popular choice in the latter application due to their size and accuracy.

10. TRACKING STAIRS TAKEN ON TOP OF YOUR 10,000 STEPS

Some fitness bands and wearable devices use pressure sensors to calculate the change in air pressure and correlate that to height differences. Combined with readings from an accelerometer, the devices can determine when you've chosen the stairs over the lift and award you the extra points that come with healthier option.

The gamification of daily activity continues to grow and can now be more accurately measured - and rewarded!

Pressure sensors: 11 life-enhancing consumer applications

11. DETECTING FALLS IN ASSISTED LIVING DEVICES

Air pressure measuring principles are now used in patient monitoring and assistive living solutions, where a sudden rapid change in altitude can indicate a fall.

Pressure sensors in this application space will typically be capable of measuring changes in air pressure in hundredths of a milli-bar with an accuracy of 2mbar or better. That means they can register an altitude change of around 10cm, easily accurate enough to determine if a patient is on the floor.

An alert will be sent to the relevant service provider (or family member) to enable them to contact the wearer immediately and/or send assistance as appropriate.

As the examples above illustrate, modern life is increasingly reliant on pressure sensing devices to deliver a wide range of features and functions in automated devices. As lifestyles continue to evolve, new applications are also using pressure sensors to deliver key functionality.

NEED SOME ADVICE?

Our pressure sensor experts are on hand to help you make the right choice for your application. Get in touch at **avnet-abacus.eu/ask-an-expert**

Types of pressure sensors: a comprehensive overview

There's a vast array of pressure sensors available on the market today - and wrapping your head around all the differences can take a bit of time.

That said, the sensors can largely be categorised according to the type of pressure measurement they make, the sensing principle employed, the output signal and the media they're measuring.

Beyond that, there are a few other distinguishing factors, like whether or not they're MEMS sensors, or whether they're medically-approved.

Below we'll take you through a brief explanation of the different types of pressure sensors to help you understand your options.

TYPE OF PRESSURE MEASUREMENT

Pressure sensors can be categorised in one of three main measurement modes:

- **Absolute**
- **Gauge**
- **Differential**

For a more in-depth explanation of each measurement mode, jump to chapter 5.

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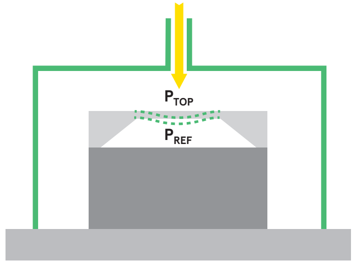
Absolute

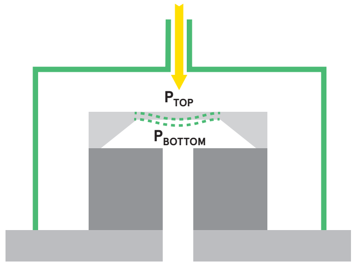
In an absolute pressure sensor (see diagram below), the reference point is zero, or a vacuum. One side of the sensor is exposed to the medium to be measured, and the other side is sealed to effect a vacuum.



▲ Absolute pressure measurement

Gauge

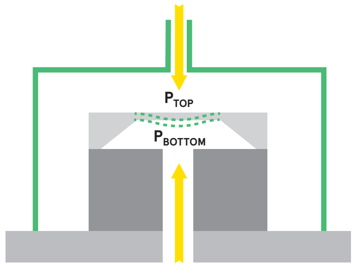
A gauge sensor (see diagram below) measures pressure relative to atmospheric pressure. One side is connected to the system, which may be a pump such as a suction pump, while the other side is vented to the atmosphere. It's important to ensure the vent hole won't become obstructed.



▲ Gauge pressure measurement

Differential

A differential pressure sensor (see diagram below) measures the difference between pressure experienced at two exposed ports. Typical uses include measuring liquid or gas flow in pipes or ducts, or detecting a blockage or seized valve.



▲ Differential pressure measurement

Types of pressure sensors: a comprehensive overview

SENSING PRINCIPLES

The sensing principle employed by a sensor, can influence accuracy, reliability, measurement range, and compatibility with the target environment. Below we'll look at 5 different ways the mechanical displacement taking place inside a sensor is turned into an electrical output:

- **Resistive**
- **Capacitive**
- **Piezoelectric**
- **Optical**
- **MEMS**

Resistive

Resistive pressure sensors utilise the change in electrical resistance of a strain gauge bonded to the diaphragm that's exposed to the pressure medium.

The strain gauges often comprise of a metal resistive element on a flexible backing bonded to the diaphragm, or deposited directly using thin-film processes. The metal diaphragm gives high over-pressure and burst-pressure capability.

Otherwise, strain gauges can be deposited on a ceramic diaphragm using a thick-film deposition process. Over-pressure and burst-pressure tolerance are typically much lower than for metal-diaphragm devices.

Piezoresistive sensors take advantage of the change in resistivity of semiconductor materials, when subjected to strain due to diaphragm deflection. The magnitude of the change can be 100 times greater than the resistance change produced in a metal strain gauge. Hence piezoresistive sensors can measure smaller pressure changes than metal or ceramic sensors.

SYSTEM REQUIREMENT	SENSOR TECHNOLOGY		
	Metal thin-film	Ceramic thick-film	Piezoresistive
Absolute pressure measurement	No	No	Yes
Very low pressure range	No	No	Yes
Very high pressure range	Yes	No	No
Shock and vibration resistance	Good	Medium	Medium
Long-term stability	Good	Medium	Good

▲ This table compares the relative strengths of metal, ceramic, and piezoresistive sensors

Types of pressure sensors: a comprehensive overview

Capacitive

Capacitive sensors, which display a capacitance change as one plate deflects under applied pressure, can be highly sensitive, can measure pressures below 10mbar, and withstand large overloads. Constraints on materials, and joining and sealing requirements, however, can restrict applications.

Piezoelectric

Piezoelectric pressure sensors utilise the property of piezoelectric materials like quartz, to generate a charge on the surface when pressure is applied. The charge magnitude is proportional to the force applied, and the polarity expresses its direction. The charge accumulates and dissipates quickly as pressure changes, allowing measurement of fast-changing dynamic pressures.

Optical

Optical sensors, which utilise interferometry to measure pressure-induced changes in optical fibre, are undisturbed by electromagnetic interference, allowing use in noisy environments or near sources such as radiography equipment. They can be created using tiny components or MEMS technology, can be medically safe for implantation or topical use, and can measure the pressure at multiple points along the fibre.

MEMS technology

MEMS (Micro Electro-Mechanical System) sensors contain a piezo or capacitive pressure-sensing mechanism fabricated on silicon at micron-level resolution. Co-packaged signal-conditioning electronics convert the small-magnitude MEMS electrical output to an analogue or digital signal. They are tiny surface-mount devices typically only about 2-3mm per side.

For a more on the core sensor technologies, head to chapter 6.

OUTPUT SIGNAL: TRANSDUCER OR TRANSMITTER?

The terms sensors, transducers and transmitters often appear to be used interchangeably. To clarify things, a 'sensor' can be seen as an umbrella term for devices that perform as a transducer or a transmitter.

In simple terms transducers produce an output voltage that varies with the pressure experienced, while transmitters produce an output current. The most common distinctions here are the following:

- **Millivolt-output transducers**
- **Volt-output transducers**
- **Transmitters**

In practice, the excitation voltage for a resistive bridge can be as low as 3V or 5V, or 10V-30V, or higher. Sensitivity is typically only a few millivolts per volt which means the raw output signal has low magnitude.

Millivolt-output transducers

If the connection distance is short, and noise is not a problem, a millivolt-output sensor can be easy to design-in but requires a regulated power supply to prevent fluctuations in the excitation voltage affecting the output.

Voltage-output transducers

A voltage-output transducer amplifies the bridge signal, making it a good choice where longer cable lengths are required. Lower noise susceptibility, and a lower-cost unregulated power supply are additional advantages.

Transmitters

A pressure transmitter converts the voltage output to a current signal, typically 4-20mA. Noise susceptibility is extremely low and cable lengths can be several hundred metres, although power consumption is greater.

For a more in-depth look at sensors, transducers and transmitters, read chapter 4.

Types of pressure sensors: a comprehensive overview

MEDIA COMPATIBILITY

When searching for the right pressure sensor, you'll want to consider the media they're designed to measure, i.e. the different types of gases and liquids:

- **Air**
- **Gas**
- **Atmospheric / barometric**
- **Pneumatic**
- **Water**
- **Liquid**
- **Hydraulic**
- **Corrosive Media**

Although many of the above can be adapted for use with corrosive substances, you can also find sensors specifically designed to measure corrosive media.

Sensors used in chemical processes may need to withstand exposure to corrosive media such as acids or alkalis. Many can be specified with a stainless steel case and/or diaphragm for increased corrosion resistance. These can also withstand corrosion due to atmospheric humidity or water splashes, or withstand permanent immersion in untreated water, or in water containing chemicals such as in treatment plants or swimming pools.

Sea water, salt spray or coastal environments can present corrosion hazards beyond the resistance of ordinary low-grade stainless steels. Case and diaphragm materials such as super-nickel alloys or titanium are often recommended.

Sensors may also be specified with parts such as o-rings made from viton, instead of rubber, for increased resistance to ageing and corrosion. Alternatively, the diaphragm may be welded to the sensor body to enhance corrosion resistance.

For more on the different types of media that pressure sensors are designed to measure, jump to chapter 7.

OTHER FACTORS TO CONSIDER

Industrial sensing

Among general industrial pressure sensors, the measurement range can be 0-25 bar or 0-50 bar for light hydraulics applications or similar, while higher-range sensors can be designed for measuring up to 1000 bar or 5000 bar, or more. Sensors designed for general industrial applications can be used in a wide variety of hydraulic or pneumatic systems.

Medically safe sensors

Medical sensors in contact with the body must be safe for the patient. This impacts not only the choice of sensor materials, but also hygiene. Some manufacturers' medical ranges include disposable sensors that are discarded after use.

Surface-mount packages or ready-to-use modules

Pressure sensors are available in a variety of forms, such as individual sensing elements in surface-mount packages, or ready-to-use sensor modules complete with process connection and electrical interface.

Screw-mount process connections in general industrial sensors may conform to a standard size, such as G ¼" or G ½", or UNF or NPT sizes. Specifications such as DIN 3852 or EN 837 define various types of seals. High-pressure sensors may utilise a larger thread size, such as M16 x 1.5, and metal-to-metal sealing.

Small board-mount sensors can be specified with a moulded manifold, a standard-size barbed port for push-on tube connection, or port-less.

Overall, the variety of individual sensor types now available in the marketplace provides flexibility for design engineers to identify a suitable sensor for almost any given application.

Pressure sensor vs transducer vs transmitter

You may hear electronic pressure detectors referred to as sensors, transducers, or transmitters. And understanding the difference in what these three terms mean is important to ensure the chosen device is right for the end application; particularly with regards to cost, power consumption, susceptibility to noise, and constraints around wiring and installation.

So how do you differentiate between these terms?

The term 'pressure sensor' can be regarded as a generic description for any device that measures pressure and provides an appropriate output in response.

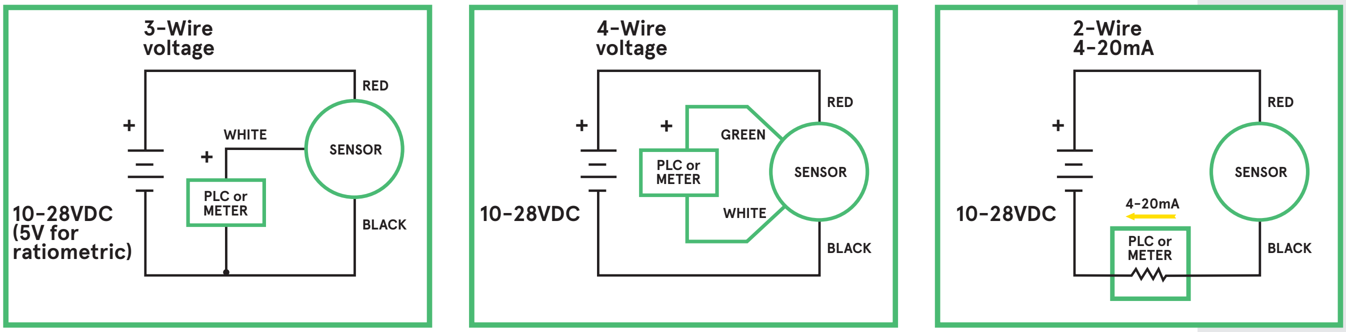
PROPERTIES OF THE OUTPUT INTERFACE

The properties of the output interface define the type of sensor.

To differentiate between the different types, it can be helpful to consider transducers as devices that have a voltage output, which may have a magnitude of a few millivolts or several volts. Transmitters, on the other hand, have a current output, usually designed for connecting to the standard 4-20mA current loop widely used in industrial sensing and control. The distinctions we'll discuss here are:

- **Millivolt-output pressure transducers**
- **Voltage-output pressure transducers**
- **Transmitters**

The diagrams below show how a voltage-output transducer or current-output transmitter can be connected to a programmable logic controller (PLC) or meter to monitor pressure in a typical industrial equipment or process control application.



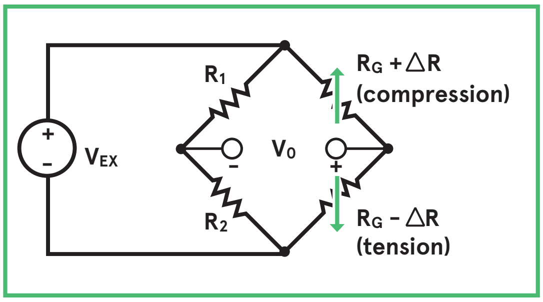
▲ Connecting a pressure transducer or transmitter to industrial instrumentation.

Pressure sensor vs transducer vs transmitter

MILLIVOLT-OUTPUT PRESSURE TRANSDUCERS

As is in the name, these transducers output in millivolts (mV). The output signal is proportional to the power supply, for example, a 5VDC supply with a 10mV/V output signal produces a 0-50mV output on the sensor. Older foil-type strain-gauge sensors can produce an output of about 2-3mV/V, whereas today's MEMS sensors can provide about 20mV/V with good linearity. Any variation in pressure is determined by measuring small changes in this voltage, which is a result of tiny changes in resistance (about 0.1%) in the strain gauges themselves.

The diagram below shows a half-bridge strain-gauge pressure sensor, illustrating the excitation voltage and output voltage. A larger excitation voltage, say 10V as opposed to 3V, produces a larger output voltage.



▲ A half-bridge strain gauge with millivolt output.

The simple interface circuitry of a millivolt output transducer helps ensure low cost and small package size, and gives designers the flexibility to design interface circuitry to suit their own application. However, there are several limitations to consider.

Because the full-scale output is directly proportional to the excitation, the excitation voltage must usually be generated using a regulated power supply.

In addition, owing to the low amplitude of the output, millivolt-output transducers are not usually suitable for use in electrically noisy environments.

And because the output voltage is attenuated by the resistance in connecting wires, these wires must be kept short, implying that the sensor must be close to the monitoring instrumentation. About three to six meters is usually the maximum practicable distance.

VOLTAGE-OUTPUT PRESSURE TRANSDUCERS

A voltage-output transducer contains additional signal amplification to increase the output voltage of the bridge to a larger value such as 5V or 10V.

Having a larger output, these are less susceptible to noise, allowing for use in harsher electrical environments. Longer connecting wires can be used, allowing the sensor to be further from the panel.

Supply voltages are typically from 8-28VDC. This allows the use of a lower-cost unregulated power supply, except where the output is 0.5-4.5V, which requires a 5VDC regulated supply. Lower current consumption means they are also suitable for battery operated equipment.

Older voltage output transducers do not have a 'live zero', meaning they do not output a signal when at zero pressure. The risk with these is that the system can't recognise the difference between a failed sensor with no output and zero pressure.

Pressure sensor vs transducer vs transmitter

PRESSURE TRANSMITTERS

In contrast to a voltage-output transducer, a pressure transmitter has a low-impedance current output, most commonly designed to transmit analogue 4-20mA signals. The output may be designed for use with either a 2-wire or 4-wire current loop, as both types are widely used throughout industry.

4-20mA pressure transmitters provide good electrical noise immunity (EMI/RFI), making them ideal when the signal must be transmitted long distances. Transmitters can be powered by an unregulated supply, but current output is generally unsuitable for battery powered equipment when operating at full pressure.

TRANSDUCERS V TRANSMITTERS: CHOOSING THE RIGHT ONE

Pressure transducers and transmitters are categories of pressure sensors widely used in industrial equipment and process control applications and differ in their output characteristics. To help select the right sensor for a given task, their strengths and weaknesses can be summarised as follows:

Millivolt transducer:

- Lowest cost
- Suitable where connection distances can be short and noise is not a problem
- Needs stable bridge-excitation voltage

Voltage transducer:

- Less susceptible to noise
- Shorter connection distances than pressure transmitter
- Lower power consumption than pressure transmitter
- Can work with unregulated bridge-excitation voltage
- Low power consumption

Transmitter:

- Easy to use in ubiquitous 4-20mA industrial sensing
- Long communication distance
- Low susceptibility to noise
- Typically higher power consumption than transducer types

NEED SOME ADVICE?

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Types of pressure measurement

ABSOLUTE VS GAUGE VS DIFFERENTIAL PRESSURE SENSORS

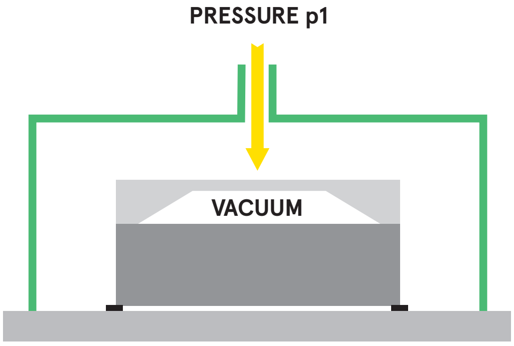
What's the difference between absolute, gauge and differential pressure sensors?

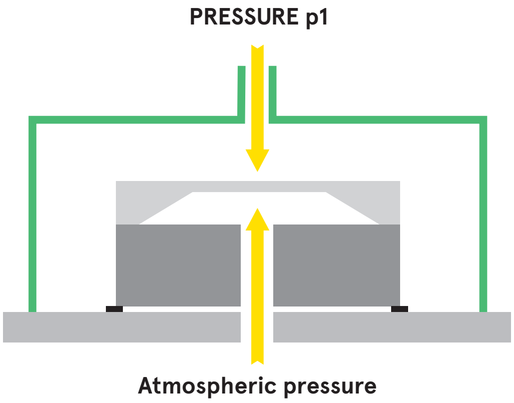
Different applications require different ways of measuring things. In electronic systems, as an example, sometimes we want to know the voltage across a specific component. Other times we're only interested in the difference in voltage between two points in the circuit.

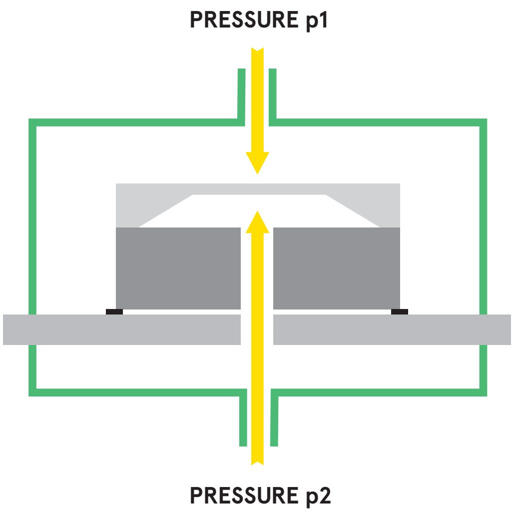
It's a similar situation when we're measuring the pressure of liquids and gases. And for each situation there's a pressure sensing method that best matches the application.

An absolute pressure sensor provides a pressure measurement relative to a reference of zero pressure. This reference pressure is as close as possible to a vacuum (as shown in the diagram above). This can be compared to measuring temperature in Kelvin, a measurement unit that uses the coldest possible temperature, 0°K, as its reference point. A pressure measurement of 1 bar will be the same, regardless of where in the world, or at what altitude, it's measured.

Gauge pressure sensors provide a pressure measurement relative to the local atmospheric pressure. This is comparable to measuring a DC voltage with a voltmeter, where the voltage at the red probe is either positive or negative with respect to the point to which the black probe is connected.





