Get ahead of Condition Monitoring and Predictive Maintenance with sensors

Practical insights on how to implement magnetic sensor-based vibration sensing and barometric pressure air-flow monitoring

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Abstract

This article explains the importance of using semiconductor-based sensors as the basis for systems that provide accurate Predictive Maintenance and Condition Monitoring to save money and reduce downtime.

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1. Why Condition Monitoring and Predictive Maintenance are important?

Almost everything needs maintenance to ensure that it functions correctly. Parts wear out and need to be replaced but waiting till something breaks to replace it can be very costly. Unscheduled downtime can mean lost productivity, inconvenience or expensive overtime rates. Just think how much you would have to pay a plumber to come out at 3am on Christmas day.

You could study how long parts typically work before they need replacing. For example, historically every two years a part needs replacing, so you schedule a replacement every year and a half. This is called Preventative Maintenance. However, you can still be caught out by a part failing earlier than expected and conversely a part might still have plenty of useful life left in it when replaced, for example, replacing filters in HVAC equipment before they need to be changed as dust levels have been unusually low. Both scenarios cost you money.

Far better to continually monitor a device or system to provide an early warning for when something is actually starting to go wrong. You can then schedule in a replacement at a convenient time before it becomes serious.

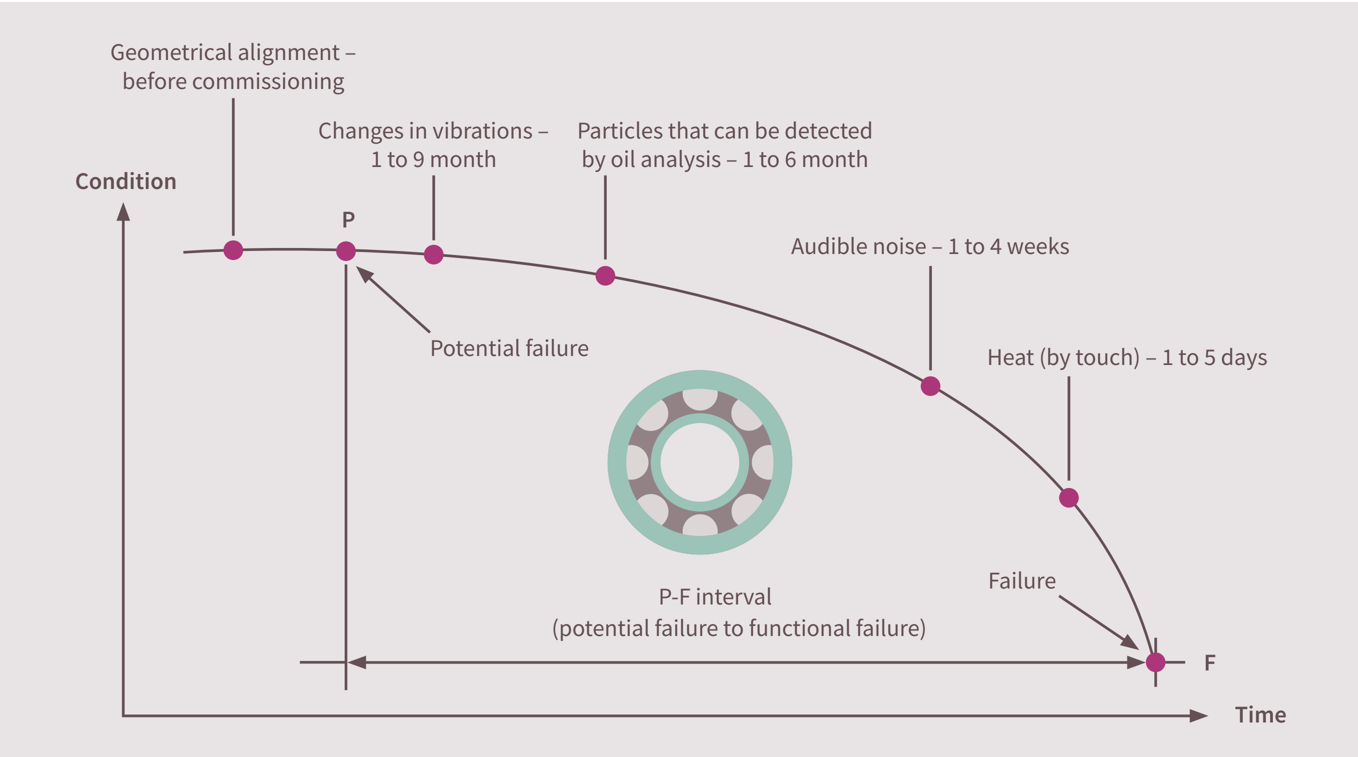


Figure 1: Potential-to-failure diagram for ball bearing

The easiest way to understand this is with a simple mechanical example which in this case is a ball bearing. Please see figure 1. It starts out in perfect condition, which then deteriorates as parts wear through use. This can be detected in stages as shown on the graph. Initially, changes in vibrations occur as wear starts and, as this wear continues, particles created by wear can be found in the lubricating oil. Then you start to hear the noise caused by the worn parts that then start rubbing together badly enough to generate heat from friction. And finally, it seizes up and fails.

Here is another example, which this time is for a motor. Please see figure 2. Here you can see how different techniques can be used to detect problems in sequence on the path to failure. This enables an informed decision to be made on the timing of the motor replacement based on a detailed understanding of the motor's actual fault status.