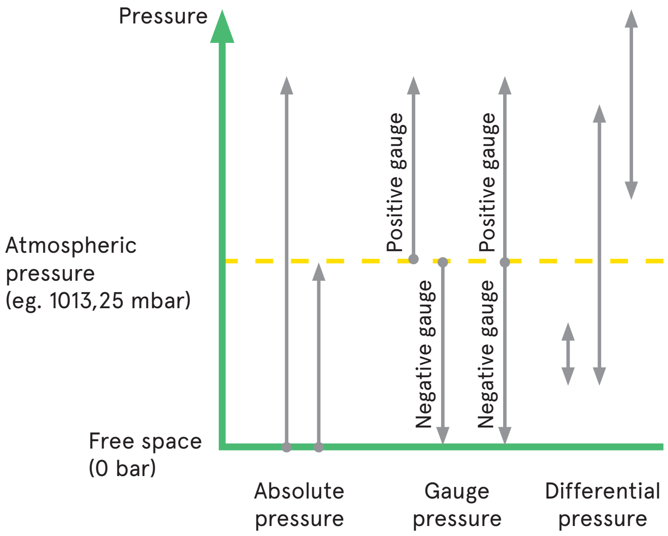


▶ From top to bottom, an absolute, gauge and differential pressure sensor

Types of pressure measurement

If the gauge pressure sensor measures a pressure of 1 bar in a vessel, this is 1 bar more than the atmospheric pressure. A 1 bar reading at high altitude (where air pressure is lower) would mean the pressure in the vessel has a lower absolute pressure than a 1 bar reading at sea-level.

Finally, differential pressure sensors measure the difference in pressure between two points in a system. Typically, this is because this difference can be used to measure the flow of a liquid or a gas in pipes or ducts. Alternatively, it may simply be used to detect a blockage or seized valve. If the pressure before a valve is higher than after it (in the direction of flow), there must be something impeding the progress of the media between the two measurement points.



▲ Graph showing how the measurement methods of the three pressure sensor types compare with one another

How do I know which pressure sensor to use?

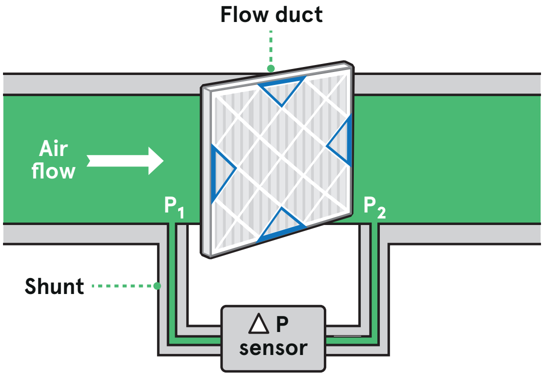
In order to select the appropriate pressure sensor for an application, you'll need to consider the purpose of the measurement you're making.

If the measurement should not be influenced by local atmospheric pressure changes, you most probably need an absolute pressure sensor. When the application is using air pressure to determine elevation, such as in an altimeter, an absolute pressure sensor is needed. These sensors are also used in weather stations to measure atmospheric pressure changes.

Sometimes only a small pressure or partial vacuum is all that's required. This is often the case in medical applications, where partial vacuums are used to remove fluid from wounds. In such situations, the amount of vacuum or pressure needs to be generated with reference to the local atmospheric pressure. This is where the gauge pressure sensor would find a home.

Gauge pressure sensors are also used in industrial applications to determine the fill level of open tanks. The level of liquid can be calculated using the hydrostatic method, which leverages knowledge of the liquid's specific gravity.

If the exact pressure measurement is of less importance, and you only need to determine the pressure difference between two points in the system, a differential pressure sensor is required. Many systems, such as HVAC, employ filters to clean the air passing through their ducts. You could use a differential pressure sensor here to determine whether or not the filter needs replacement. The sensor would measure the air pressure both before and after the filter. Once the pressure difference rises above a predefined threshold, it is time to replace the filter (see diagram below).



▲ By providing a pressure difference measurement, a differential pressure sensor can detect when an air filter needs replacement

Types of pressure measurement

Do absolute, gauge and differential pressure sensors measure pressure differently?

The sensing element of a pressure sensor, the part that turns the pressure into an electrical value, is independent of the type of pressure sensor and its sensing method.

Environmental conditions where the sensor will be used and the media being measured will influence which sensing element should be used. This will have been considered by the pressure sensor manufacturer during the sensor's development.

When you research board-level pressure sensors for example, you'll most likely find there's a single datasheet covering all three sensors. The absolute, gauge and differential sensors share the same type of element and are simply provided in packages that differ in the number of ports provided for attaching hoses and pipes.

Are absolute, gauge and differential pressure sensors connected to my circuit differently?

As with the sensor technology discussed above, the sensing method won't determine how the pressure measurement is presented to the circuit or system.

Pressure sensors can be broadly split into devices that are board-level, and those that are industrialised.

Board-level sensors are typically designed to connect to other electronic circuitry, commonly in association with a microcontroller that's capable of evaluating its output. Such sensors range from the simple, requiring signal conditioning and amplification, through to the intelligent, which combine signal conditioning and deliver the measurement via a digital output. Most digital output pressure sensors support I2C and SPI.

Industrial pressure sensors are designed to be integrated into industrial automation systems. Such systems utilise a programmable logic controller (PLC). These are designed to support the various analogue and digital interfaces supported today.

On the analogue side, outputs range from a voltage signal to 4 – 20 mA current loops. The system will need to be programmed to understand how the pressure measured relates to the voltage or current the PLC sees.

On the digital side, there are a wide range of bus networks available. These include CANopen, IO-Link, Fieldbus and PROFIBUS. With such sensors, the PLC receives the pressure measurement encapsulated in a packet of data.

The following sections go deeper on the individual measurement types, and design considerations for each:

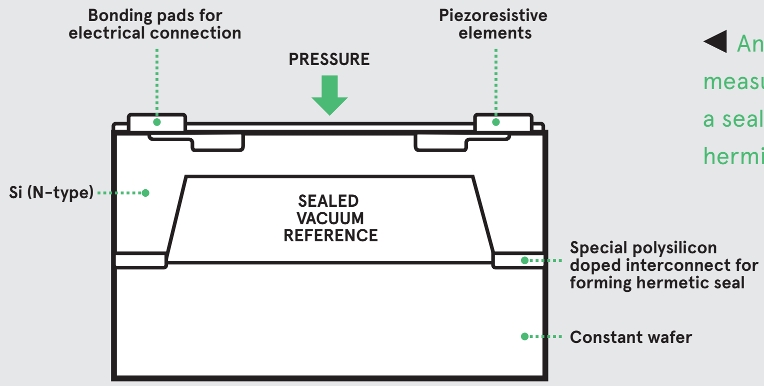
What are absolute pressure sensors?

With a wide variety of pressure sensors available, it can be challenging to know which one is best suited to a specific task. When it comes to measuring air pressure, specifically for applications such as barometric measurements for weather or in altimeters, an absolute pressure sensor is the device of choice. However, your possible application usage isn't limited just to air or gas.

The absolute measurement is made possible by measuring the target pressure relative to the known pressure of an absolute vacuum (see diagram below). This can be compared with measuring temperature in Kelvin, where the lowest possible temperature is 0 °K.

By using a vacuum as the reference against which everything is measured, all measurements will deliver a value larger than the absolute minimum as defined by the reference. This is essential to accurate measurement, since Boyle's Law states that the pressure of a gas is inversely proportional to its volume at a constant temperature. Thus, anything other than a perfect vacuum will result in an absolute pressure sensor whose measurement varies with temperature.

Cross sectional view of an intergrated circuit sensor element



◀ An absolute pressure sensor measures pressure relative to a sealed vacuum reference in a hermitically sealed chamber

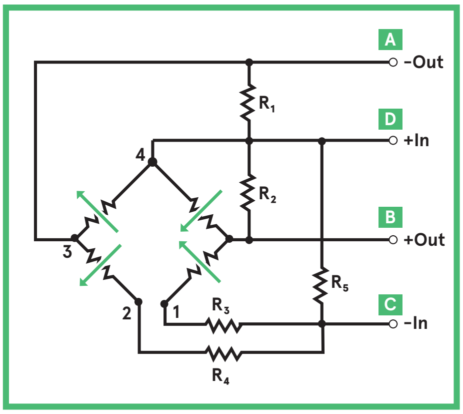
A perfect vacuum is, however, highly challenging to achieve, especially if the sensor is to remain within an acceptable price range. Thus, absolute sensors typically have to make do with an approximate vacuum, typically in the range of 35 microbar (0.0005 PSI).

How do absolute pressure sensors work?

With a sealed vessel as the reference point, a sensing technology is then applied to the surface of the vessel whose electrical characteristic varies with changes in strain. There are many different approaches to this.

One common method is the piezoresistive strain gauge. These embed a resistor, (whose value changes with respect to mechanical strain) into a material such as silicon, polysilicon, metal foil, or as sputtered metal onto a thin film. In order to maximise the output signal and reduce errors, the sensor typically uses four resistors in the Wheatstone bridge configuration.

With today's high levels of integration, it is not uncommon for your piezoresistive sensor to also include compensation circuitry, such as resistors, all on a single substrate (see below).



▲ Wheatstone bridge structure of an absolute pressure sensor

What are absolute pressure sensors?

Other sensing technologies also make use of a component's value variation when deformed. For example, capacitors vary in capacitance when placed under strain. Sometimes a change in an inductor's inductance can be caused by a locally placed diaphragm that moves in reaction to pressure changes.

The piezoelectric effect is also a common pressure measuring technology. This makes use of the fact that some materials, such as quartz, generate a voltage dependent on applied pressure.

As a result of the massive advances in silicon manufacturing technology in recent years, some mechanical elements are being machined into silicon chips known as microelectromechanical systems or MEMS devices.

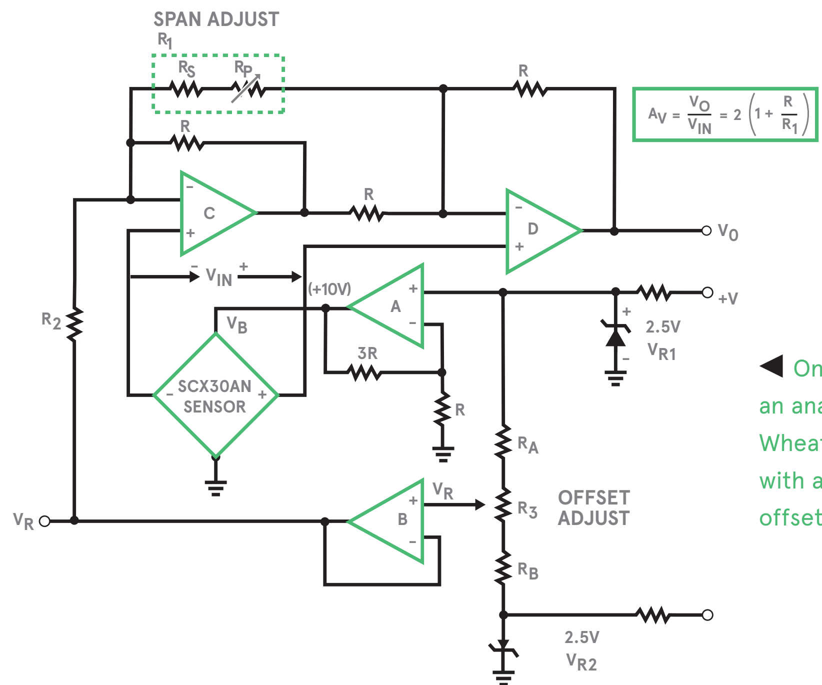
They mostly utilise the same physical properties of the electronic components already mentioned, but leverage some moving parts machined into the semiconductor material. Such devices rarely provide the sensing element's output signal; instead they precondition the signal electronically before outputting it via a package pin.

How do I integrate an absolute pressure sensor into my circuit?

With so many different pressure sensing technologies available, there is no single way to integrate a sensor into your circuit. In most cases, you will be looking to connect your absolute pressure sensor to a microcontroller.

Some sensors are so simple they require a significant amount of circuitry to condition the signal for use with a microcontroller. A sensor that simply provides access to a Wheatstone bridge circuit will require significant amplification to deliver an output large enough for a typical microcontroller's analogue-to-digital converter (ADC) to measure.

A quad op-amp configuration as shown in the diagram below provides an example for such an amplification circuit. Such circuitry needs to be carefully designed and may also require proper screening and low-noise design techniques to guarantee a reliable output signal.



◀ One method to generate an analogue output from a Wheatstone bridge sensor, with adjustments for both offset and span

What are absolute pressure sensors?

Due to process variation and component tolerances, your circuit may also need individual calibration for each circuit board you produce. Temperature compensation may also need to be considered.

Sensors with digital outputs are much easier to connect to a microcontroller. These will include all the signal conditioning, amplification and temperature compensation. The measurements are then converted into a digital value and stored in an internal register.

The interfaces offered to the microcontroller are typically I2C or SPI. Some sensors may support both, allowing you to select between the one that suits your application best. This is the case with the example shown below.

A sensor with a digital interface may not meet your needs if you need to measure rapid variations in pressure. An SPI or I2C interface only supports a certain number of data transfers per second. With more than one device on the bus, the available bandwidth drops with the increase of devices hanging on the bus.

For measurement of pressure that varies quickly, it is likely that you will need to invest time in the development of your own analogue front-end, coupled with an ADC with a suitable conversion time.

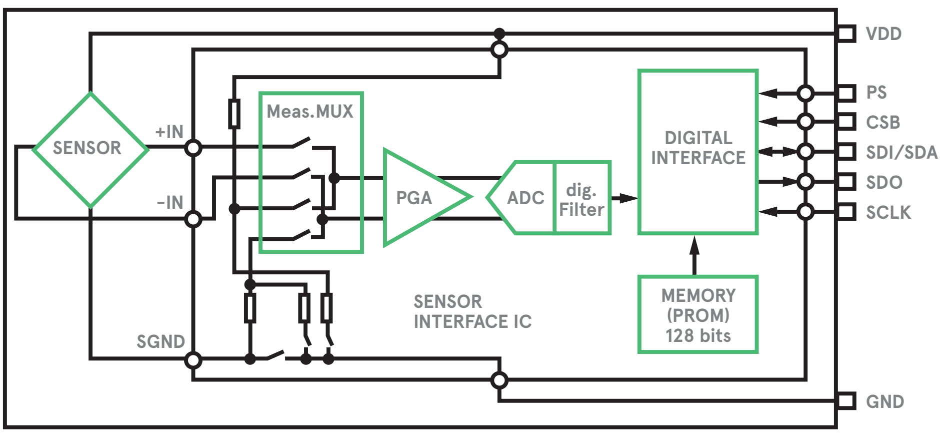
Can I use an absolute pressure sensor in my design?

Many absolute pressure sensors are provided in a small housing suitable for fixing through-hole or surface-mount to a printed circuit board (PCB). These are known as board level sensors. This makes them ideal for a consumer application where sensing can be undertaken on the PCB, e.g. in an altimeter or sports watch.

However, such sensors are not suited to the high temperature of liquids or gases. Neither are they suitably protected against dust, moisture or the chemicals often used for cleaning in industrial environments.

Industrial sensors are typically robustly packaged. They are likely to be made of a non-corroding material, such as stainless steel, and are threaded, allowing them to be fitted to pipes and storage tanks.

Industrial engineers typically want to select their hardware and link it all together. They are not so interested in building custom circuitry to handle the sensor output. As a result, industrial sensors are grouped into three main types: sensors, transducers, and transmitters. We touch on these briefly on the following page, but for more information on these sensor types read chapter 4.



◀ The integrated circuitry inside the sensor can perform amplification, conditioning and digitisation of the sensor measurement

What are absolute pressure sensors?

The term ‘sensor’ typically indicates a device that generates a ratiometric output. This means that your sensor’s output will be dependent on the sensor’s supply voltage. Thus, a sensor with a 10mV/V output will generate a 0 – 50 mV output for a 5.0 VDC supply. Such devices can be quite raw in their packaging, with pads or legs suitable for soldering to a circuit board or cabling.

A ‘transducer’ is a complete sensor, including signal conditioning, designed for you to fit directly into an industrial environment. Your output signal will typically be a voltage that relates to pressure, generally lying in the 0 – 10V range. However, some transducers generate an alternating signal in the 1 – 6 kHz range.

Some older transducers do not have a “live zero” when the sensor is at its lowest measuring point. This makes it impossible for you to determine the difference between a minimum pressure measurement and a broken sensor or connecting cable. This is something to be considered for systems with a high-level safety requirement.

A pressure ‘transmitter’ typically indicates a sensor that uses a 4 – 20 mA output signal rather than a voltage output. These devices often only require a two-wire interface (supply and ground), and offer good electrical noise immunity (EMI/RFI). Supply voltage for such sensors lies in the range of 8 – 24 VDC.

Such sensors are designed for use with other industrial equipment, such as a programmable logic controller (PLC). These then communicate via digital buses with one another and other industrial systems. Buses include Fieldbus, standardised as IEC 61158, IO-Link, PROFIBUS and CANopen. With more intelligence being built into industrial sensors, it is becoming increasingly common to find that they are ready to be directly attached to such industrial networks.

What applications are absolute pressure sensors used in?

With the rise in smart watches and navigation systems, absolute pressure sensors find homes wherever elevation above sea level (altimeter measurement) is required. Weather stations also use them for barometric pressure measurements.

Petrol and diesel vehicles make use of them too, measuring the pressure in the engine manifold. Such sensors are known as manifold absolute pressure sensors, or MAP sensors for short. The engine’s electronic control unit (ECU) uses this information to determine optimal combustion of the air-fuel mix and ignition timing.

In industrial applications, it is often necessary to develop a partial vacuum. This is the case in food packing, where the residual pressure determines the shelf life of the produce. The absolute pressure sensor can ensure that the pressure in each package is the same.

At the other extreme, industrial absolute pressure sensors are available that support measurements of more than 300 bar (4400 PSI).

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What are gauge pressure sensors?

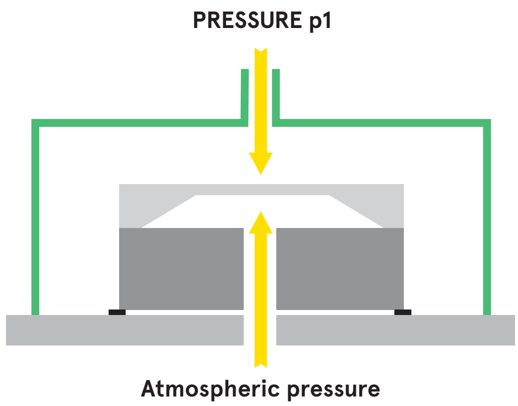
In some applications the exact pressure or vacuum being generated is not of key importance. Instead, you just want to understand how much the pressure or vacuum differs in comparison to atmospheric pressure.

Atmospheric pressure varies across the globe depending on our altitude and even changes in the weather.

Consider, as an example, the vacuum pumps used during or after surgery. These are used to remove bodily fluids, gases and even tissue. Typically, only a small, finely controlled vacuum is required in order to avoid injury. This needs to be set in relation to the local atmospheric pressure. In a hospital at sea level, the atmospheric pressure will be higher than at a hospital high in the mountains.

A gauge pressure sensor measures the pressure at its port with respect to the local atmospheric pressure. This can be compared to using a multimeter's DC measurement range, where the display shows the voltage at the positive probe with respect to the negative probe.

Gauge pressure sensors are typically packaged with a port, to which a pipe can be attached, as well as a vent that is open to the atmosphere. The pipe can then be connected to the system where the measurement is to be made.



▲ A gauge pressure sensor measures pressure relative to the local atmospheric pressure

When positioning the sensor in your application, it is important that the vent is open to the atmosphere. This may require a hole in your printed circuit board and even the housing of your product.

How does a gauge pressure sensor work?

There are a variety of strategies for measuring the pressure in a gauge sensor. Most of them use a membrane that is fitted with an electrical component, such as a resistor, whose value varies when flexed.

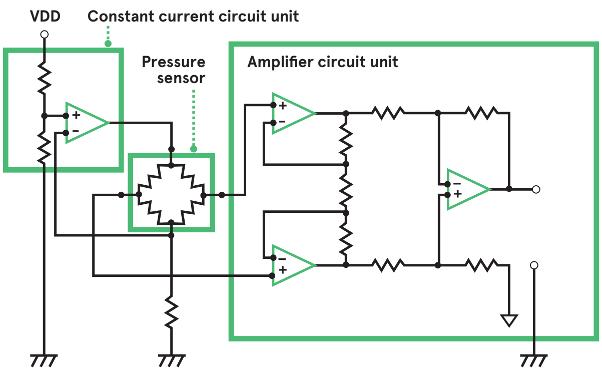
Nowadays, microelectromechanical systems, commonly known as MEMS, are utilised. Small and light structures are etched into silicon that can flex or vibrate. Since the base medium is silicon, further electronic circuitry can be integrated alongside the MEMS element.

The short electrical paths help to ensure low noise and high measurement accuracy, whilst the MEMS element can result in a sensor that is better isolated from temperature changes.

What are gauge pressure sensors?

In all likelihood, your chosen commercial gauge sensor will probably be a piezoresistive type. Such sensors are constructed as a Wheatstone bridge (see diagram below) and require some analogue circuitry to amplify the signal for use with a microcontroller or other systems.

This can also include compensation for temperature and a calibration adjustment. A constant current circuit is used to power the bridge.



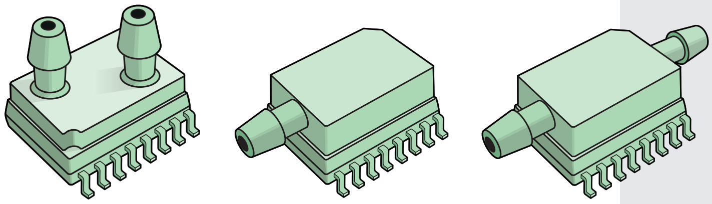
▲ A piezoresistive Wheatstone bridge circuit with amplifier, powered by a constant current circuit

How do I integrate a gauge pressure sensor into my circuit?

With such a broad array of gauge pressure sensors available, it can be difficult to know where to start.

If you're intending to interface your sensor with a microcontroller, you may find that a board-mounted sensor is the best option. Gauge pressure sensors tend to provide an analogue output, although some suppliers provide devices with digital interfaces.

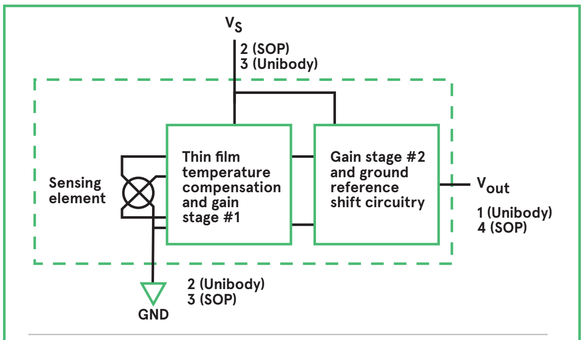
Board mounted sensors come in a variety of packages, often with a short section of barbed manifold (see examples above right) allowing the sensor to be connected by tube to the system to be measured.



▲ A range of gauge pressure sensors with barbed manifolds

Many analogue sensors integrate the amplifier, temperature compensation and support for calibrating the device (see image below). This leaves an output signal in the range of 0 – 5 VDC which is suitable to connect to the analogue-to-digital converter of a microcontroller.

One thing to watch is the quality of the power supply, as many sensors are ratiometric. This means that the output signal varies with the input supply to the sensor.



Pins 1 and 5 through to 8 are NO CONNECTS for small outline package
Pins 4, 5 and 6 are NO CONNECTS for unibody package

▲ Some analogue sensors provide a considerable amount of analogue circuitry around the sensing element

What are gauge pressure sensors?

When developing firmware to read the pressure provided, note should also be taken of the warm-up time of the sensor. After initial power on, it may take several milliseconds before the output can be relied upon.

If the sensor is part of a control loop, the response time for the sensor should also be reviewed. Gauge pressure sensors' response times are often specified by the time taken for the output to change from 10% to 90% for a step change in pressure.

Sensors with a digital output tend to support the I2C or SPI protocol. However, there are exceptions. Some sensors use the single wire bi-directional ZACwire™ communication protocol (See diagram below). This is typically not native to microcontrollers, so supporting this interface in firmware will require some significant programming effort, as well as demanding a lot of processing time.

If you're developing a low-power application, you will probably want to stick with protocols natively supported by the microcontroller's peripherals.

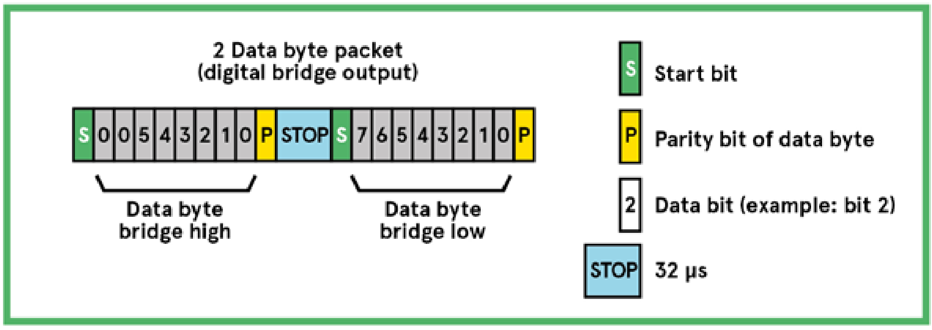
Can I use an industrial gauge pressure sensor in my design?

Board level sensors are ideal for integrating onto a PCB, but they're typically limited in the temperature range they support. You will also find that they're not suited for monitoring most liquids and chemicals.

Industrial gauge sensors are an ideal alternative. They're typically housed in a robust metal case, making them suitable for use in damp and corrosive environments. They also feature a screw thread, allowing them to be fixed to tanks and pipes with ease.

However, one of the challenges you may face is interfacing them to your system, especially a microcontroller.

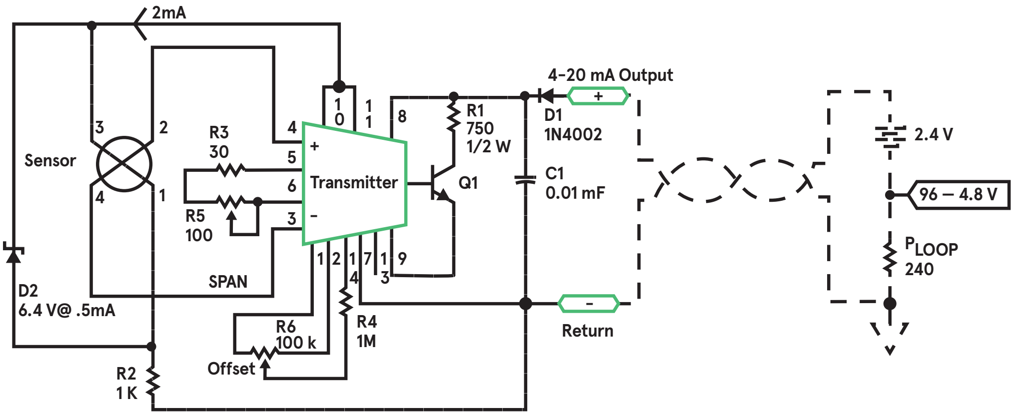
Industrial complexes are often required to fulfil high levels of safety to protect their workers from the high pressures, corrosive liquids and dangerous equipment in their environment. Industrial gauge sensors are therefore designed with interfaces that are intended to guarantee that the measurements they deliver are always reliable.



▲ Some manufacturers offer the single-wire ZACwire™ protocol on their gauge sensors, although this is uncommon in microcontrollers

What are gauge pressure sensors?

Many 'transmitter' type sensors encode their output as an analogue signal in the form of a current between 4 and 20 mA. This can be in the form of a two-wire interface that doubles as the power supply to the sensor. This would need to be replicated in your circuitry as shown in the diagram below.



▲ An example circuit showing how a gauge sensor transmitter may be implemented

Some industrial sensors have now gone digital, utilising protocols such as Fieldbus, standardised as IEC 61158, IO-Link, PROFIBUS and CANopen. Some of the electrical interfaces and associated signalling are compatible with microcontrollers, such as CANopen. All that is required is the matching software stack. Others, such as IO-Link and PROFIBUS, may require specialised microcontrollers or external circuitry to implement the interface.

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What applications are gauge pressure sensors used in?

If the pressure measurement you intend to take needs to be relative to the local atmospheric pressure, you will need to use a gauge pressure sensor. For example, the level of a liquid in an open tank will change with variation in atmospheric pressure. A gauge pressure sensor allows this to be measured and compensates for those atmospheric pressure changes.

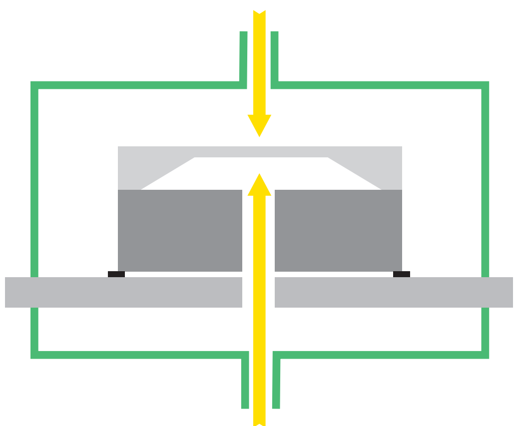
Medical applications also make regular use of gauge pressure sensors, for fluid extraction from wounds, in hyperbaric chambers, and ex-vivo blood pressure measurements. In such situations, the pressure, or vacuum, to be developed is often small, and requires fine control in order to avoid harm to the patient.

What are gauge differential sensors?

Sometimes it's not necessary to know the absolute pressure of a liquid or a gas. Instead, only the difference between two points in the system being monitored need be known. In such situations, you can turn to differential pressure sensors.

The differential pressure sensor will give you a comparative measurement between two points (see diagam below). One example may be before and after a valve in a pipe. If the valve is fully open, the pressure on both sides should be the same. If there's a difference in the pressure, it could be the valve isn't fully open or there's a blockage.

Differential pressure sensors are typically packaged with two ports to which pipes can be attached. The pipes are then connected to the system where the measurement is to be made. Industrial differential sensors may be integrated into a standardised fitting, allowing it to be built into existing pipework.



▲ A differential pressure sensor measures the difference in pressure at its two ports

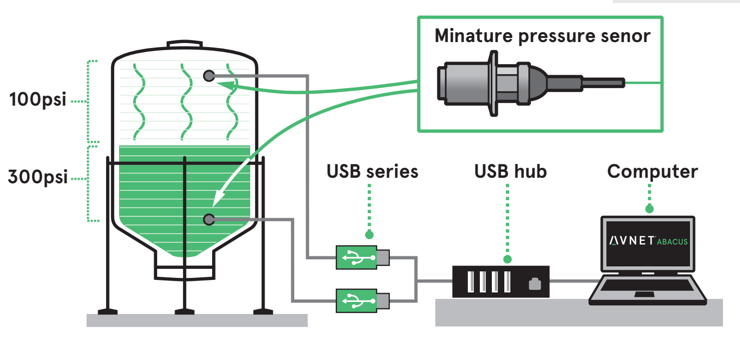
The measurements made are fully independent of atmospheric pressure, unlike gauge sensors.

How does a differential pressure sensor sense pressure?

Typically, the two pressures to be measured are applied to opposite sides of a single diaphragm. The deflection of the diaphragm, either positive or negative with respect to the resting state, determines the difference in pressure.

Some industrial differential sensors actually use two separate absolute sensors, utilising internal electronics to calculate and provide the difference in pressure to the control system.

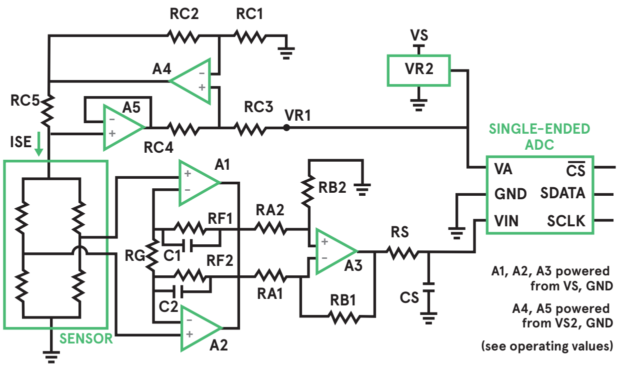
This may be the case in situations where two different types of sensors are required due to the medium being measured, such as a liquid and a gas, or the environment of the measurement (see below).



▲ If required, a differential pressure measurement can be made using two absolute pressure sensors and software on the control system

What are differential sensors?

Many of the board-level sensors available utilise piezoresistive sensing elements. The simplest of these use a Wheatstone bridge configuration which requires a signal conditioning circuit to amplify its output (see below).



▲ An example circuit for amplifying the signal from a Wheatstone bridge piezoresistive pressure sensor.

Circuits like the above diagram apply a constant current to the bridge. The output signal is then amplified and applied to the input of the measurement system. If your application is based upon a microcontroller, the signal could be connected to an ADC input pin. Otherwise, there are many standalone ADCs with digital outputs that could be sourced as an alternative.

The analogue front end (AFE) may also need to allow provision for offset voltage, temperature compensation, and span.

If you're looking for a simpler solution, many manufacturers provide fully integrated differential sensors. For example, some may include temperature compensation circuitry together with two stages of amplification, enabling it to be simply connected to the ADC input of a microcontroller.

How do I integrate a differential pressure sensor into my circuit?

If you're developing a microcontroller-based differential pressure measurement system there are a wide range of board-mounting sensors available to choose from. As we've already seen, some provide a conditioned and amplified analogue output that can be applied to an ADC input.

Others digitise the signal inside the sensor, allowing them to be connected to a digital serial interface such as I2C or ZACwire™.

I2C is a relatively well-known interfacing technology and is even available on some of the smallest 8-bit microcontrollers. Requiring just two wires, one is used for a clock while the second is a bi-directional data line.

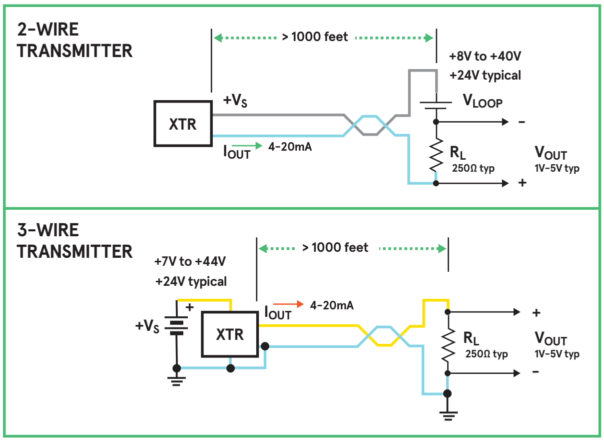
Since I2C supports multiple nodes, it's also important to consider the overall bandwidth of the bus. As more devices are added to the bus, the risk that the pressure sensor cannot be accessed as often as desired increases. Another important consideration is the dimensioning of the pull-up resistors on the bus. The official specification for I2C provides a proper explanation of how to calculate the necessary values.

What are gauge differential sensors?

Can I use an industrial differential pressure sensor in my design?

There's an obvious attraction to using an industrial pressure sensor over board-level devices. They're robustly built, housed mostly in a steel casing, and feature a threaded fitting, making them easy to fit to pipes and tanks. Industrial pressure sensors are primarily designed for integration into manufacturing environments, linked to a programmable logic controller (PLC).

Because industrial sensors are used in systems that require high levels of functional safety and robustness, the interfaces they offer can seem a little unusual. Most analogue output sensors provide a voltage output with a wide range (0 – 20 V) or provide their output as a current in the range of 4 – 20 mA. The goal behind such sensor interfaces is to minimise sensitivity to background noise over the long cable lengths employed. Some examples of transmitter type gauge sensor circuitry are shown below.



▲ Example circuits showing how a gauge sensor transmitter may be implemented

Like in other business sectors, industrial sensors are also moving to digital interfaces. This has the advantage that several sensors can all be connected to the same wiring loop, saving on cabling complexity. Some of these interfaces, such as CANopen, can be connected to a microcontroller relatively easily. As long as a CAN interface is available, all that's needed is a compliant CAN transceiver on the hardware side. In order to implement your software, youlll find a range of software stacks from various embedded software vendors.

What applications are differential pressure sensors used in?

Differential pressure sensors often find a home in industrial environments where a difference in pressure can be used to determine the flow of gases or liquids. This can include effluent treatment plants, offshore and subsea gas and oil processing, and remote heating systems utilising heated water or steam.

They also find their way into the sprinkler systems installed for fire protection.

If it's necessary to measure the volume of liquid in a closed vessel, a differential pressure transmitter can also be used. As long as the density of the fluid does not change with temperature variation, the height of the column of liquid can be determined from the pressure, liquid density and gravity.

In the medical field, differential pressure sensors are used for treatment of deep vein thrombosis, infusion pumps, and respirator and breathing detection equipment.

Core pressure sensor technologies

Electronic pressure sensors measure a physical reaction to applied pressure by converting the resulting proportional change into an electronic signal. Commonly used phenomena include changes in capacitance, or changes in ohmic resistance of a strain gauge or piezoelectric element, which are proportional to the magnitude of the deflection when pressure is applied.

The sensing principle used can influence accuracy, reliability, measurement range, and compatibility with the target environment. In this section of the guide we'll look at some of the key technologies available to engineers, how they work and the advantages and disadvantages of each type.

Capacitive vs piezoresistive vs piezoelectric pressure sensors

The first pressure gauges were purely mechanical. They used mechanisms such as a diaphragm or a "Bourdon tube" that changed shape under pressure to move a pointer on a dial.

Various techniques have since been developed to convert mechanical displacements into electrical signals. Here we'll consider the relative advantages of piezoresistive, capacitive and piezoelectric pressure sensors.

PRINCIPLES OF OPERATION

In a piezoresistive strain gauge sensor, the change in electrical resistance of one or more resistors mounted on a diaphragm is measured. The change in resistance is directly proportional to the strain caused by pressure on the diaphragm. The resistors are connected in a Wheatstone bridge circuit, which is a very sensitive way of converting the small changes to an output voltage.

Capacitive pressure sensors measure changes in electrical capacitance caused by the movement of a diaphragm. A capacitor consists of two parallel conducting plates separated by a small gap. One of the plates acts as the diaphragm that is displaced by the pressure, changing the capacitance of the circuit. The resulting change of resonant frequency of a circuit can be measured. Or, in a digital system, the time taken to charge and discharge the capacitor can be converted to a series of pulses.

Piezoelectric sensors use materials, such as quartz crystals or specially formulated ceramics, which generate a charge across the faces when pressure is applied. A charge amplifier converts this to an output voltage proportional to the pressure. A given force results in a corresponding charge across the sensing element. However, this charge will leak away over time meaning that the sensor cannot be used to measure static pressure.

All three types of sensors can be miniaturised using silicon fabrication techniques and combined with electronics as microelectromechanical systems (MEMS). This allows very small sensing elements to be constructed and combined with the electronics for signal conditioning and readout.

Piezoresistive and capacitive pressure sensors can be used for absolute, gauge, relative or differential measurements.

Piezoelectric sensors are sensitive to changes in pressure so the output is usually treated as a relative pressure measurement, referenced to the initial state of the piezoelectric material.

ADVANTAGES AND DISADVANTAGES OF THE THREE SENSOR TYPES

Piezoresistive strain gauge sensors

These are the earliest and most widely used type of pressure sensor.

The simple construction means low cost and durability. The sensors are robust with good resistance to shock, vibration, and dynamic pressure changes.

The readout circuits are very simple and enable high-resolution measurement.

The output is linear with pressure and the response time is typically below one millisecond.

They can be used for a wide range of pressure measurements from 3 psi up to about 20,000 psi (21 kPa to 150 MPa). The output is also stable over time.

The resistive elements can be bonded to the diaphragm. This is a standard technique that has been in use for a long time but there can be problems with the adhesives at high temperatures and overpressure.

Capacitive vs piezoresistive vs piezoelectric pressure sensors

Alternatively, thin film resistors can be created directly on the membrane. These can operate at higher temperatures and are more suitable for use in harsh environments.

The main disadvantage is that the sensor has to be powered. This makes them unsuitable for low power or battery operated systems. Scaling down the size reduces the resistance and increases the power consumption.

There are also limitations on scaling because strain averaging reduces the sensitivity of the sensor. However, very small sensors can be fabricated as MEMS devices.

The sensor output is temperature dependent. This can be a big disadvantage for applications such as tyre pressure measurement where there are large temperature changes over the operating cycle.

Silicon strain gauges are much more sensitive and can measure pressures down to 2 kPa.

The accuracy of MEMS devices can be reduced by junction leakage current. This can be mitigated by using silicon on insulator (SOI) technology, but this adds to the cost.

Capacitive sensors

The capacitive element is mechanically simple and robust.

Capacitive sensors are able to operate over a wide temperature range and are very tolerant of short-term overpressure conditions.

They can be used to measure a wide range of pressure from vacuum (2.5 mbar or 250 Pa) to high pressures up to around 10,000 psi (70 MPa). They're ideal for both lower-pressure applications and reasonably harsh environments.

Because no DC current flows through the capacitor, they are inherently low power.

Passive devices may not require a power source at all; the excitation signal can be provided by the external reader. This makes them suitable for wearable or implanted medical devices. These applications can be enhanced by new technologies that enable the construction of sensors that are flexible or moulded to shape.

Capacitive sensors exhibit low hysteresis and good repeatability of measurements. They also have low temperature sensitivity.

The response time is in the order of milliseconds, and even faster in the case of MEMS devices.

Because they're inherently AC devices, capacitive sensors are suitable for wireless applications. They can be used in an oscillator circuit to generate a signal, with a frequency proportional to pressure, that can be received wirelessly.

Alternatively, the reader can use inductive coupling to measure the change in resonant frequency – this is particularly suitable for passive devices that require no power supply.

One of the main disadvantages of capacitive sensors is the non-linearity exhibited because the output is inversely proportional to the gap between the parallel electrodes. This can be improved by using the sensor in touch mode, where the diaphragm is in contact with the insulating layer on the lower electrode. However, this can reduce sensitivity and increase hysteresis. They are also sensitive to vibration.