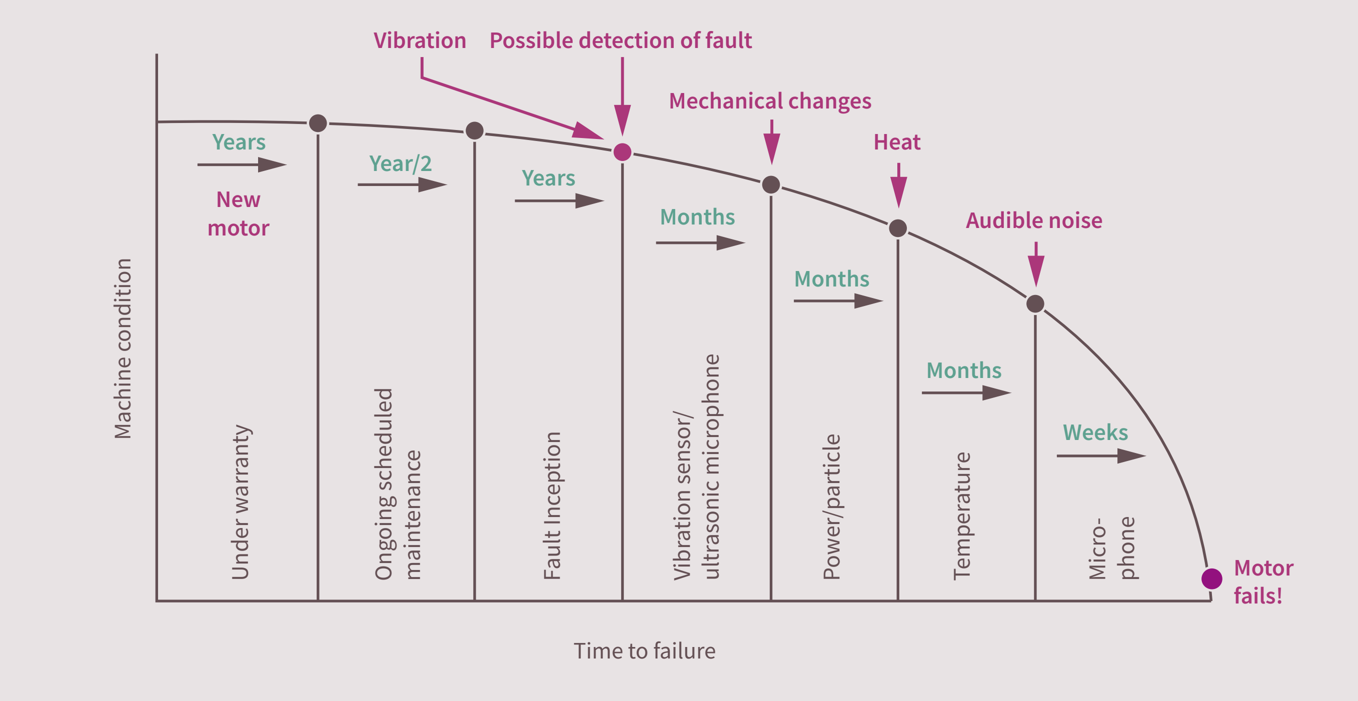


Figure 2: Potential-to-failure diagram for an electric motor

2. How semiconductor sensors are becoming the solution of choice

One of the traditional ways to monitor equipment was to use piezoelectric (PE) vibration sensors but these solutions can be large, complex and relatively expensive to implement, which has limited their deployment.

Instead, designers are now using MEMS (Micro-Electro-Mechanical System) sensors that can provide similar or better performance levels to PE. These miniature devices combine mechanical and electrical components on a microscopic scale. Mass production enables these to be less expensive than PE. They can also have electronics integrated into the packaged sensor such as Analog-to-Digital Converters (ADCs), filters and even some on-chip processing of data to make them smart. This makes them easy to integrate into intelligent monitoring solutions leading to their increasingly widespread use.

3. Support structure for sensors

Once the raw data has been collected from the sensors, microcontrollers process the data at the edge so that it can be forwarded further on in the system. It is more efficient to send processed rather than raw data. It is known as Edge Processing or Edge Computing.

There are several ways to take this data to the next stage. This can be wirelessly using one of the many options such as Bluetooth, Wi-Fi etc. or wired depending on the system. For example, wired might be a better choice in an electrically ‘noisy’ factory. Sometimes this connection may need to be two-way to provide command and control back to the monitored equipment.

All the information from the deployed network of sensors is brought together and analyzed using special software, which is usually based in central building management or cloud systems, and intelligently determines the status of equipment being monitored and if any actions need to be taken. This is the Enterprise stage and has the Human Machine Interface (HMI) for presenting the status with dashboards and graphs, etc. in a user-friendly way.

4. Innovative 3D magnetic sensor for vibration measurement

Vibration monitoring is often used for condition monitoring as it provides an early warning that a mechanical device is not running smoothly. A part that starts to wear moves asymmetrically and starts a detectable vibration. With appropriate analysis of the amplitude and frequency of the vibrations, more details can be determined as to the precise cause such as load imbalance, misalignment or ball bearing wear.

Normally, this is detected using an accelerometer that has to be physically attached to the part being monitored for best results otherwise distance attenuates the vibration and weakens the signal. However, if this is located deep within a device, such as on a motor shaft, it is not easy to access and replace if needed and, in addition, getting the data out is also challenging. It must also be small so that its mass does not affect the machine's vibration characteristics or cause an imbalance.

Infineon has a novel solution to this that uses a Hall-based, 3D magnetic sensor. As this detects changing magnetic fields, the sensor does not have to be on the moving part, i.e. there is no physical connection required. For example, a magnet can be fixed to the shaft and the sensor located on the housing (providing this does not block magnetic fields). The magnet can therefore be small or designed in a way so that its mass has minimal effect on the performance of the part being monitored thus solving the issue with accelerometer sensors mentioned in the paragraph above.

This ability to locate the sensor remotely from the moving part without compromising the sensitivity opens up new applications that require physical isolation, such as those where it is very hard or dangerous to access due to high voltages or chemicals.

Interestingly, the analysis of the results from this 3D sensor is different from those of an accelerometer. In the latter case, the acceleration information needs several stages of filtering and processing to generate useful intelligence on what is happening. Specifically, the stages are first, DC removal to eliminate sensor bias and any effects of gravity. This signal provides accelerator information directly and can also be integrated over time to provide the velocity. Further processing with an FFT moves this from the time domain into the frequency domain, where frequency peaks can indicate issues such as a part hitting another part and harmonics indicating a general looseness, for example.

The 3D sensor data, however, requires much less processing to provide useful intelligence about what is happening as it gives the absolute/relative position so that even the amount of bend of a component can be detected, making it especially useful for deriving displacement and velocity information. It measures all three components of a magnetic field simultaneously, which opens up a multitude of applications with different ranges. From the components of a magnetic field, the distance between the sensor and the magnet can be modeled and calculated. From the distance between the sensor and the magnet, the absolute displacement can be obtained and, with differentiation, the velocity can be calculated.