The interface needs to minimise stray capacitance by having the electronics as close as possible to the sensor. This is another benefit of MEMS technology.

Capacitive vs piezoresistive vs piezoelectric pressure sensors

Piezoelectric sensors

The main advantages of piezoelectric sensors are robustness and low power requirements.

The sensing elements are made of rigid materials, which can be natural crystals such as quartz or specially formulated ceramics. These require only a very small deformation to generate an output, so there are effectively no moving parts.

This means the sensors are extremely robust and suitable for use in a range of very harsh environments. They can also tolerate very high temperatures; some materials can be used at up 1,000ºC.

This makes piezoelectric sensors suitable for applications such as measuring pressures in jet engines.

The sensor elements are self-powered so they're intrinsically low-power devices. It also means they're insensitive to electromagnetic interference.

However, designing the electronic interface is more complex than the other sensor types. A charge amplifier is required to convert the very high impedance charge output to a voltage signal. This needs to be located close to the sensing element.

Some sensors include integrated electronics, which simplifies the use of the sensor but reduces the operating temperature range.

With ceramic materials, a usable output can be obtained with very small displacements. This means they can be used for measuring a very wide range of pressures, between 0.1 psi and 10,000 psi (0.7 kPa to 70 MPa), with very high accuracy.

The piezoelectric elements can be very small with an extremely fast response to changes in pressure. Some devices can measure rise times in the order of 1 millionth of a second. As a result, piezoelectric sensors are used for measuring pressure changes in explosions.

The sensors are simple to construct and can be made from inexpensive materials.

The main limitation of piezoelectric sensors is that they can only be used for dynamic pressure measurement.

The sensors are sensitive to vibration or acceleration, which may be common in the applications where they are used. This can be minimised by using an extra "compensation" sensor attached to a dummy mass. The output from this is used to correct for acceleration experienced by the sensor.

Overall, these three sensor types are robust and low cost. They function over a wide range of pressures and temperatures so there are suitable sensors available for almost every application.

For more on each sensor technology refer to chapters 6.2, 6.3 and 6.4 respectively.

Piezoresistive strain gauge pressure sensors

Piezoresistive strain gauges are among the most common types of pressure sensors. They use the change in electrical resistance of a material when stretched to measure the pressure.

These sensors are suitable for a variety of applications because of their simplicity and robustness. They can be used for absolute, gauge, relative and differential pressure measurement, in both high- and low-pressure applications.

In this article we'll discuss the various types of piezoresistive pressure sensors available, how they work, and their relative merits.

WORKING PRINCIPLE

The basic principle of the piezoresistive pressure sensor is to use a strain gauge made from a conductive material that changes its electrical resistance when it is stretched. The strain gauge can be attached to a diaphragm that recognises a change in resistance when the sensor element is deformed. The change in resistance is converted to an output signal

There are three separate effects that contribute to the change in resistance of a conductor. These are:

- The resistance of a conductor is proportional to its length so stretching increases the resistance
- As the conductor is stretched, its cross-sectional area is reduced, which also increases the resistance
- The inherent resistivity of some materials increases when it is stretched

The last of these, the piezoresistive effect, varies greatly between materials. The sensitivity is specified by the gauge factor, which is defined as the relative resistance change divided by the strain:

$$GF = \frac{\left(\frac{\Delta R}{R}\right)}{\epsilon}$$

Where strain is defined as the relative change in length:

$$\epsilon = \frac{\Delta L}{L}$$

PRESSURE SENSING ELEMENTS

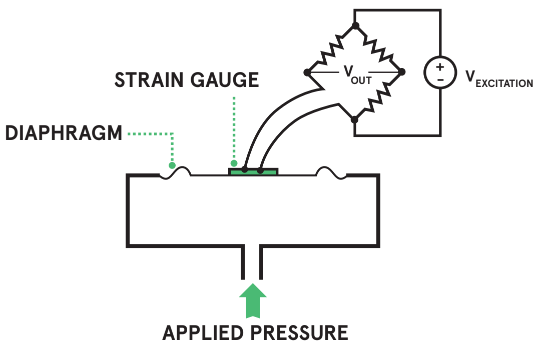
Strain gauge elements can be made of metal or a semiconducting material.

The resistance change in metal strain gauges is mainly due to the change in geometry (length and cross-section area) of the material. In some metals, for example platinum alloys, the piezoresistive effect can increase the sensitivity by a factor of two or more.

In semiconducting materials, the piezoresistive effect dominates, typically being orders of magnitude larger than the contribution from geometry.

FUNCTION

The change in resistance in the sensor is usually measured using a Wheatstone bridge circuit (as shown below). This allows small changes in the resistance of the sensor to be converted to an output voltage.



▲ Piezoresistive strain gauge measurements are made using a Wheatstone bridge circuit

Piezoresistive strain gauge pressure sensors

An excitation voltage needs to be provided to the bridge. When there is no strain and all the resistors in the bridge are balanced then the output will be zero volts. A change in pressure will cause a change in resistances in the bridge resulting in a corresponding output voltage or current.

This is calculated using the formula:

$$V_O = \left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right] \cdot V_{ex}$$

Performance can be improved by using two or four sensing elements in the bridge, with the elements in each pair being subject to equal and opposite strain. This increases the output signal and can minimise the effects of temperature on the sensor elements.

Construction metal sensing elements

One or more strain gauge sensors made from a length of wire can be attached to the surface of a diaphragm.

Pressure on the diaphragm will stretch the wires and change the resistance. The sensor elements can be bonded on to the surface with adhesive or the conductor can be directly deposited on the diaphragm by sputtering. The latter method removes potential problems with adhesives failing at high temperatures and also makes it easier to construct small devices.

A metal wire sensor can also be made by wrapping a wire between posts that are displaced by changing pressure. This construction can also work at higher temperatures because no adhesive is needed to attach the wire to the posts.

Construction semiconductor sensing elements

Semiconducting materials, most commonly silicon, can also be used to make strain gauge pressure sensors. The characteristics of the sensing element, particularly the size of the piezoresistive effect, can be adjusted by doping; in other words by adding carefully controlled amounts of impurities (dopants) to the semiconductor.

More lightly doped silicon results in a higher resistivity and a higher gauge factor. However, this also increases the thermal sensitivity of both the resistance and gauge factor.

FABRICATION PROCESS

Semiconductor sensors can be constructed in a similar way to metal wire sensors, by depositing the silicon strain gauge elements on to a diaphragm.

They can also be constructed directly on a silicon surface by using the same manufacturing methods used for making electronic semiconductor devices. This allows very small sensors to be manufactured cheaply with precisely controlled properties such as sensitivity, linearity and temperature response.

Electronic components can also be fabricated on the same silicon chip to provide signal conditioning and simplify the electrical interface. Sensors based on these microelectromechanical mechanical systems (MEMS) are described in more detail in chapter 6.5.

DESIGN

To ensure the highest accuracy, you'll need to consider several factors that could affect the output. Any variation or noise in the excitation voltage will cause a corresponding change in the sensor output. You will need to ensure that this is less than the required measurement accuracy.

You may need to provide an adjustable calibration resistor in the bridge circuit to set the output voltage to zero when there is no pressure.

You'll need to keep the resistance of the wires to the sensor small to avoid introducing an offset to the measurement and reducing sensitivity. Also, the temperature coefficient of the copper wires may be greater than that of the sensor, which can introduce undesirable thermal sensitivity.

Piezoresistive strain gauge pressure sensors

Longer wires are also more likely to pick up noise. This can be minimised by using twisted pairs and shielding.

Using a higher excitation voltage increases the sensor output and improves the signal to noise ratio. However, the higher current can cause heating of the sensing element, which will change the resistivity and sensitivity of the sensor.

This self-heating can also affect the adhesive bonding the strain gauge to the diaphragm, which can introduce errors and cause accuracy to degrade over time. The self-heating effects can be reduced by using a higher-resistance strain gauge.

The optimum supply voltage is a balance between minimising self-heating and obtaining a good signal. You can determine this experimentally. For example, with no pressure and the sensor output zero, you can increase the excitation voltage until the output is seen to change (because of self-heating). The excitation voltage should then be reduced until the output error disappears.

If possible, you should use an amplifier circuit close to the sensor to minimise connection lengths, boost the output signal and improve the signal-to-noise ratio. This can also do some filtering of the sensor output to remove external noise.

You can minimise the effects of any changes in the excitation voltage, such as a voltage drop caused by long wires, by monitoring the excitation voltage at the sensor and either subtracting that from the sensor output or using it as a reference voltage for the analogue to digital converter (ADC).

NEED SOME ADVICE?

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SPECIFICATIONS

Typical metal strain gauge sensors have a gauge factor of around 2 to 4. With a typical maximum strain of a few parts per thousand, this means a change in output of around 1mV for each volt of excitation.

Silicon-based sensors are usually doped to provide a gauge factor of around 100 to 200, which gives a good compromise between sensitivity and thermal characteristics. The output from a silicon sensor can be around 10 mV/V.

ADVANTAGES AND DISADVANTAGES

Piezoresistive strain gauge pressure sensors have the advantage of being robust. Their performance and calibration is also stable over time.

One disadvantage of these sensors is that they consume more power than some other types of pressure sensor. This may mean they are not suitable for battery powered or portable systems.

Metal film sensing elements have the advantage of simple construction and durability. They also have a higher maximum operating temperature (up to about 200°C) than silicon strain gauges, which are limited to below 100°C.

Silicon strain gauges provide a much larger output signal, making them well-suited to low-pressure applications, down to around 2 kPa.

MEMS pressure sensors can be made much smaller than metal wire sensors and can be integrated with electronics for signal processing, which can control for non-linearity and temperature dependence.

Capacitive pressure sensors

Capacitive pressure sensors measure pressure by detecting changes in electrical capacitance caused by the movement of a diaphragm.

WORKING PRINCIPLE

A capacitor consists of two parallel conducting plates separated by a small gap. The capacitance is defined by:

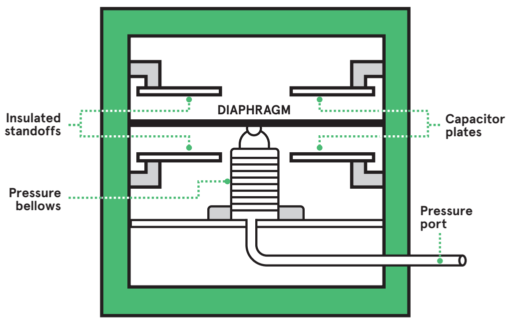
$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

where:

- ε_r is the dielectric constant of the material between the plates (this is 1 for a vacuum)
- ε_0 is the electric constant (equal to 8.854x1012 F/m),
- A is the area of the plates
- d is the distance between the plates

Changing any of the variables will cause a corresponding change in the capacitance. The easiest one to control is the spacing. This can be done by making one or both of the plates a diaphragm that is deflected by changes in pressure.

Typically, one electrode is a pressure sensitive diaphragm and the other is fixed. An example of a capacitive pressure sensor is shown below:



An easy way of measuring the change in capacitance is to make it part of a tuned circuit, typically consisting of the capacitive sensor plus an inductor. This can either change the frequency of an oscillator or the AC coupling of a resonant circuit.

CONSTRUCTION

The diaphragm can be constructed from a variety of materials, such as plastic, glass, silicon or ceramic, to suit different applications.

The capacitance of the sensor is typically around 50 to 100 pF, with the change being a few picofarads.

The stiffness and strength of the material can be chosen to provide a range of sensitivities and operating pressures. To get a large signal, the sensor may need to be fairly large, which can limit the frequency range of operation. However, smaller diaphragms are more sensitive and have a faster response time.

A large thin diaphragm may be sensitive to noise from vibration (after all, the same basic principle is used to make condenser microphones) particularly at low pressures.

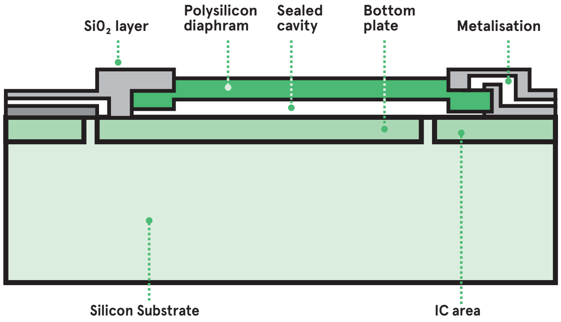
Thicker diaphragms are used in high-pressure sensors and to ensure mechanical strength. Sensors with full-scale pressure up to 5,000 psi can readily be constructed by controlling the diaphragm thickness.

By choosing materials for the capacitor plates that have a low coefficient of thermal expansion, it’s possible to make sensors with very low sensitivity to temperature change. The structure also needs to have low hysteresis to ensure accuracy and repeatability of measurements.

Because the diaphragm itself is the sensing element, there are no issues with extra components being bonded to the diaphragm, so capacitive sensors are able to operate at higher temperatures than some other types of sensor.

Capacitive pressure sensors

Capacitive pressure sensors can also be constructed directly on a silicon chip with the same fabrication techniques that are used in manufacturing semiconductor electronic devices (see diagram below). This allows very small sensing elements to be constructed and combined with the electronics for signal conditioning and reporting. Pressure sensors using microelectronic mechanical systems (MEMS) are described in more detail in chapter 6.5.



▲ A cross section of a capacitive MEMS sensor construction

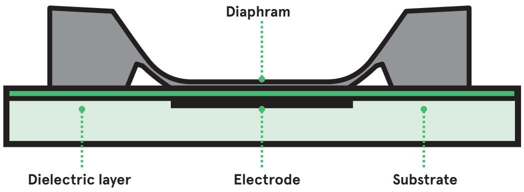
FUNCTION

The change in capacitance can be measured by connecting the sensor in a frequency-dependent circuit such as an oscillator or an LC tank circuit. In both cases, the resonant frequency of the circuit will change as the capacitance changes with pressure.

An oscillator requires some extra electronic components and a power supply. A resonant LC circuit can be used as a passive sensor, without its own source of power.

The dielectric constant of the material between the plates may change with pressure or temperature and this can also be a source of errors. The relative permittivity of air, and most other gasses, increases with pressure so this will slightly increase the capacitance change with pressure. Absolute pressure sensors, which have a vacuum between the plates, behave ideally in this respect.

A more linear sensor can be constructed by using 'touch mode' where the diaphragm makes contact with the opposite plate (with a thin insulating layer in between) throughout the normal operating range (as shown below). The geometry of this structure results in a more linear output signal.



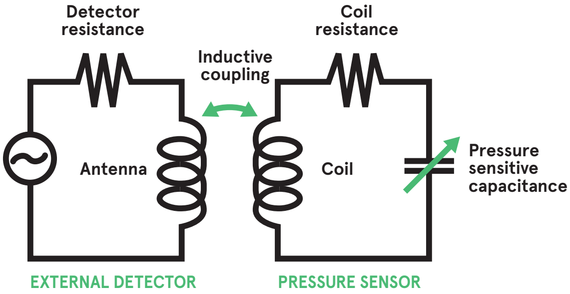
This type of sensor is also more robust and able to cope with a larger over-pressure. This makes it more suited to industrial environments. However, this structure is more prone to hysteresis because of friction between the two surfaces.

DESIGN

The electronics for measuring and conditioning the signal need to be placed close to the sensing element to minimise the effect of stray capacitance.

Because they can be incorporated as components in high-frequency tuned circuits, capacitive sensors are well suited for wireless measurement.

In the case of passive sensors an external antenna can be used to provide a signal to stimulate the tuned circuit and so measure the change in resonance frequency (see diagram below). This makes them suitable for medical devices that need to be implanted.



▲ An external antenna in some passive sensors to stimulate the tuned circuit

Capacitive pressure sensors

Alternatively, for an active sensor, the frequency generated by the oscillator can be picked up by an antenna.

APPLICATIONS

Capacitive pressure sensors are often used to measure gas or liquid pressures in jet engines, car tyres, the human body and many other places. But they can also be used as tactile sensors in wearable devices or to measure the pressure applied to a switch or keyboard.

They are particularly versatile, in part due to their mechanical simplicity, so can be used in demanding environments. Capacitive sensors can be used for absolute, gauge, relative or differential pressure measurements.

ADVANTAGES AND DISADVANTAGES

Capacitive pressure sensors have a number of advantages over other types of pressure sensors.

They can have very low power consumption because there is no DC current through the sensor element. Current only flows when a signal is passed through the circuit to measure the capacitance. Passive sensors, where an external reader provides a signal to the circuit, do not require a power supply – these attributes make them ideal for low power applications such as remote or IoT sensors.

The sensors are mechanically simple, so they can be made rugged with stable output, making them suitable for use in harsh environments. Capacitive sensors are usually tolerant of temporary over-pressure conditions.

They have low hysteresis with good repeatability and are not very sensitive to temperature changes.

On the other hand, capacitive sensors have non-linear output, although this can be reduced in touch-mode devices. However, this may come at the cost of greater hysteresis.

Finally, careful circuit design is required for the interface electronics because of the high output impedance of the sensor and to minimise the effects of parasitic capacitance.

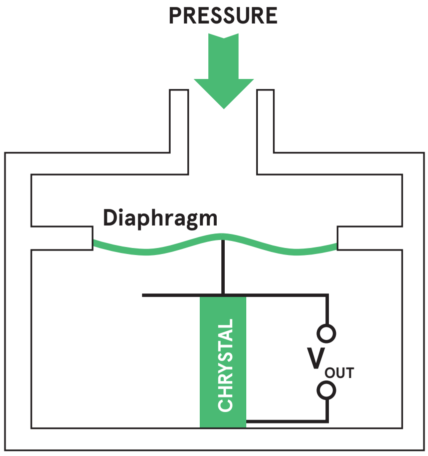
Piezoelectric pressure sensors

Piezoelectricity is the charge created across certain materials when a mechanical stress is applied.

Piezoelectric pressure sensors exploit this effect by measuring the voltage across a piezoelectric element generated by the applied pressure. They are very robust and are used in a wide range of industrial applications.

WORKING PRINCIPLE

When a force is applied to a piezoelectric material, an electric charge is generated across the faces of the crystal. This can be measured as a voltage proportional to the pressure (see diagram below).



▲ When force is applied to a piezoelectric diagram, a voltage proportional to the pressure is generated

There is also an inverse piezoelectric effect where applying a voltage to the material will cause it to change shape.

A given static force results in a corresponding charge across the sensor. However, this will leak away over time due to imperfect insulation, the internal sensor resistance, the attached electronics, etc.

As a result, piezoelectric sensors are not normally suitable for measuring static pressure. The output signal will gradually drop to zero, even in the presence of constant pressure. They are, however, sensitive to dynamic changes in pressure across a wide range of frequencies and pressures.

This dynamic sensitivity means they are good at measuring small changes in pressure, even in a very high-pressure environment.

FUNCTION

Unlike piezoresistive and capacitive transducers, piezoelectric sensor elements require no external voltage or current source. They generate an output signal directly from the applied strain.

The output from the piezoelectric element is a charge proportional to pressure. Detecting this requires a charge amplifier to convert the signal to a voltage.

Some piezoelectric pressure sensors include an internal charge amplifier to simplify the electrical interface by providing a voltage output. This requires power to be supplied to the sensor.

An internal amplifier makes the sensor simpler to use. For example, it makes it possible to use long signal cables to connect to the sensor. The amplifier can also include signal-conditioning circuitry to filter the output, adjust for temperature and compensate for the changing sensitivity of the sensing element.

The presence of the electronic components does, however, limit the operating temperature to not much more than 120°C.

For higher temperature environments, a charge-mode sensor can be used. This provides the generated charge directly as the output signal. It therefore requires an external charge amplifier to convert this to a voltage.

Care is required in the design and implementation of the external electronics. The high impedance output of the sensor means the circuit is sensitive to noise caused by poor connections, cable movement, electromagnetic and RF interference.

The low frequency response of the sensor is determined by the discharge time of the amplifier.

Piezoelectric pressure sensors

CONSTRUCTION

The piezoelectric effect requires materials with a specific asymmetry in the crystal structure. This includes some natural crystals, such as quartz or tourmaline.

In addition, specially formulated ceramics can be created with a suitable polarisation to make them piezoelectric. These ceramics have higher sensitivities than natural crystals. A useful output can be generated with as little as 0.1% deformation.

Because the piezoelectric materials are rigid, only a very small deflection of the material is required to get a usable output signal. This makes the sensors very robust and tolerant of over-pressure conditions. It also means they respond rapidly to changes in pressure.

The pressure sensor can be affected by any external force on the piezoelectric element, for example, by forces caused by acceleration or noise.

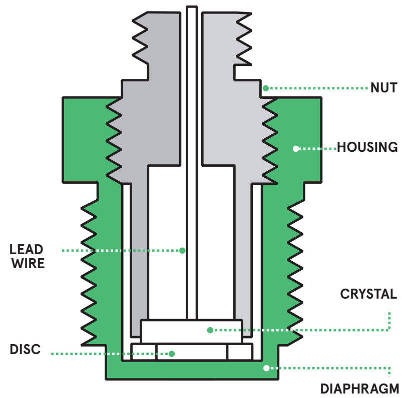
Microsensors can be constructed using thin films. Zinc oxide was one of the first materials used. This has largely been replaced by ceramics made from materials such as lead zirconate titanate (PZT) because of their larger piezoelectric effect.

Microelectromechanical systems (MEMS) [LINK] can be created by combining piezoelectric thin films with micromachined silicon membranes.

Piezoelectric materials are also used in some other types of MEMS sensors. For example, the inverse piezoelectric effect is used to generate surface acoustic waves through a diaphragm. The distortion of the surface under pressure can then be detected by the changes it causes in the waves that are received by another piezoelectric element.

DESIGN

Piezoelectric pressure sensors are often constructed in a threaded tube (as shown in the diagram below) to make it easy to mount them in equipment where pressure is to be monitored. Care is needed when installing these because over-tightening can affect the output sensitivity.



▲ A cross-section of a piezoelectric pressure sensor construction

In some of the typical applications of piezoelectric sensors, they may be exposed to thermal shock (a sudden change in temperature) caused by either radiant heat or the flow of hot gases or liquids past the sensor.

This can cause changes to the output due to heating of the crystal, the diaphragm or the casing of the sensor. Note that this is not the same as the static temperature sensitivity of the sensor.

The effects of thermal shock can be minimised by the design of the enclosure and mounting the sensor to provide isolation.

SENSITIVITY

The output is linear over a wide range, typically 0.7 KPa to 70 MPa (0.1 to 10000 psi) with an accuracy of about 1%.

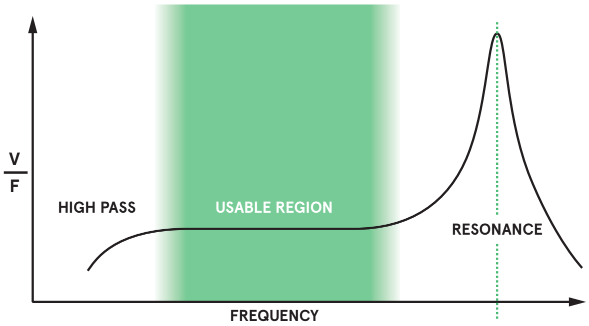
Ceramic sensors are subject to a loss of sensitivity over time. But this is usually quite small; typically less than 1% per year.

Piezoelectric pressure sensors

There may also be a small loss in sensitivity when first exposed to high pressure and temperature. The effects of this can be avoided by cycling the sensor through the maximum expected pressure and temperature before deploying them.

The frequency response of a piezoelectric sensor drops off at low frequencies because the generated charge cannot be retained.

At high frequencies there is a peak corresponding to the resonant frequency of the piezoelectric element. The sensor is normally used within the flat region of the response curve between these two extremes (see below).



▲ The frequency response of a piezoelectric sensor

APPLICATIONS

The robustness, high frequency and rapid response time of piezoelectric pressure sensors means they can be used in a wide range of industrial and aerospace applications where they'll be exposed to high temperatures and pressures.

They are often used for measuring dynamic pressure, for example in turbulence, blast, and engine combustion. These all require fast response, ruggedness and a wide range of operation.

Their sensitivity and low power consumption also makes them useful for some medical applications. For example, a thin-film plastic sensor can be attached to the skin and used for real-time monitoring of the arterial pulse.

ADVANTAGES AND DISADVANTAGES

One of the main advantages of piezoelectric pressure sensors is their ruggedness. This makes them suitable for use in a variety of harsh environments.

Apart from the associated electronics, piezoelectric sensors can be used at high temperatures. Some materials will work at up to 1,000°C. The sensitivity may change with temperature but this can be minimised by appropriate choice of materials.

The output signal is generated by the piezoelectric element itself, so they are inherently low-power devices.

The sensing element itself is insensitive to electromagnetic interference and radiation. The charge amplifier and other electronics need to be carefully designed and positioned as close as possible to the sensor to reduce noise and other signal errors.

Piezoelectric sensors can be easily made using inexpensive materials (for example quartz or tourmaline), so they can provide a low cost solution for industrial pressure measurement.

MEMS pressure sensors

Microelectromechanical systems (MEMS) devices combine small mechanical and electronic components on a silicon chip.

The fabrication techniques used for creating transistors, interconnect and other components on an integrated circuit (IC) can also be used to construct mechanical components such as springs, deformable membranes, vibrating structures, valves, gears and levers.

This technology can be used to make a variety of sensors including several types of pressure sensor. It enables the combination of accurate sensors, powerful processing and wireless communication (for example, Wi-Fi or Bluetooth) on a single IC.

Large numbers of devices can be made at the same time so they benefit from the same scaling advantages and cost efficiencies as traditional ICs.

FUNCTION

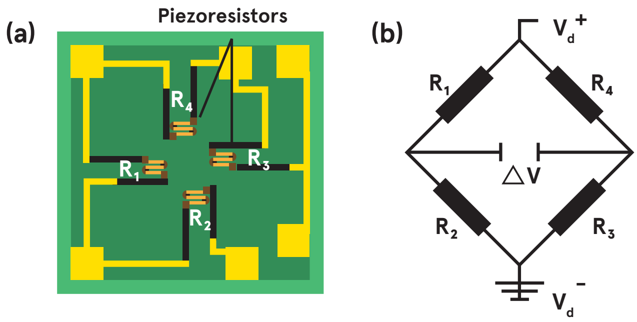
Several types of pressure sensor can be built using MEMS techniques. Here we will discuss two of the most common: piezoresistive and capacitive. In both of these, a flexible layer is created which acts as a diaphragm that deflects under pressure but different methods are used to measure the displacement.

MEMS piezoresistive strain gauge sensors

Piezoresistive strain gauge sensors were the first successful MEMS pressure sensors and are widely used in applications such as automotive, medical and household appliances.

Conductive sensing elements are fabricated directly on to the diaphragm. Changes in the resistance of these conductors provide a measure of the applied pressure. The change in resistance is proportional to the strain, which is the relative change in length of the conductor.

The resistors are connected in a Wheatstone bridge network, which allows very accurate measurement of changes in resistance. The piezoresistive elements can be arranged so that they experience opposite strain (half are stretched and the other half are compressed) to maximise the output signal for a given pressure (see diagrams **below**).



▲ Two ways in which piezoresistive elements might be arranged

An excitation voltage Vex is applied and the output voltage is proportional to the change in resistance:

$$V_o = \frac{\Delta R}{R} V_{ex}$$

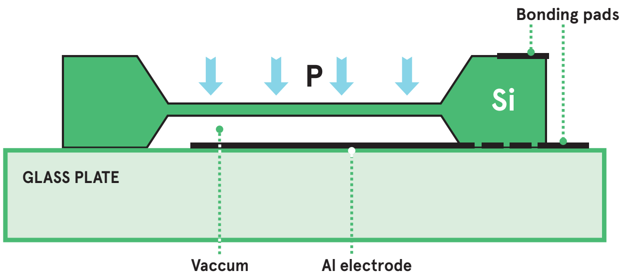
For more information on piezoresistive strain gauge sensors read chapter 6.2.

MEMS pressure sensors

MEMS capacitive pressure sensors

To create a capacitive sensor, conducting layers are deposited on the diaphragm and the bottom of a cavity to create a capacitor. The capacitance is typically a few picofarads.

Deformation of the diaphragm changes the spacing between the conductors and hence changes the capacitance (see below). The change can be measured by including the sensor in a tuned circuit, which changes its frequency with changing pressure.



▲ A cross section of a MEMS capacitive pressure sensor

The sensor can be used with electronic components on the chip to create an oscillator, which generates the output signal. Because of the difficulty of fabricating large inductances on silicon, this will usually be based on an RC circuit.

This approach is well suited for wireless readout because it generates a high frequency signal that can be detected with a suitable external antenna.

Alternatively, the capacitance can be measured more directly by measuring the time taken to charge the capacitor from a current source. This can be compared with a reference capacitor to account for manufacturing tolerance and to reduce thermal effects.

In both cases, the proximity of the electronics and the sensor element minimises errors caused by stray capacitance and noise.

For more information on capacitive pressure sensors read chapter 6.3.

Other MEMS pressure sensors

There are other ways of making MEMS pressure sensors that can be used.

For example, a mechanical structure can be created with a resonant frequency that is a function of applied pressure (like tuning a piano string). A signal is applied to cause the structure to vibrate and the change in resonant frequency is measured. Such devices can be very accurate but are difficult to manufacture and are sensitive to other environmental factors, such as temperature, that also change the resonant frequency.

A surface acoustic wave (SAW) sensor works by sending vibrations through a thin film of piezoelectric material. The waves are picked up by another transducer and converted back to an electrical signal. The changes in the amplitude or phase of the acoustic signal caused by deformation of the surface can be measured to give an indication of pressure.

CONSTRUCTION

MEMS sensors can be used to measure physical parameters such as acceleration, temperature and pressure. Electronic components can be constructed on the same chip to measure the output of the sensors, perform signal processing and provide wireless communication.

Alternatively, the sensor and the electronics can be on separate devices connected together in a single multi-chip package.

MEMS pressure sensors

FABRICATION

The techniques for constructing MEMS are based on those used for semiconductor manufacturing.

Manufacturing starts with a wafer of high-purity silicon. A combination of lithographic patterning with photoresist, etching and deposition of materials is used to build up multi-layer structures to create the components and the connections between them.

Mechanical components can be made by removing surrounding material to create a structure that is free to move. This technique is used to make devices such as accelerometers, inkjet nozzles and even complete "lab on a chip" systems.

Finally, the wafer is cut into individual die, which can be less than a millimetre to several millimetres in size so there can be thousands per wafer. These are then packaged and connecting wires attached. The final cost can be from 10s of pence to a few pounds.

A single wafer can be used to create a variety of different chips at the same time, spreading the manufacturing costs across several products or customers. This also enables relatively low cost semi-customised sensors where specific parameters of a standard device can be customised for a particular application.

The semiconductor material normally used is silicon. This may be combined with other materials for particular applications. For example, for high-speed, low-power electronics, the silicon structures may be constructed on an insulating material such as sapphire or silicon dioxide to create silicon on insulator (SOI) devices.

Silicon is not suitable for very high temperature pressure sensors because its mechanical and electrical properties degrade above about 500°C. For high temperature applications, the sensor may be constructed from silicon carbide (SiC). This has greater stiffness and fracture strength and also resists wear, oxidation and corrosion better than silicon. This makes it a better material for producing stable pressure sensors for harsh environments.

Packaging

The packaging of the sensor needs to be designed to cope with the environment where the device will be used. A particular challenge for pressure sensors is providing sufficient environmental exposure to allow the external pressure to be measured while also giving adequate protection from magnetic fields, temperature, shock, liquids and gases.

An important aspect of the packaging process for pressure sensors is obtaining a good seal, particularly for absolute pressure sensors, which need to maintain a vacuum cavity below the sensor to achieve long-term stability.

The pressure sensor is often bonded onto a Pyrex glass substrate because its thermal properties are a very close match to silicon.

APPLICATIONS

Pressure sensors have long been used in medicine, in non-invasive applications such as controlling the air pressure in respiratory equipment and measuring blood pressure. More recently, the miniaturisation provided by MEMS devices has enabled use in more invasive applications such as catheter tip sensors, as well as for implantable devices monitoring properties such as blood pressure and heart rate.

For medical applications there is a challenge in making the standard package (which is made from rigid material with sharp edges) compatible with the biological environment. This can be achieved by enclosing the device in biocompatible plastic or wire.

The small size, low power consumption and long-term stability of MEMS devices also makes them well suited to markets such as aerospace where long life and reliability are important. They are used in a variety of applications including cabin pressure monitoring, engine control, and instruments such as altimeters and barometers.

MEMS pressure sensors

ADVANTAGES AND DISADVANTAGES

Because of their small size and close integration with the electronics, MEMS sensors can be very low power. In some cases, they can be powered by a small battery that lasts for several years. Some can even operate without a battery, either using energy harvested from the environment or provided by the external device that reads the sensor data.

The capacitive sensor has the advantages of lower power consumption, greater sensitivity and temperature independence.

The main advantages of piezoresistive sensors are high linearity and stability.

MEMS sensors have the advantage of very small size. This means they can respond rapidly to small changes in pressure. It also enables them to be used in new application areas such as implantable medical devices.

NEED SOME ADVICE?

Our pressure sensor experts are on hand to help you make the right choice for your application. Get in touch at **avnet-abacus.eu/ask-an-expert**

Optical pressure sensors

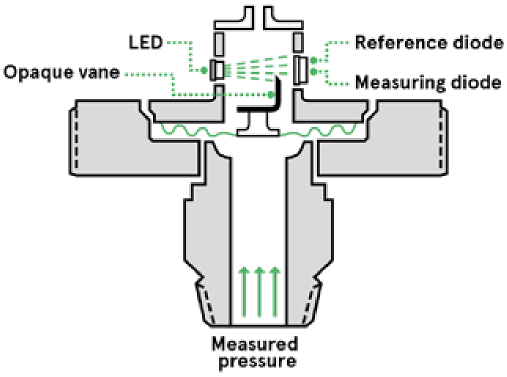
Optical pressure sensors detect a change in pressure through an effect on light.

In the simplest case this can be a mechanical system that blocks the light as the pressure increases. In more advanced sensors, the measurement of phase difference allows very accurate measurement of small pressure changes.

WORKING PRINCIPLE

In an intensity-based optical pressure sensor, an increase in pressure will cause the source of light to be progressively blocked. The sensor then measures the change in light received.

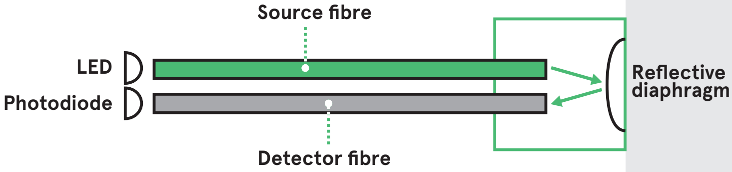
For example, in the simple mechanism shown below, the pressure moves a diaphragm and the attached opaque vane blocks more of the light from the LED. The fall in light intensity is detected by the photodiode and gives a direct measurement of pressure.



▲ A simple optical pressure sensor

A simple optical pressure sensor like this needs a reference photodiode (as shown above), which is never blocked by the vane. This allows the sensor to correct for changes in the light output due to other factors, like aging of the light source, variations in supply voltage, etc.

These mechanical systems are relatively large. Much smaller versions can be constructed with a reflective membrane and two optical fibres, one as a source of light and the other to receive the reflected light. Pressure bends the membrane and changes the amount of light reflected back to the detector (see below).



Other fibre-optic sensors use interferometry to measure changes in the path length and phase of light caused by changing pressure. The rest of this article will focus on these.

FUNCTION

Fibre-optic pressure sensors can be classified as either extrinsic, where the sensing takes place outside the fibre, or intrinsic, where the fibre itself changes in response to pressure.

Very sensitive optical measurements can be made by exploiting interferometry: measuring the change of phase between light that has taken two different paths. This can detect changes in distance corresponding to a fraction of the wavelength of light.

There are two common types of pressure sensor that use interferometry. These are the Fabry-Pérot interferometer (FPI) and fibre Bragg grating (FBG).

The FPI is an extrinsic sensor that uses interference between multiple light rays reflected back and forth between two surfaces in a cavity. As the spacing between them changes, interference will change the amount of light received at a particular wavelength.

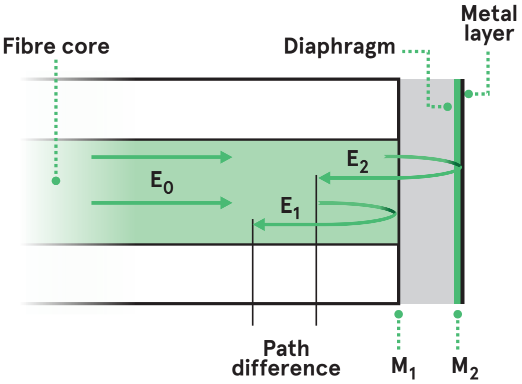
Optical pressure sensors

This is one of the best optical sensor technologies. It is simple, accurate and easily scaled for different sizes and pressure ranges.

An FBG is an intrinsic sensor that has a regular series of reflective structures in the fibre that are affected by stretching or squashing the fibre. This causes the wavelengths of the reflected light to change.

CONSTRUCTION

A Fabry-Pérot cavity with two parallel reflecting surfaces can be constructed on the tip of an optical fibre (as shown below).

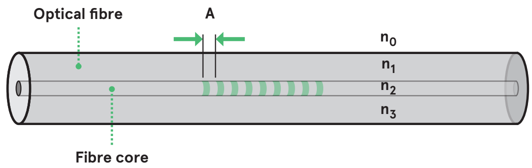


A semi-reflecting surface is attached to the fibre (M1) and a reflective membrane is created at the opposite end of the cavity (M2). This membrane forms a diaphragm that is moved by pressure.

The change in spacing between the mirrors causes a difference in the path travelled by each ray of light (E1 and E2) and hence a relative phase shift between them. The resulting interference will reinforce or reduce particular wavelengths of light.

The multiple reflections and the large number of interfering rays result in a very high-resolution measurement.

A Bragg grating can be created within a fibre using a series of periodic changes in the refractive index of the fibre. This causes particular wavelengths of light to be reflected or transmitted, based on the ratio between the wavelength and the spacing. As a result, the spectrum of the reflected light changes as the fibre, and the spacing, is stretched.



▲ Bragg grating created within an optical fibre

The fibre can be attached to a diaphragm that stretches the fibre when pressure is applied. Compressing the fibre also changes the effects of the grating, creating two peaks in the spectrum.

The output from either type of sensor can be measured in two ways. If a monochromatic or narrow-band source is used, there will be a change in the amplitude of the output signal as the length of the cavity (or the spacing of the grating) modifies how much of that wavelength is reflected.

A wide-band light source, such as a white light, can also be used. In this case, the frequencies at which constructive or destructive interference occurs will change with pressure. This can be measured with a spectrum analyser.

These structures, in particular Fabry-Pérot cavities, are also suitable for silicon fabrication techniques allowing even smaller optical sensors to be made as microelectromechanical systems (MEMS) devices.

Waveguides (equivalent to optical fibres) and mechanical components such as cantilevers and membranes can be constructed at the micrometre scale.

These sensors can respond very rapidly to pressure changes because of their small size. Light-emitting diodes, solid state lasers, photodiode detectors and electronics can all be integrated on the same device.

Optical pressure sensors

APPLICATIONS

Because of their freedom from electromagnetic interference, fibre-optic sensors are very useful in harsh environments.

One example is the oil and gas industry. Conditions in a well can easily reach 20 kpsi and 185°C. Optical sensors continue to perform well under these extremes.

Their small size, flexibility, the absence of any potentially hazardous voltages, and the fact that the sensors are made of non-toxic materials makes them very well suited to medical applications.

There are many places in the body where measuring pressure can be important for diagnosis, long-term monitoring or during treatment.

As well as more obvious measurements such as pressure in blood vessels and the lungs, it is often useful to measure pressure in the digestive tract, bladder, brain, bones and joints. Fibre-optic sensors allow this to be done in a minimally invasive way.

The immunity to electromagnetic interference is valuable when pressure needs to be monitored during MRI scans or RF ablation procedures.

The requirements for a pressure sensor vary depending on the reason for the measurement, where the measurements are made, the range of values to be measured, and whether it's for a single measurement or long-term monitoring. There are also various standards defined for medical equipment. Fibre-optic sensors can be designed to meet a wide range of these requirements.

A Fabry-Pérot sensor can be used to accurately monitor pressure at a specific location in the body and is typically introduced via a catheter.

Multiple fibre Bragg gratings can be created within a fibre, allowing pressure to be measured along its length. This has been used, for example, to measure the pressure changes throughout the colon during digestion.

The fibre can also provide measurement over a 2D area. This is useful for monitoring the pressure on the body for bed-bound patients to reduce the risk of ulcers.

ADVANTAGES AND DISADVANTAGES

Intensity based sensors are not very sensitive to temperature change because the measurement and reference detectors are affected equally. Because the amount of movement needed is very small, hysteresis and repeatability errors are very low.

The small size and flexibility of fibre-optic sensors means they can be deployed in locations that would be hard to access with other techniques.

The fact that the sensing element itself is passive and does not need a power supply enables the sensors to be used in a wide range of applications where getting power to the sensor could be a problem. This also eliminates signal transmission problems due to parasitic capacitance, electromagnetic interference, etc.

On the other hand, their small size can mean they are not as robust as other sensor types. Their high sensitivity can also make them more sensitive to acoustic or mechanical vibration.

Pressure sensors for different media types

There are a number of different media types that pressure sensors can measure. Dependent on the application, a pressure sensor may come into contact with a variety of chemicals, liquids or gases, or have to function in extremely harsh environments.