5. Example 1: How to use a 3D magnetic sensor to detect linear movement

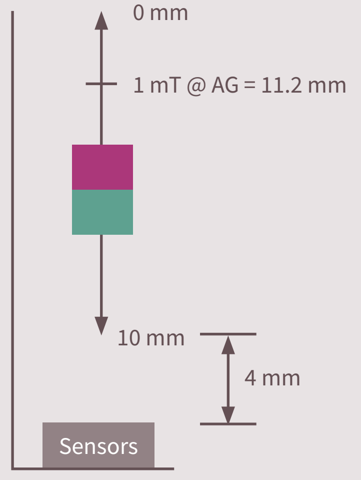


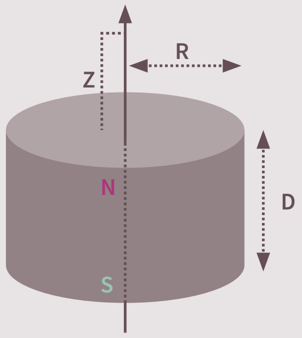
Figure 3: This setup detects movement in one direction, in this case it is up and down, i.e., the z-axis. In the illustration, a cylindrical bar magnet is shown as the red and blue block that moves closer or further away from the sensor in a 'heads on' configuration

Looking at the relationship between the magnetic field along the z-axis and the shape and distance of the magnet, the formula for measurement of the movement along the z-axis is:

Formula for cylinder magnet flux density

Formula for the B field on the symmetry axis of an axially magnetised cylinder magnet (disc or rod):

$$B=\frac{B_r}{2}\left(\frac{D+z}{\sqrt{R^2+(D+z)^2}}-\frac{z}{\sqrt{R^2+z^2}}\right)$$



B_r: Remanence field, independent of the magnet's geometry (see physical magnet data)
z: Distance from a pole face on the symmetrical axis
D: Thickness (or height) of the cylinder
R: Semi-diameter (radius) of cylinder

Figure 4: Formula for cylinder magnet flux density and illustration

For z >> l, i.e., far from the magnet, the field is:
$B_z(0,0,z) \sim \mu_0 m / 2\pi z^3$ where $m = M_0 \pi a^2 l$

Unlike gravity and electromagnetic radiation that decrease by the square of the distance from the source, magnetism diminishes by the cube of the distance, i.e., there is a much steeper field decline as distance increases. On the one hand, long-range detection sensitivity decreases with distance but, on the other hand, this provides very sensitive short-range detection as small distance changes have a big impact on the strength of the magnetic field. Moreover, this also means that this sensing technique is less sensitive to interference from stray fields and other magnets.