Manufacturers will consider operating conditions when designing and fabricating and many offer sensor packages designed for specific media. However, they will also provide warnings on the limitations and restrictions on their sensors, and recommendations on how to overcome these limitations.

This chapter explores the different types of media that pressure sensors can measure, the applications of each type, and the different sensor options for your design.

Air pressure sensors

Pressurised air is used for multiple purposes in engineering. And air pressure sensors offer measurement and control of these important pressure levels.

Measuring atmospheric air pressure, or barometric pressure, is a different topic that's covered in a separate article. This article focuses solely on applications in which air pressure is deliberately raised above normal atmospheric levels.

A very simple example of air under pressure is the air compressed in a football, without which the ball wouldn't bounce. In a tyre, compressed air gives a combination of rigidity and cushioning. In inflatable boats, it creates a rigid but light and buoyant structure.

The ideal functioning of any of the above depends on reaching and keeping the right level of air pressure – hence the need for air pressure sensors.

While a manual pump will – with a lot of effort – inflate smaller items, you'll naturally turn to the power of a compressed air system for larger inflatables.

Compressed air, processed from atmospheric air using an electrical or engine-powered compressor, has been used in industry since the mid-1800s and does much more than pump up footballs.

Tanks of compressed air can be used by divers for breathing underwater, by firefighters to survive in smoke-filled buildings, and by medics to ensure ventilation of patients' lungs.

However, it's the ability of compressed air to store and transfer energy that accounts for most of its industrial applications. Think of powerful air-driven tools, air brakes, air-assisted paint spraying, and heating, ventilation and air conditioning (HVAC) systems. These are just a few examples of compressed air's power and versatility.

APPLICATIONS

In each of the examples above there's an ideal air pressure for operation, which air pressure sensors will monitor. Knowing the air pressure also enables you to measure other variables, like air flow rate, indirectly. Crucially, there's a maximum safe air pressure level for any piece of equipment containing compressed air, above which it becomes dangerous.

Consider the energy stored by compressed air in an industrial tyre, for instance. If the tyre is filled beyond bursting point, you can imagine the explosive results when all that energy is suddenly released. That's why air pressure sensors are so vital as part of a control and switching system.

The capacity of compressed air for transmitting high levels of energy is very obvious in tools like pneumatic drills, and it can even be used to drive vehicles. Safety is obviously a key concern when handling that kind of power.

For trains and heavy goods vehicles, air brakes are often specified for their known efficiency and reliability. To maintain their failsafe performance, pressure levels must be monitored.

Concentrated, controlled, accurate levels of power are needed for devices such as the air tools now used by many dentists. Air pressure is one of the measurable criteria which affect overall precision and performance.

Systems supplying breathing assistance for patients require similarly reliable air flows. In cleanrooms, maintaining a small but very specific positive pressure is critical to keeping out dirty air.

From sandblasting rusty sheet metal and grimy stone buildings to gently removing dust from small spaces, compressed air is moving all around us. In every case, air pressure sensors are helping to ensure the optimum air pressure, flow rate and effect.

Air pressure sensors

To give an idea of the more detailed functions of air pressure sensors, let's take a closer look at their use in an air conditioning system.

Recommended air flow rates exist for public buildings and industrial plants. If the pressure, and therefore the flow, drops below the ideal, air pressure sensors will register the change and adjustments can be made or causes investigated.

Differential air pressure sensors are used specifically to monitor pressure before and after filters. In doing so, they can indicate when a dirty filter needs replaced.

Sensors also help avoid energy wastage through unnecessarily high pressure in a system. A small reduction, while staying within the optimum pressure range, can lead to significant savings on electricity.

MEASUREMENT OPTIONS

Depending on your system's needs, you'll normally choose between the following types of sensor (which measure pressure in different ways):

- **Absolute air pressure sensor** – measuring pressure in relation to that of a perfect vacuum (this is your least likely choice, except perhaps for experimental work).
- **Gauge air pressure sensor** – measuring pressure in relation to atmospheric pressure (in tyre pressure measurement, for example, a reading of zero means the internal air pressure is equal to that of the atmosphere).
- **Differential air pressure sensor** – measuring the difference in pressure between two points (such as before and after a filter in an air conditioning system).

TECHNOLOGY

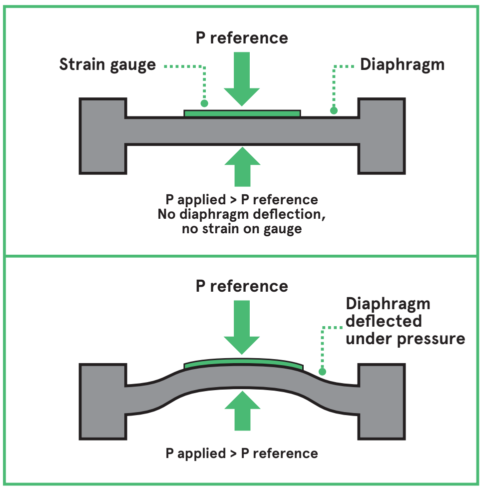
In the simplest air pressure gauges, there's a direct mechanical connection between the pressurised air and a pointer on the gauge. Common mechanisms for this include bourdon tubes and pistons. The higher the pressure, the further the pointer moves.

For greater accuracy and control, however, you should look at air pressure sensors which convert pressure's effect into a proportional electrical signal. This type of pressure sensor tends to be referred to as a pressure transducer.

Many different technologies and operating principles have been used to achieve precise pressure measurements, each with their own advantages and disadvantages. Summaries of the three most common approaches used in the air pressure sensor field are given below.

1. Resistive air pressure transducer or strain gauge

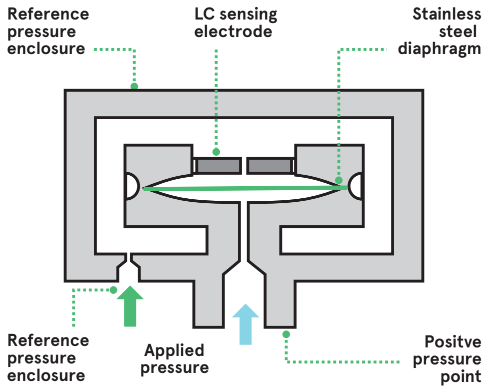
A diaphragm, in contact with the air whose pressure is being measured, deforms as pressure increases (see diagram below). Strain gauges attached to the non-contacting surface of the diaphragm are similarly deformed. The piezoresistive effect, in which the strain gauge material's resistance alters when deformed, is converted into an electrical signal.



▲ A representative diagram of a resistive air pressure sensor.

2. Capacitive air pressure transducer

In this approach, two capacitive plates are separated from each other by a small gap. One is fixed, while the other, which is in contact with the air, acts as a flexible diaphragm (see diagram below). Increasing air pressure deforms the diaphragm, which narrows the gap and decreases capacitance. The change in capacitance is converted into an electrical signal.



▲ A capacitive air pressure sensor

3. Inductive air pressure transducer

Here the deformation of a diaphragm is converted into linear movement of a ferromagnetic core using the principle of inductance. The core's movement causes variation in the induced current which is generated by an AC-powered coil on another secondary pick-up coil. This change is, in turn, converted into an electrical signal.

OPTIONS AND SPECIFICATIONS

No two applications are exactly alike. You'll have to assess how well the air pressure sensors on your shortlist meet your needs and make the best – if not perfect – choice. Here are some criteria to consider:

- **Pressure range**. At the very least, this should cover the maximum pressure permissible in your equipment. Excess pressure is a common cause of air pressure sensor failure.
- **Precision**. Most air pressure sensors are reasonably accurate at room temperature but less so at higher temperatures. If accuracy is a priority, choose a sensor with a high-precision specification and use digital electronics. Sensors offering calibrated and temperature-compensated signals are available.
- **Location flexibility**. Vibration, shocks and high temperatures may affect sensors placed close to the equipment they monitor. If installation at a distance isn't possible, look for a robust design. If sensors may be exposed to hot or wet weather, ensure their housing offers suitable protection.
- **Compatibility**. Will the sensor's fittings allow it to thread easily onto your existing set-up? Is its analogue output compatible with your signal conditioning instrumentation?
- **Response time**. Some pressure transmitters allow easy adjustment of response time, which can be useful in eliminating false triggering.
- **Price**. Don't pay more than you need to, but bear in mind that with low-cost sensors you'll have to compromise on things like durability and accuracy.
- **Lifetime cost.** Factors like ease of installation, low maintenance needs, robustness and longevity should be assessed alongside the purchase price.

LIMITATIONS

The chances are, your broad choice will be between resistive and capacitive air pressure transducers.

Of these, resistive – or strain gauge – is the category most used. It offers advantages in terms of overpressure protection, effective resolution, and resilience in the face of vibrations, shocks and dynamically varying pressures.

However, when selecting a resistive air pressure transducer you should be aware of the different material choices. These vary in stability with respect to temperature, humidity and sensor output.

Capacitive air pressure transducers also cope well with overpressure and are better than strain gauges for use at low pressures. They score well on hysteresis, linearity, stability, repeatability and measurement of static pressure.

On the other hand, they are larger and more expensive to make. They can also be adversely affected by particulates and humidity in the gap between their capacitive plates.

NEED SOME ADVICE?

Our pressure sensor experts are on hand to help you make the right choice for your application. Get in touch at **avnet-abacus.eu/ask-an-expert**

Barometric pressure sensors

The technology and applications of barometric pressure measurement have come a long way since the old barometer you remember on your grandparents' wall.

Today's compact electronic barometric pressure sensors can be found fulfilling functions in your smartphone and your car engine, for example, along with their traditional weather-forecasting role.

Since atmospheric pressure decreases with increasing height, a barometer can also serve as an altimeter if appropriately calibrated. Many of the most exciting recent and ongoing developments in applying barometric pressure measurement relate to this capability.

APPLICATIONS

To this day, barometric pressure sensors are contributing to the field of weather forecasting, but now they allow weather stations to be miniaturised. In fact, you can even forecast the weather with the help of tiny sensors in your mobile phone or tablet.

Other environmental applications include evapotranspiration calculations, whereby scientists monitor the transfer of water into the atmosphere via evaporation from surfaces and transpiration from plants. Pressure sensors also provide supporting data to correct the output of instruments such as oxygen sensors which are affected by fluctuating pressure.

For both indoor and outdoor navigation, the altimeter function of barometric pressure sensors enables accurate vertical positioning. This is important when, for example, you're moving between floors in a building or levels in a car park. In some cases, the accuracy is sufficient to distinguish between points separated by less than the height of one step.

Barometric measurements can help with dead reckoning, in which a device calls on other sensors to calculate its current position when GPS signals are temporarily difficult or impossible to receive.

Systems like those outlined above are now small enough to fit into your smartphone or tablet. You might already have a barometer in your phone without even knowing it.

Wearable devices for monitoring leisure, sport and fitness activities are certain to benefit increasingly from the expanding capabilities of barometric pressure sensors. For instance, instead of relying on accelerometers to count steps, the new sensors will do this by monitoring air turbulence as the body moves. Even gesture recognition is possible.

Another application is in engine management. Changes in atmospheric pressure, when driving between different altitudes, in particular, have a bearing on performance. Accurate monitoring of pressure enables computation of the ideal air-fuel mixture and control of spark advance for optimum efficiency.

Unmanned aerial vehicles, or drones, are fast becoming a realistic answer to certain industrial challenges. Precise height monitoring through barometric pressure sensors will have a part to play in their continued development.

In warehouses, for instance, the ability to rise to an exact specified shelf height will be a great advantage in stocktaking and retrieving stored items. For delivery of goods in built-up areas, the height as well as the geographical location of addresses will need to be specified.

Looking more widely, there are multiple opportunities within the Internet of Things for objects and equipment to be monitored remotely in relation to issues affected by pressure. Meanwhile, virtual reality, gaming equipment and toy developers are sure to be looking for ways of exploiting advances in positional sensing.

Barometric pressure sensors

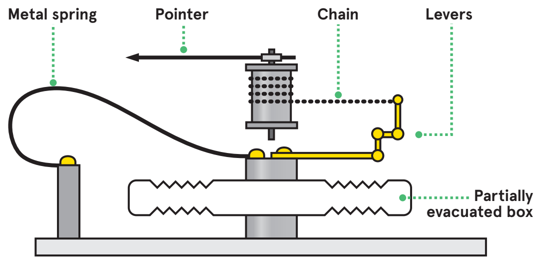
MEASUREMENT OPTIONS

When measuring pressurised air in other contexts (e.g. the pressure of air within a sealed system), the choices include gauge pressure (air pressure compared to atmospheric pressure) and differential air pressure (pressure difference between points). Barometric pressure sensors instead measure absolute air pressure. This is the air's pressure in relation to a perfect vacuum.

TECHNOLOGY

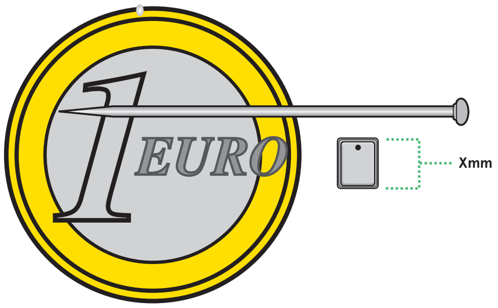
For much of our history, barometers depended on the behaviour of mercury or some other liquid in response to changing air pressure. The aneroid barometer, whose name refers to the absence of liquid, was invented in 1844. It uses deformation of metal instead.

In the aneroid barometer, a partially evacuated metal cell is subjected to pressure from the atmosphere. As the pressure increases or decreases, the cell contracts or expands. This movement is translated and amplified, via an opposing spring, a system of levers and a pointer, to register a reading on the barometer's dial.



▲ A classic aneroid barometer

Modern barometric pressure sensors are, in a sense, aneroid barometers, as their method of operation does not involve liquid. In construction and appearance, though, they are very different from their predecessors – often using the latest microelectromechanical system (MEMS) technology.



▲ Modern MEMS sensors are so small they can be integrated into almost anything

In common with the original aneroid barometers, they detect atmospheric pressure via its effect on a flexible structure – in this case a membrane or diaphragm. The degree of deformation in the membrane is proportional to the pressure and is translated into an electrical signal – hence the sensors are sometimes referred to as pressure transducers.

These small pressure transducers are built around one of two main measurement approaches: resistive or capacitive.

A resistive barometric pressure sensor is also known as a piezoresistive sensor or a strain gauge. One face of its diaphragm is in contact with the atmosphere. The other face has strain gauges attached to it.

Increasing pressure deforms both the diaphragm and the strain gauges. Deformation of the strain gauge material alters its resistance, due to the piezoresistive effect, and the sensor reflects this change in its electrical signal.

A capacitive barometric pressure sensor's technology is based on two capacitive plates with a small gap between them. The plate in contact with the atmosphere is flexible and forms a diaphragm which deforms under pressure. The other is stiff.

Deformation of the diaphragm alters the distance between the plates and changes the system's capacitance. The sensor's electrical signal reflects this proportional variation.

Barometric pressure sensors

OPTIONS AND SPECIFICATIONS

Here are some of the variables you might want to consider when trying to match your application with the right sensor:

- **Precision.** There are resistive pressure sensors which offer thermal compensation and calibration to produce a linear, stable, accurate output. Those who favour the capacitive approach stress that their sensors are naturally less susceptible to temperature-induced variation and are simpler to calibrate.
- **Sensitivity.** In addition to being reliably accurate, you also need to consider whether your sensor needs to be able to distinguish between very small pressure differences. In positioning or navigation devices, for instance, will it be able to tell between one step and the next on a staircase?
- **Pressure and temperature limits.** As well as being able to function at each extreme, make sure the sensor can deliver the accuracy you need throughout the specified range.
- **Energy consumption.** If the pressure sensor is part of a compact device with space for only a small battery, low power needs will be a big advantage. Resistive pressure measurement tends to add significantly to energy demand compared to capacitive. A sleep mode, where appropriate, is one aid to conserving power.
- **Operating environment.** If the sensor is to be deployed in harsh conditions, is it robust enough? Does it need a waterproof and impact-resistant housing?
- **Size.** Many of the trending applications, such as wearable devices, require miniaturisation. The tiny footprint of some pressure sensors on the market is very welcome in those cases.

LIMITATIONS

As the above criteria suggest, measurement accuracy and other performance criteria vary greatly amongst products. This is true both within and between the two main categories (resistive and capacitive). Some argue, however, that capacitive pressure sensing technology has major inherent advantages over resistive – especially in relation to temperature stability.

Gas pressure sensors

APPLICATIONS

Gas pressure sensors can be used to gauge altitude in aircraft, rockets or balloons. They're frequently used in automotive design, from optimising engine function and controlling emissions to monitoring pressures in tyres and airbags, and even controlling inflatable air bolsters in dynamic seats.

In industrial settings, they can be used to measure the speed with which gas is flowing (sometimes known as 'impact pressure'), to confirm that suction is present, to manage source pressures or to test for leaks.

MEASUREMENT OPTIONS

Gas pressure sensors are designed (or can be configured) to measure gas pressure in different ways.

- **Gauge pressure** is measured in relation to the surrounding atmospheric pressure. Atmospheric pressure is around 100kPa (14.7 PSI) at sea level. The sensor built into air pumps for tyres measures pressure in this way, showing the air pressure inside the tyre in relation to the local atmospheric pressure. A reading of zero indicates the pressures are equal inside and out.
- **A sealed gas pressure sensor** is similar to a gauge gas pressure sensor but has been pre-calibrated to measure gas pressure in relation to sea-level atmospheric pressure. So its readings won't change if the unit is taken to a different altitude or location.
- **Vacuum pressure** is the measure of the negative difference between the gas pressure at a given location and atmospheric pressure.
- **Absolute gas pressure** is measured from zero, or a perfect vacuum (0 PSI). Again, unlike gauge pressure, this isn't affected by the conditions around the unit, which can vary with changes in altitude and other factors.
- **Differential pressure** is the difference between two gas pressures – for example, those in two gas hoses connected to the sensor. As with gauge pressure, the sensor may be able to measure changes of gas pressure in either direction (that is, positive or negative differences).

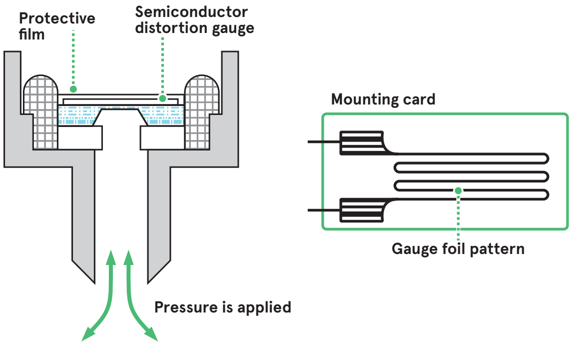
Beyond the different types of measurement, some gas pressure sensors are also designed to measure rapid pressure changes in dynamic environments, such as combustion pressure in an engine cylinder or a gas turbine.

TECHNOLOGY

Gas pressure sensors are transducers: they generate an electrical signal in proportion to the pressure they measure. This allows pressure to be monitored by microprocessors, programmable controllers, computers and other electronic devices connected to the sensor.

Some gas pressure sensors are analogue, providing pressure feedback in the form of an electrical current. There are also digital sensors, which provide a digital value for gas pressure, and sensors that provide other types of feedback, such as optic, visual or auditory signals. The most commonly used technology in analogue gas pressure sensors is the piezoresistive strain gauge, which uses the principle of piezoresistance.

The sensor is based around a diaphragm made from monocrystalline silicon, polysilicon thin film, bonded metal foil, thick film or sputtered thin film. The diaphragm acts as a semiconductor distortion gauge: when gas presses on it, it is bent out of shape, which distorts the crystalline structure of the material. This, in turn, changes the electrical resistance of the diaphragm, allowing the sensor to reflect changes in pressure in the form of a change in current (see diagram below).



▲ The cross-section of a semiconductor distortion gauge, as used in many gas pressure sensors.

Gas pressure sensors

Other, less commonly used, technologies for gas pressure sensors include capacitance (similar to piezoresistance, but the capacitance of the material changes), electromagnetic, piezoelectric (for changes in pressure only), optical and potentiometric.

Some electronic sensors use other properties, such as density, ionisation or thermal conductivity, to infer the pressure of a gas rather than measuring it directly.

A resonant sensor uses changes in resonant frequency (the frequency at which a gas vibrates most readily) to measure changes in gas density caused by pressure. The sensing element can be made from vibrating wire, a vibrating cylinder, quartz or silicon.

Ionisation sensors measure gas pressure by monitoring the flow of charged gas particles (ions), as it varies as a result of density changes. Examples of ionisation sensors include hot-cathode and cold-cathode gauges.

Thermal sensors use changes in the thermal conductivity of a gas (how readily it conducts heat) to measure pressure. An example is the Pirani gauge, which features a heated metal filament suspended in a tube and measures the heat lost from the filament to the surrounding gas.

In digital gas pressure sensors, a silicon chip converts the current through the semiconductor distortion gauge into a numerical reading, and the data is then passed out of the unit via a process connector. This can then be monitored and/or stored by a computer or other electronic monitoring device.