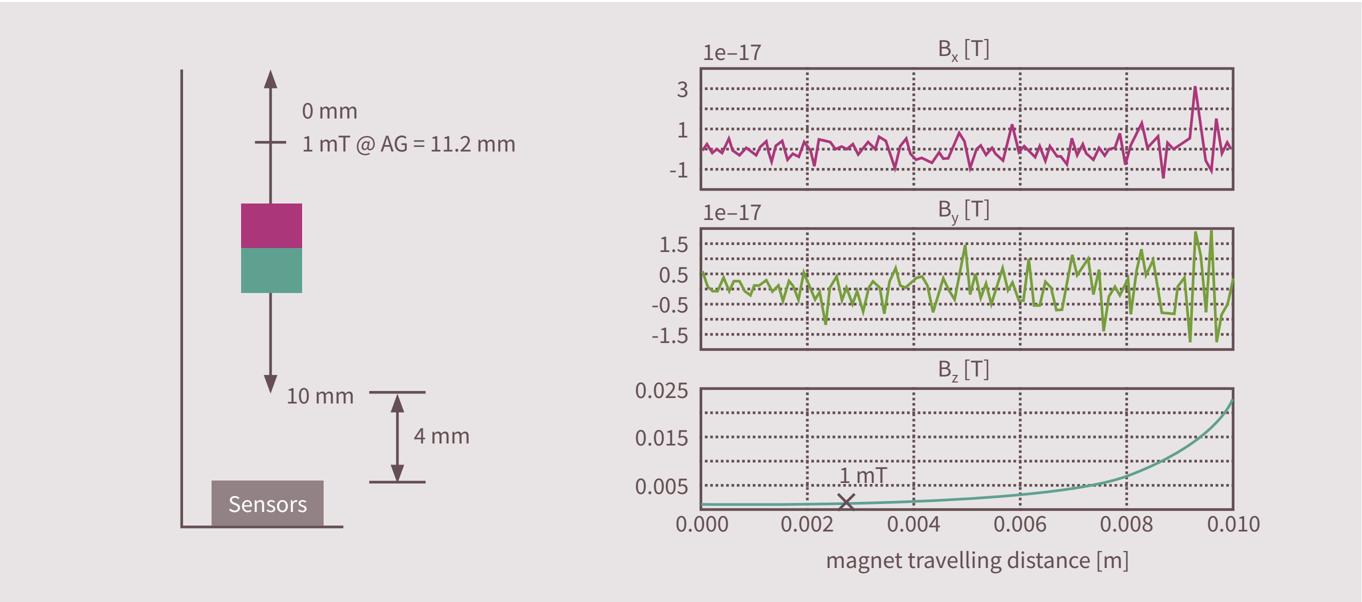


Figure 5: This shows a one-dimensional movement along the z-Axis with the B_z component being illustrated at the bottom

Please note that any influence of temperature changes must be cancelled out by the microcontroller in order to get proper position detection.

From here, two things can now be concluded:
- from the magnetic field, the position z along the z-axis can be calculated (direct absolute/relative position)
- from the magnetic field, a direct threshold can be 'defined' that relates to a long, big, absolute movement (maximum vibration & movement). This enables detection of crossing the 'wake up' upper and lower thresholds