In recent years, wireless pressure sensors have been introduced. These advanced sensors can be controlled remotely, which allows them to be used for applications where wired connections wouldn't be possible. They are usually battery-powered, making them completely self-contained and self-sufficient until the battery needs replacing. They typically offer more customisation and control options than standard sensors, and some allow settings such as high and low limits to be altered while the unit is in operation.

Some wireless sensors can connect to mobile devices such as smartphones, which can monitor, collect and store data from the sensor, carrying out functions which previously required a computer.

OPTIONS AND SPECIFICATIONS

A wide range of gas pressure sensors is available. They vary in terms of application suitability, cost, technology used, physical dimensions, fittings, process connectors and manufacturing materials used.

Gas pressure sensors normally have a working range defined in kilopascal (kPa), atmospheres (atm) or millimetres of mercury (Hg). They'll also have an accuracy rating. For example, a sensor might have a working range of 0–210kPa, with accuracy of ±4kPa.

They may come with a stated response time, which reflects how long it takes them to provide a pressure reading – for example, 10ms.

And they typically have a temperature range of operation, since the sensitivity of a pressure gauge can be affected by temperature.

LIMITATIONS

Basic gas pressure sensors can only be used to measure the pressure of gases that are non-corrosive or non-flammable. For more information on measuring the pressure of corrosive gases, see our article on pressure sensors for corrosive media.

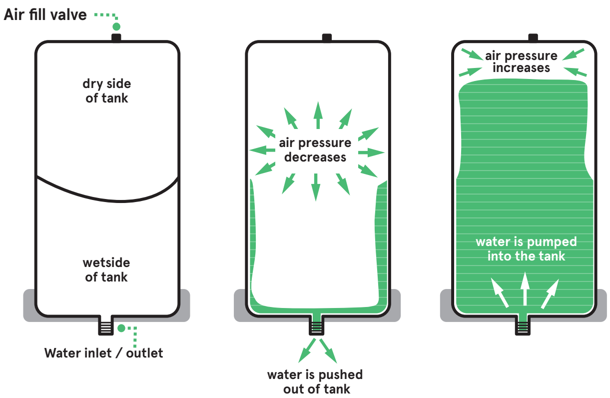
NEED SOME ADVICE?

Our pressure sensor experts are on hand to help you make the right choice for your application. Get in touch at **avnet-abacus.eu/ask-an-expert**

Water pressure sensors

APPLICATIONS

Water pressure sensors are often used to measure the level of water in a tank, or the rate of change in that level (as shown below). The sensor is fitted to the top of an open-ended tube submerged within the container. As the water level rises, the air above the water in the tube is compressed, increasing the pressure on the sensor. An analogue-to-digital convertor (ADC) is used to convert the signal from the sensor into a digital value.



They can also be used to gauge the pressure in pipes where water is flowing – for example, in water distribution systems, to automatically determine whether pumps need to be activated to increase the flow rate.

And they can be used to gauge the depth of a submerged object – for example, in deep-sea diving.

MEASUREMENT OPTIONS

Water pressure sensors can measure pressure in several different ways:

- **Absolute** water pressure is measured against zero. This is similar to the way gas pressure sensors measure gas pressure as compared with a vacuum.
- **Gauge** pressure measures water pressure against the atmospheric pressure around the sensor. If the water pressure sensor is completely submerged in water, a vent line is used to allow air from above the surface to enter the sensor, to provide the reading for atmospheric pressure. The vent line can often be run through the power cable supplying the sensor.
- **Differential** pressure reflects the difference between two bodies of water – for example, in two separate tanks or containers, or two water pipes. This can be used to measure pressure drops across filters, or measure flow rates by measuring the difference in pressure across a restriction.

TECHNOLOGY

Water pressure sensors are transducers, generating an electrical signal in proportion to the pressure they measure.

▲ A typical switching water pressure sensor, popular with makers

Water pressure sensors usually contain a physical diaphragm, often made of silicon, which bends as pressure is applied. The diaphragm is a strain gauge, which varies its electrical resistance when force is applied. This resistance is used to modify the output voltage of the sensor.

Some water pressure sensors provide zero-based outputs, where zero pressure results in no output signal at all. For example, their output might be in the range 0–5V. Others offer voltage at zero pressure, with a range such as 1–5V.

Water pressure sensors

One drawback of zero-based output is the difficulty of identifying problems with the sensor itself. For example, in a water-pumping system, a pump might be configured to activate when the water pressure rises above a certain point, perhaps indicating that a certain depth of water has accumulated. If the water pressure sensor has a 0V signal, that might indicate zero pressure – or the sensor may have failed completely, which would mean that the pump did not activate as water levels rose, perhaps leading to a flood. In contrast, a zero reading from a 'voltage at zero pressure' sensor would clearly indicate a fault.

OPTIONS AND SPECIFICATIONS

Specifications to consider when choosing a water pressure sensor include:

- **Type of measurement** (absolute vs. gauge)
- **Pressure measurement range**
- **Accuracy** (usually expressed as a percentage)
- **Media compatibility**
- **Moisture resistance**
- **Operating temperature range**
- **Venting** (see below)
- **Vibration resistance**

For wireless water pressure sensors, additional relevant options are:

- **Transmitter wiring** (cable or flying lead)
- **Transmitter accuracy**
- **Radio frequency**
- **Electromagnetic interference**

Sensors that measure gauge pressure must be vented, so you may need to consider sealing methods for outdoor applications, high-pressure water jets (in a car wash or industrial process, for example), or where the sensor will be exposed to a lot of water vapour,. An alternative is to use a sealed gauge, or a sensor that measures absolute pressure.

Pumping systems may sometimes be subject to 'water-hammer', where the opening or closing of valves sends a shock-wave through the water, causing a pressure transient or pressure spike that may exceed the measurement range of the sensor. To protect against this, some sensors can be fitted with restrictor plugs to slow down water flow and mitigate the effects of the spike.

Some water pressure sensors can indicate that they have developed a fault by sending their signal output out of range (either below the lowest point or above the highest point). In pumping applications, this can help to prevent flooding, or protect the pump from running dry or incurring extra damage.

LIMITATIONS

Since water pressure sensors may come into contact with different kinds of water, you may want to consider their suitability for different pH levels (acidic or alkaline), salt water, chemicals or other contaminants.

Not all pressure sensors may be suitable for use with potable (drinking) water. The regulations concerning what materials can come into contact with drinking water vary from country to country.

Liquid pressure sensors

APPLICATIONS

Many normal pressure sensors are suitable for use with a wide range of liquids and gases, including water and air. However, more viscous liquids call for specially designed sensors. Examples of viscous media include melted plastics, paper pulp, bitumen, rubber, asphalt, crude oil, sewage, sludge, paint, sealants and adhesives, as well as certain foods (such as ice cream) and pharmaceutical products.

MEASUREMENT OPTIONS

Pressure sensors for viscous liquids usually measure pressure in one of two ways: absolute or gauge.

Absolute pressure is measured relative to a particular value, such as zero or atmospheric pressure at sea level. With this method, the reading is always the same, regardless of where the unit is located.

Gauge pressure is measured relative to the surrounding atmosphere, meaning that readings can vary based on location and altitude. Sensors measuring gauge pressure within a liquid need a vent tube in order to measure the surrounding pressure, which is often combined with the electrical cable connection.

TECHNOLOGY

Viscous liquid pressure sensors are transducers, generating an electrical signal in proportion to the pressure they measure. This allows pressure to be monitored by electronic devices such as microprocessors, programmable controllers, or computers.

Pressure sensors for viscous liquids usually feature a physical diaphragm, often made of stainless steel or ceramic, which bends as pressure is applied. The diaphragm is a strain gauge, which increases in electrical resistance as more force is applied to it – in this case, from the pressure of the viscous liquid on the sensor. This resistance is used to modify the output voltage of the sensor.

Standard liquid pressure sensors often feature a relatively narrow vent that allows liquid to enter the unit and press on the diaphragm. However, this is impractical when working with more viscous fluids that have lower flow rates and tend to solidify or coagulate, particularly when a process is halted and the temperature falls and/or the media dries out. The sensor may get clogged up and take some time to begin working properly again when the process is restarted.

To address this, pressure sensors for viscous fluids usually have flatter, more open designs, perhaps with a flush diaphragm, that allow the fluid to move freely across the face of the sensor. They may also be designed so that all surfaces that come into contact with the fluid are accessible, to allow for easy cleaning and the removal of built-up residue.

▲ Pressure sensors for use with viscous liquids are often designed with a flush diaphragm and accessible surfaces for easier cleaning

Liquid pressure sensors

OPTIONS AND SPECIFICATIONS

Sensors for viscous fluids will typically be specified using features such as:

- Pressure range (for example, 0–0.4 bar)
- A reference type (absolute or gauge; see previous page)
- Response time
- Output signal
- Accuracy (expressed as a percentage)
- Installation type
- Housing and diaphragm material
- Process connection
- Cable length and type

Another important specification is the type of seal used on parts of the sensor exposed to the fluid, particularly if the media is volatile or corrosive.

Sensors will have an operational temperature range, which is vital to consider for media that are subject to intense heat, such as molten plastic or bitumen. Some sensors can be supplied with cooling elements that protect the electronics from the temperature of the media, extending their usable temperature range. For example, some sensors may feature an integral oil-filled capillary that transfers pressure from the diaphragm to the piezoresistor, putting extra distance between the media and the electronics within the sensor.

Some sensors for viscous fluids have nose cones that protect the sensor in use, but can be removed for cleaning. They may also include sealed cable exits to protect the sensor from cleaning processes used for surrounding areas, or from flooding in use.

Sensors for viscous fluids that are suitable for use in hazardous environments may be certified under a standard such as ATEX 95 (for Europe) or IECEx 02 (worldwide). Under EU law, ATEX 95 is required for all electrical and non-electrical equipment that's used in hazardous environments, while IECEx 02 is intended only for electrical equipment in hazardous environments. Hazardous environments include those involving dust or flammable materials, including bio-gas that may be present along with viscous fluids such as sewage.

Sensors may be available with submersible cable connections, protecting them from spillage or allowing them to be continuously submerged in liquid when in use.

LIMITATIONS

Not all sensors are suitable for use with foods. Sensors that are suitable for sanitary food and biotech applications will usually be available with a food-grade oil behind the diaphragm, so the media will not be contaminated if the diaphragm is accidentally damaged and oil leaks out of the sensor.

Pneumatic and hydraulic pressure sensors

APPLICATIONS

Examples of systems built around pneumatic technology include vehicle tyres, air brakes (on buses, trucks and trains), air compressors, compressed-air engines, vacuum pumps and more.

Examples of hydraulic applications include vehicle braking systems, power steering systems, shock absorbers, utility vehicles such as excavators and aerial platforms, lifts and industrial machinery such as hydraulic presses.

The overarching application of pressure sensors in pneumatics and hydraulics is to ensure the pressure within the system is at the correct level, or within an optimum range.

This is particularly important for hydraulics, where the liquid in the system may be volatile or flammable (for example, mineral oil) and reach very high pressures and temperatures, making leaks and accidents potentially dangerous.

Pressure sensors feature as part of pressure regulators, or automatic valves designed to control the pressure in the system (as shown below). Pressure regulators match the demand for gas or liquid to the demands of the system, while maintaining a constant output pressure. As the system demands more power, so the load flow increases, and the regulator flow must increase, or the controlled pressure will fall.

MEASUREMENT OPTIONS

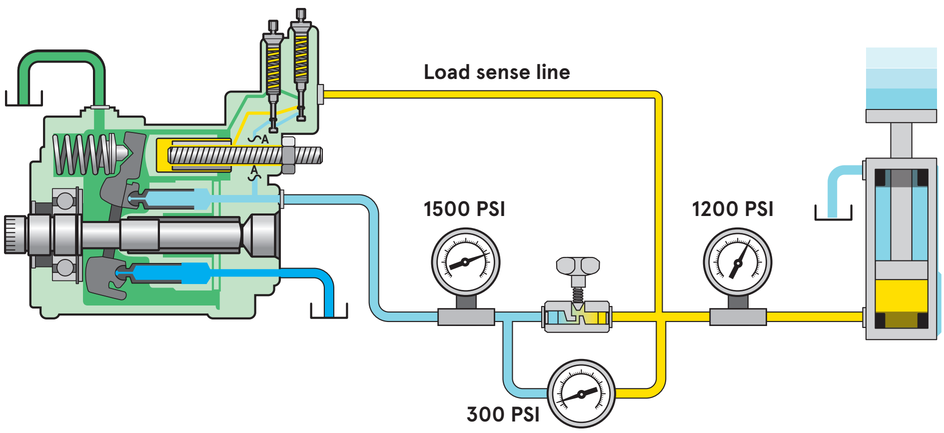
Like other types of pressure sensor, sensors used in pneumatics and hydraulics can measure differential pressure (the difference between two pressures) or absolute pressure (measured against zero or another absolute value).

In pressure regulators, differential pressure sensors compare the pressure on either side of a valve, to determine whether the inlet flow is equal to the outlet flow.

TECHNOLOGY

Pneumatic and hydraulic pressure sensors are transducers, generating an electrical signal in proportion to the pressure they measure. This allows pressure to be monitored by a range of electronic devices.

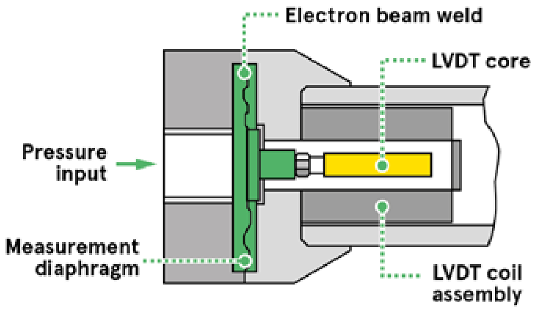
The technology used most often in pneumatic and hydraulic pressure sensors uses a physical diaphragm, often made of silicon, which bends as pressure is applied to it. The diaphragm is a strain gauge, which varies its electrical resistance when force is applied – in this case, from pressure exerted by air, gas or hydraulic liquid on the sensor. This resistance is used to modify the output voltage of the sensor.



▲ A load-sensing hydraulic system featuring three pressure sensors

Pneumatic and hydraulic pressure sensors

Some pressure sensors for power-steering applications use a linear variable differential transformer (shown below). This includes a core that moves within a hollow tube to monitor the movement of a directional control valve with high precision, allowing hydraulic fluid to flow into different areas of the system.



▲ A cross-section of a linear variable differential transformer pressure sensor

Many pressure sensors are now standalone, incorporating all the electronics and temperature compensation technology they need into the unit itself.

However, as the pressure used in hydraulics systems increases to drive efficiency, and systems overall become smaller and more compact, this isn't always possible. An alternative is embedded sensors, where the electronic components are located away from the sensor itself. This allows the sensor to work in environments characterised by high temperature, vibration and radiation.

To withstand harsh environments, pressure-sensing chips have been designed such that the medium (gas or liquid) only comes into contact with silicon, helping to protect electronic components.

Some pressure sensors for pneumatics and hydraulics function by measuring the expansion of a flexible tube, rather than the pressure in the gas or liquid directly. This can help to detect blockages within the tube and monitor pump performance.

OPTIONS AND SPECIFICATIONS

Pneumatic and hydraulic pressure sensors will usually have a range of pressures they can measure – for example, 0 to 200 bar. They may also specify a safe limit of pressure, above which the unit may malfunction, and a temperature range within which they will provide accurate readings (for example, -40°C to 85°C).

Most pneumatic and hydraulic pressure sensors will also specify an error band – for example, ±0.05% – indicating the level of accuracy of the sensor.

Other options may include input and output connection type and output signal, as well as physical specifications such as material (including for parts in contact with liquid), dimensions and thread sizes.

LIMITATIONS

Hydraulics, in particular, are used in harsh and challenging environments involving extreme heat, water, dust and even radiation. Hydraulics on heavy vehicles may be subject to physical shocks and vibration, and may also be subject to sudden pressure spikes. Pressure sensors therefore need to be able to withstand these conditions and still function correctly.

Pressure sensors for corrosive media

Some pressure sensors are specifically designed to work with corrosive, aggressive or highly contaminated liquids and gases, collectively known as 'corrosive media'.

These corrosive substances will destroy or damage other substances that they come into contact with, including metals and organic compounds. This makes them difficult and dangerous to work with and raises unique challenges for the design of pressure sensors with corrosive media compatibility.

APPLICATIONS

Pressure sensors for corrosive media are used in applications such as industrial measurement and control, industrial boilers, monitoring the levels of chemical storage tanks, waste management, medical devices, instrumentation and analytical devices.

They also find applications in energy technologies such as those using natural gas, biogas, landfill gas and CHP (combined heat and power).

MEASUREMENT OPTIONS

Pressure sensors for corrosive media usually measure pressure in one of two ways: absolute or gauge.

Absolute pressure is measured relative to a particular value, such as zero or atmospheric pressure at sea level. With this method, the reading is always the same, regardless of where the unit is located.

Gauge pressure is measured relative to the surrounding atmosphere, meaning that readings can vary based on location and altitude.

TECHNOLOGY

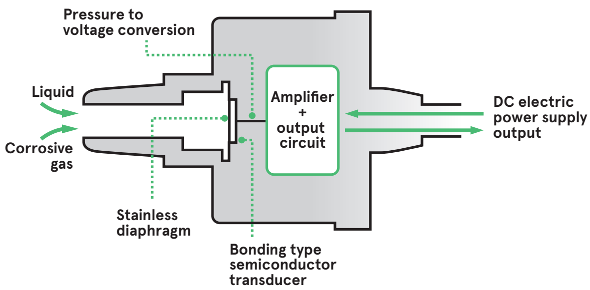
Pressure sensors for corrosive media are transducers, generating an electrical signal in proportion to the pressure they measure. This allows pressure to be monitored by various devices with a suitable interface.

Most pressure sensors for use with corrosive media use the principle of piezoresistance. The sensor is based around a diaphragm made from a ceramic material that's elastic but resistant to corrosion and abrasion.

The diaphragm acts as a semiconductor distortion gauge: when the corrosive liquid or gas presses on it, it is bent out of shape, which distorts the crystalline structure of the material. This, in turn, changes the electrical resistance of the diaphragm, allowing the sensor to reflect changes in pressure in the form of a change in current.

OPTIONS AND SPECIFICATIONS

Pressure sensors for use with corrosive media often feature housings made from stainless steel or plastics such as PVDF, PVC or PPS. The sensor elements themselves are typically ceramic, although some sensors use a stainless steel diaphragm backed by silicon oil that transfers pressure to the sensing element.



▲ A typical pressure sensor designed for corrosive media

The pressure sensors will usually specify a suitable pressure range (for example, 200 mbar–35 bar). Certain sensors may be able to measure both absolute and gauge pressure (see above), with a pressure range specified for each. Some sensors can be configured to measure negative pressure as well as positive.

Pressure sensors for corrosive media

Some sensors for corrosive media are temperature-compensated, so their readings are not affected by changes in media temperature.

Sensors will also specify the voltage output that they use to indicate pressure changes, and their output at zero pressure (for example, 100mV).

In some cases, the O-ring used to seal the ceramic diaphragm to the body of the sensor can be made from different materials, such as fluorocarbon plastomer (which resists mineral acids, petroleum oil, salt solutions and chlorinated hydrocarbons), nitrile rubber (which resists paraffin-based materials, fatty acids, glycerines or alcohols) or EPDM - ethylene propylene diene monomer (which resists many acids and alkalis).

Some sensors may be certified under a standard such as ATEX 95 (for Europe) or IECEx 02 (worldwide). Under EU law, ATEX 95 is required for all electrical and non-electrical equipment that's used in hazardous environments, while IECEx 02 is intended only for electrical equipment in hazardous environments. Hazardous environments include those involving flammable materials or dust.

LIMITATIONS

Many sensors are suitable for use with either corrosive liquids or corrosive gases. Their datasheet or other supporting material will specify which media they're compatible with.

Other sensors are suitable for use with specific types of liquid or gas. However, manufacturers will sometimes be able to modify their sensors to suit specific requirements.

Engineers may need to consider what will happen in the event of the sensor failing. Corrosive or hazardous media could enter the sensor, leading to contamination. Conversely, internal parts or materials (such as oil used as a filling fluid) may leak into the process media.

Pressure sensors for harsh environments

You've heard the phrase 'if you can't stand the heat, get out the kitchen'. Well for pressures sensors, if they can't stand the boiling heat, the freezing cold, corrosive substances, being submerged in salt water, constant exposure to the outside world, or even being sent into space, then they might not be fit for the job.

These hardy little sensors need to withstand some pretty challenging conditions.

In some cases, the ambient temperature may fluctuate widely and quickly, or the pressure media itself may be at a high temperature.

In other applications, corrosive pressure media can present a threat to sensor components such as the diaphragm, or to the integrity of the sensor as a whole. Commonly encountered media include industrial acids, alkalis, salt water in a marine environment, or even fresh water if the sensor is to be used outdoors or underwater.

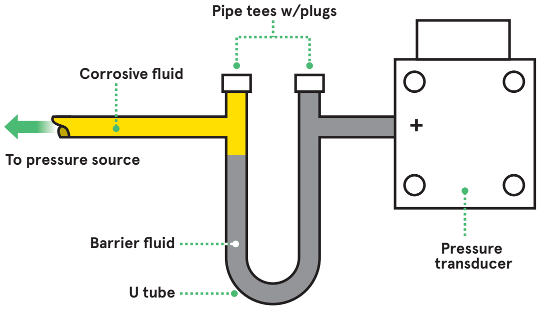
Sometimes it's not the environment that can damage the sensor, but the potential for the opposite to happen, such as in food-preparation equipment, where materials in the sensor may present a contamination threat to the pressure media.

Wherever the environment or pressure media are particularly challenging, the chemical compatibility and temperature capability of the sensor are important selection criteria.

Given that special sensors – designed to operate at extreme temperatures, or withstand exposure to salt spray or harsh chemicals – will likely carry a cost premium, engineers might consider isolating the sensor from the pressure media, if possible.

PHYSICAL SEPARATION FROM HAZARDOUS MEDIA

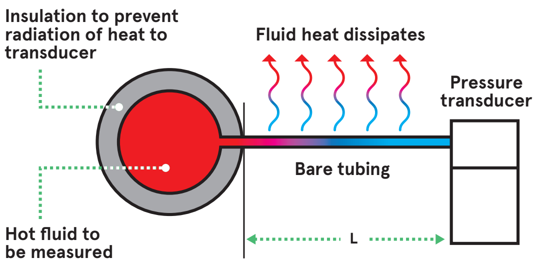
A fluid-isolation barrier (see diagram below) can be implemented to prevent corrosive media coming into direct contact with the sensor diaphragm.



▲ Isolating a pressure sensor from corrosive media.

The fluid-isolation system (as shown above) is closed to allow accurate measurement taking advantage of the incompressibility of the liquid. A suitable liquid must be chosen that will not mix with the pressure media, or present risk of contamination to the process being monitored. Heavy industrial oil is often used.

Temperature isolation can be implemented in a similar way, by inserting a standoff such as an uninsulated tube between the main vessel containing the media and the sensor –industrial pipework or a flask might be used, for example.



▲ Temperature isolation to protect the pressure sensor.

Pressure sensors for harsh environments

Heat is dissipated from the media in the tube (see diagram on previous page), thus exposing the sensor diaphragm to a safe temperature. The length of tubing needed is calculated according to the temperature of the media, thermal properties of the tubing, and the maximum temperature of the pressure sensor.

ISOLATION DIAPHRAGMS FOR HARSH ENVIRONMENTS

Similar principles to the above are applied to create upgraded pressure sensors, capable of withstanding exposure to extreme conditions. An isolation diaphragm can be designed to extend chemical compatibility by using a material such as titanium, tantalum, stainless steel, or another alloy, and filled with a dielectric oil to transfer pressure to the more sensitive diaphragm of the standard sensor. The isolation diaphragm can be an effective barrier to corrosive media or media at a higher temperature than the sensor is able to withstand.

WITHSTANDING EXTREME TEMPERATURES

Pressure sensing at extreme temperatures is required in numerous industrial sectors, such as in the petrochemical industry where vast networks of pipelines must be monitored accurately. Pipeline pressures must be monitored at locations throughout an entire refining and distribution network that can span extreme climates from near-arctic conditions to desert heat.

Meanwhile, automotive, aerospace, and other industrial applications including mining, smelting and down-hole drilling provide further examples of operating conditions that demand rugged sensors capable of withstanding extreme ambient or media temperatures.

At very low temperatures, oil in the cavity behind the diaphragm in an oil-filled sensor can harden, leading to inaccurate readings. In addition, water mixed with gas passing through pipelines can freeze in cold climates and expand, resulting in excessive pressure on the sensor. The excess pressure can be enough to distort the sensor's readings even after the water has thawed. Such damage may be temporary, or can be permanent.

In extremely low temperature conditions, other components of the sensor, such as rubber o-rings, can become embrittled, which compromises sealing and impairs accuracy. In some situations it may be practicable to heat the sensor continuously to prevent freezing. If heating is not an option, then a sensor designed for extremely low-temperature operation must be specified.

On the other hand, exposure to a high temperature environment can cause the materials used in standard pressure sensors – such as the bonding between strain gauges and substrate - to degrade, leading to inaccuracy or complete sensor failure.

High-temperature sensors feature upgraded materials or construction, using processes such as sputter thin-film deposition that creates a molecular bond between the strain gauges and the substrate, capable of withstanding higher temperatures.

Sensors can be built to operate in various ambient-temperature ranges, with the peak temperature rating of ruggedly designed sensors extending to more than 200°C.

Pressure sensors for harsh environments

OPERATING IN CORROSIVE ENVIRONMENTS

Pressure media in industrial processes, such as acids or alkalis, can have particularly aggressive corrosive properties. Liquids, such as fruit juices in contact with food-processing equipment, can also present a significant corrosion risk.

The pressure-diaphragm metallurgy is critical, to ensure suitable corrosion resistance. Titanium has excellent resistance to corrosion by acids, alkalis, or salts, and can be used to fabricate the diaphragm and other parts of the sensor that may come into contact with the media.

Other applications may require resistance to the corrosive effects of seawater, or sea fog. Some examples include platform stabilisation equipment, desalination equipment, pipeline control valves, or oil-tanker piping systems.

Seawater has several corrosion mechanisms, including chemical corrosion due to salts, oxygen, and carbon dioxide contained in the water.

In addition, bacteria in seawater cause microbial induced corrosion, by feeding on iron and manganese content in steels and ultimately promoting further microbial action resulting in chemical waste that attacks the surface of steel membranes. The severity of this type of corrosion can vary with geographical location, depending on factors such as the microbe species present and typical water temperature.

Low-grade austenitic stainless steels, such as common 304 or 316 grades, have poor corrosion resistance in seawater. Although higher-grade duplex steels can offer greater corrosion resistance than the standard grades, nickel-based superalloys such as 625 (nickel-chromium) or C276 (nickel-molybdenum-chromium) are superior - although more expensive – for applications that are exposed to seawater or sea fog. Titanium also offers good resistance to seawater corrosion.

The chemical compatibility of other important parts of the sensor, such as o-rings, should also be considered when selecting sensors for use in corrosive environments. Sensors specially designed for such applications may feature parts made from a material such as Viton, which has broader compatibility than plain rubber.

COPING WITH DYNAMIC ENVIRONMENTS

In some applications such as industrial air-blasting equipment, fluid-flow measurement or combustion performance analysis, sensors are needed to measure fluctuations in pressure superimposed on a static background pressure. More extreme applications include monitoring combustion in gas turbines or jet engines, for purposes such as engine control, fault detection, or acoustic analysis.

Piezoresistive elements have fast response times, suitable for dynamic pressure measurement, and can allow a wide bandwidth ranging from a few Hz to over 10kHz. Some sensitivity may need to be traded for faster sensor response, and vibration compensation using accelerometers may be required to increase signal-to-noise ratio.

Pressure sensors for harsh environments

CREATING ROBUST HIGH-PRESSURE SENSORS

Extremely high pressure environments exist within hydraulic actuators such as aircraft flight controls or test rigs for equipment like landing gear.

Industrial processes such as injection moulding, hydroforming, or powder metallurgy such as hot or cold isostatic processing are also dependent on generating extremely high pressures that must be monitored for safety and process-control purposes.

Other applications include mineral-extraction equipment, high-pressure cleaning equipment, and industrial test equipment such as burst-pressure or fatigue-test benches.

Heavy-duty high-pressure sensors can measure static and dynamic pressure of up to 100,000 psi (7000 bar) and more. Special features for high-pressure operation include stainless steel construction, a robust threaded pressure port, and metal-to-metal screw sealing (see image below).

▲ A high-pressure sensor featuring robust construction and metal-to-metal screw sealing.

In spite of the enormous challenges faced by pressure sensors in extreme environments, it's possible to specially engineer them to operate under a wide range of harsh conditions.

Compatibility between the sensor materials and the pressure media is vital, whether the media or environment presents a hazard to the sensor materials, or whether the sensor could present a hazard to the media, such as in medical or food-processing applications. Additional considerations in the latter application might include the use of special food-grade materials, such as non-toxic cavity oils.

Stainless steel construction is widely featured among sensors for use in harsh environments. Whereas 316 or 304 alloys are economical and robust, only higher-grade steels like nickel-based superalloys – or titanium – can withstand the most extreme corrosive media, including seawater, which has multiple biological as well as chemical corrosion mechanism.

If you're not sure where to start, our sensor experts can guide you through your options and help find the right balance between sensor performance and protection from hazardous environments.

Understanding pressure sensor specifications

THE PRESSURE SENSOR SPEC AND ITS IMPACT ON ACCURATE READINGS

There are many aspects of a pressure sensor that determine whether it is the right choice for a given application. Gauge, absolute or differential, transducer or transmitter, measurement range, fitting style/size, and absolute maximum ratings such as burst pressure are among the most important.

Several sensors may meet the application requirements, in these respects. Making the right choice can then be guided by considering factors that affect accuracy. Fundamentally, this determines whether the pressure measurements supplied are dependable to inform decisions made by the application.

FACTORS AFFECTING ACCURACY

The major sensor characteristics that influence accuracy are temperature coefficients, temperature hysteresis, pressure hysteresis, and non-linearity.

Applicable temperature coefficients include temperature-related changes to zero offset, sensitivity, and measurement span.

A datasheet may describe accuracy-related characteristics individually, or as an overall accuracy statement calculated as the root of the sum of squares (RSS) of individual factors.

Note also that accuracy can be expressed as a percentage of the full-scale range, or as a percentage of the reading. Percent of full scale (% F.S) is commonly used, meaning that if the sensor has a full-scale range of 200 psi and is specified as 1% F.S, any reading at any pressure within 0-200 psi is expected to be within ±2 psi of the true pressure.

Alternatively, if the accuracy is stated as a percentage of reading, 1% accuracy at 200 psi would translate to an error of ±2 psi as before. However, at 100 psi the error would be ±1 psi. Clearly the error cannot tend towards zero at 0 psi: at lower reading, the datasheet may quote an absolute figure, say ±0.4 psi, for pressure readings below a stated threshold.

Understanding pressure sensor specifications

UNDERSTANDING THE DATASHEET

Temperature errors are expressed over a range, called the Compensated Temperature Range (CTR), which is usually narrower than the operating temperature range.

▼ The snapshot below, taken from the datasheet for the TE Connectivity 1210 series piezoelectric sensor, illustrates how various sources of error are expressed among the sensor's key parameters. Understanding the various types of errors and how they are calculated can help when making comparisons between different sensors and choosing the most suitable component for a given application.

TEMPERATURE COEFFICIENT OF ZERO OFFSET

The sensor's zero offset is the output when pressure on both sides of the diaphragm is equal. This is expressed as the Zero Pressure Output in the datasheet snapshot below. A constant offset can be trimmed out at manufacture, but the offset also changes with temperature.

The temperature coefficient of zero offset, or Temperature Error – Zero in the datasheet below (alternatively referred to as TCZ) is calculated by measuring the difference between the offset output at the standard temperature and at the lower and upper limits of the Compensated Temperature Range (CTR), and expressing the larger of the two differences as a ratio of full-scale.

SUPPLY CURRENT: 1.SMA

Ambient Temperature: 25-C (unless otherwise specified)

PARAMETERS	MIN	TYP	MAX	UNITS	NOTES
Span	75	100	150	mV	1
Span (2 psi version)	30		60	mV	1
Zero pressure output	-2		2	mV	
Pressure non linearity	-0.1	±0.05	0.1	%Span	2
Pressure hysteresis	-0.05	±0.01	0.05	%Span	
Input & output resistance	2500	4400	6000	Ω	
Temperature error — span	-0.5	±0.3	0.5	%Span	3
Temperature error - zero	-0.5	±0.1	0.5	%Span	3
Thermal Hysteresis — zero		±0.1		%Span	3
Supply current		1.5	2.0	mA	
Response time (10% to 90%)		1.0		ms	4
Output noise (10Hz to 1kHz)		1.0		μV p-p	
Long term stability (offset & span)		±0.1		%Span	5
Pressure overload			3X	Rated	6
Compensated temperature	0		50	°C	
Operating temperature	-40		+125	°C	
Storage temperature	-50		+150	°C	
Weight			3	grams	
Solder temperature	250°C Max 5 Sec.				
Media	Non-corrosive dry gases compatible with Silicon, Pyrex, RTV, Gold, Ceramic, Nickel, and Aluminum				

NOTES

1 Ratiometric to supply current.

2 Best fit straight line.

3 Maximum temperature error between 0°C and 50°C with respect to 25°C. For 2psi devices, Temperature Error -- Zero is ±1%.

4 For a zero-to-full scale pressure step change.

5 Long term stability over a one year period with constant current and temperature.

6 2X maximum for 100psi device. 20psi maximum for 2 and 5psi devices.

Understanding pressure sensor specifications

TEMPERATURE COEFFICIENT SENSITIVITY

Sensitivity as quoted in the datasheet quantifies the change in output per unit change in applied pressure. It's typically affected by the excitation voltage and expressed in terms of output millivolts per applied volt of excitation voltage (mV/V).

The sensitivity may change with operating conditions, particularly temperature. The sensitivity shift across the Compensated Temperature Range (CTR) is expressed as a percentage of full scale per °C change in temperature.

TEMPERATURE COEFFICIENT OF MEASUREMENT SPAN

The magnitude of the sensor full-scale output is affected by temperature. This is called Temperature Error – Span in the TE datasheet sample, and may also be referred to as the temperature coefficient of span (TCS). It is calculated in a similar way to the TCZ. The full-scale output at the upper and lower CTR limits is compared with the full-scale at the standard temperature. The larger of the two differences is expressed as a ratio in percent per degree (%/°C).

▼ The illustration below shows how the temperature coefficient of sensitivity is expressed for Amphenol's NPA series surface-mount sensors.

Parameter	Units	Min	Typ	Max	Notes
Pressure range	psi		0.36 to 1		1 0"H_2O = 2.5KPa
Excitation	mA		1.5		10 VDC Maximum
Input impedance	Ω		5000±20%		
Output impedance	Ω		5000±20%		
Zero offset	mV		±75		
Full scale output	mV		40 to 120		10°H_2O
			75 to 135		1 psi
Linearity	%FSO		±0.25		BFSL
Pressure hysteresis	%FSO		±0.20		
Temperature coefficient of zero	µV / V / °C		±30		
Temperature coefficient of resistance	% / °C		0.29		
Temperature coefficient of sensitivity	%FSO / °C		-0.2		
Thermal hysteresis of zero	%FSO		±0.15		
Position sensitivity	%FSO		0.2		

Temperature coefficient of sensitivity as expressed in Amphenol NPA series datasheet

Understanding pressure sensor specifications

PRESSURE HYSTERESIS AND TEMPERATURE HYSTERESIS

A sensor may give different readings for the same measured pressure, depending on whether the pressure has increased or decreased to reach the measured value. Key factors that cause pressure hysteresis include the characteristics of the diaphragm or strain-gauge material.

Pressure sensors can also exhibit temperature hysteresis, which results in a different pressure reading being produced at a given pressure and temperature depending on whether the temperature has increased or decreased to the value at which the measurement is taken. Temperature hysteresis is influenced by measurement conditions such as dwell time and temperature range, and is expressed as a percentage of full scale over the CTR.

NON-LINEARITY

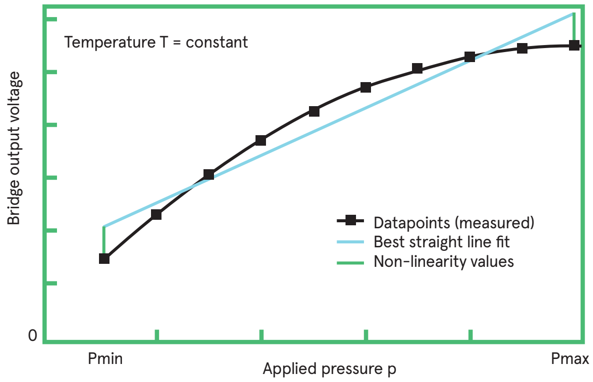
Non-linearity expresses the difference between the actual output of the sensor and the predicted response according to its typical performance. Non-linear responses can be affected by factors such as temperature, humidity, and vibration or other disturbances. Non-linearity can be expressed mathematically, as a percentage:

$$\text{Nonlinearity (\%)} = \frac{D_{in(max)}}{IN_{f.s.}} \times 100 \quad (6\text{-}1)$$

where:

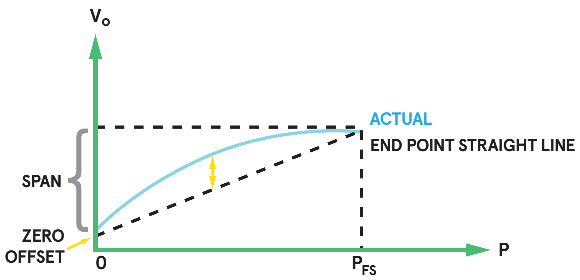
- Din(max) is the maximum input deviation
- INf.s. is the maximum, full-scale input

Non-linearity can also be shown graphically (see above right) which illustrates how the output voltage can deviate across the full-scale range. In this context, linearity can be quantified using the Best Fit Straight Line (BFSL) method, using mathematical regression to plot the BFSL that gives equal weighting to points above and below the line.



▲ A graphical representation of non-linearity using the Best Fit Straight Line method.

Alternative methods may be used, such as the terminal line technique, which expresses non-linearity as the maximum deviation from a straight line joining the zero and full-scale points (see below). The terminal line method eliminates zero-point and full-span errors, which simplifies recalibration if a sensor is replaced in the field.



▲ Terminal line method for calculating non-linearity.

The datasheet should state which method has been used. A note in the TE datasheet on page 93 tells the reader that the BFSL method was used to calculate the 1210's typical non-linearity to be ±0.05 %span.

High-linearity pressure sensors can be produced by optimising the construction of the sensor, such as the diaphragm mounting, building the sensor using high-quality materials, and applying electronic compensation.

Understanding pressure sensor specifications

Several other parameters can affect the sensor accuracy, and should be considered when choosing the right sensor for a given application. These include resolution, dynamic characteristics, and long-term stability, as we'll now explore.

RESOLUTION

Resolution is the smallest incremental change in pressure that can be displayed at the output. It may be expressed as a proportion of the reading or the full-scale range, or as an absolute figure. Depending on the application, the pressure resolution may be easily related to real-world performance: a pressure sensor with 3mbar resolution, used in a depth gauge, will allow depth-measurement resolution of 3cm in water. Note that a sensor's accuracy cannot be greater than its resolution.

RESPONSE TIME AND DYNAMIC PERFORMANCE

Response time is an expression of the sensor's ability to change and stabilise at the new value, within the specified tolerance, in response to a change in the applied pressure. The response time may be different depending on whether the change is positive- or negative-going.

The datasheet may quote response time as a time constant, which is the time for the sensor signal to change from zero to 63.2% of full-scale range when an instantaneous full-scale change in pressure is applied.

Faster-acting sensors may be described in terms of their frequency response, or flat frequency, which is the maximum pressure-change frequency that can be converted into an output signal without distortion.

Dynamic linearity is an important parameter in applications that must monitor rapidly changing pressure. It can be influenced not only by the response time, but also by other characteristics such as amplitude and phase distortion.

LONG-TERM STABILITY OR NATURAL DRIFT

Sensor accuracy tends to drift over time, due to ageing, environmental factors, and other application-related influences and factors. Such drift is not predictable, and may have a positive or negative change coefficient. Referring to the previous datasheet sample, TE expresses the long-term stability as a percentage of the full-scale range, over a period of one year and assuming the current and temperature are constant. Hence stability as quoted in the datasheet can only be used as a guide and not as a guarantee of performance in the target application.

OTHER OPERATIONAL FACTORS TO CONSIDER

In this chapter, we've described key factors that affect the accuracy of a pressure sensor. Depending on the application, some aspects such as dynamic performance or resolution may be less important than others like linearity or temperature-related drift.

Once the optimum sensor has been selected on paper, it's important to remember that other factors such as the equipment design, and day-to-day use can also influence pressure-sensing accuracy on setup and in the longer term.

Improper installation, for example, is often the underlying cause if a system fails to deliver the expected accuracy when deployed. This could be prevented by design, or by ensuring the equipment is shipped with clear installation instructions.

Application-related variables such as temperature, specific gravity of monitored fluids, dielectric characteristics, turbulence, changes in atmospheric pressure, or unexpected obstructions, blockages or vapour locks may also impair accuracy. Taking any likely effects into account when designing the equipment, and where possible selecting sensors that are immune or benefit from suitable compensation, can help to mitigate or avoid unacceptable inaccuracy.

And, of course, ensuring initial calibration, with regular recalibration and suitable intervals, is essential to safeguard long-term accuracy.