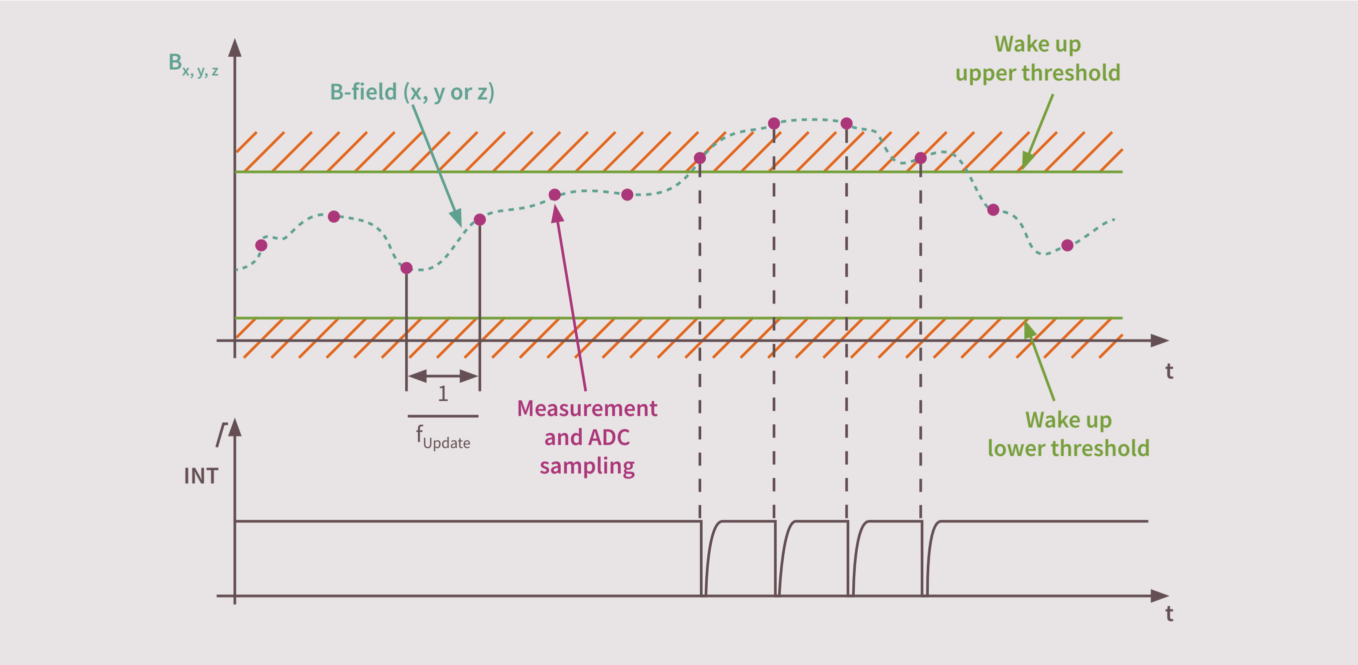


Figure 6: The extremely small form factor of the sensor means that designs can be created with double-sided printed circuit boards or with the sensor positioned between two PCBs as a buried sensor. The figure shows how changing threshold levels of the field between the PCBs can be used to trigger actions

The above features can be implemented with all members of Infineon's TLx493D product family with magnetic measurements along the x, y, and z-axis and wake-up detection. More details can be found in this article including the description of the 3D magnetic sensor here.

Further details can be found in a 3D magnetic sensor application note here.

6. Example 2: Patented barometric pressure sensor for air-flow measurement

The commonly used pressure sensors have a membrane to protect the sensor structure from dirt, humidity and liquids. Imagine the structure being in a box with a lid and a hole in the lid covered by a membrane to keep water and dirt out. However thin and flexible this protective membrane is, it reduces the ability of the sensor to detect pressure changes, i.e. it decreases the sensitivity to pressure changes.

Infineon's patented solution to this is to protect the MEMS sensor with a layer of gel, which enables it to detect pressure changes without the possibility of damage to the sensor by ingress of materials. It also means that the sensor is waterproof to an IPx8 certification (which means that it can withstand be submerged in water deeper than one meter) and, specifically, can be 50m underwater for up to one hour.

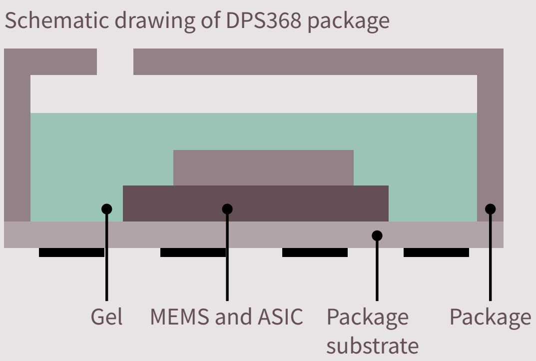


Figure 7: Schematic drawing of the XENSIV™ DPS368 pressure sensor package showing the gel protecting the MEMS structure and the hole in the casing to enable pressure changes to be detected

The use of gel has several advantages over the normal protective membrane approach. First, it can handle higher pressures with higher accuracy as there is no stiff membrane to rupture or to influence measurement precision. Infineon's XENSIV™ DPS368, for example, can handle pressures from 300 hPa up to 1,200 hPa. Second, as there is no protective membrane interfering with the pressure change, the sensitivity to pressure change is much greater than with a membrane design. This enables pressure changes of as little as ±0.002 hPa or ±2 cm of atmospheric pressure change to be detected. It is so sensitive that it can even be used to detect the changes up or down a single stair, body motions and hand gestures. Third, it helps protect the MEMS sensor from shock making it more robust and ideal for use in wearables that are often dropped for example.

How do you use a barometric pressure sensor to detect air flow? Remember the Bernoulli* effect that enables a plane to fly, i.e., air flowing over the curved wing surface causes a drop in air pressure that lifts the wing. In this case, air/gases flowing through a pipe cause a change in pressure that is proportional to the speed of the air flow, i.e., a change in air flow causes a detectable change in pressure. The sensor can be located within the pipe to monitor pressure levels and gas flow rates within it as a self-contained item, i.e., there is no need to cut an access into the pipe to sample the pressure inside.

***Bernoulli's equation**

$$\frac{v^2}{2} + \frac{p}{\rho} + gz = \text{constant}$$

Where:

v is fluid velocity

p is fluid pressure

ρ is fluid density

g is gravitational constant

z is elevation

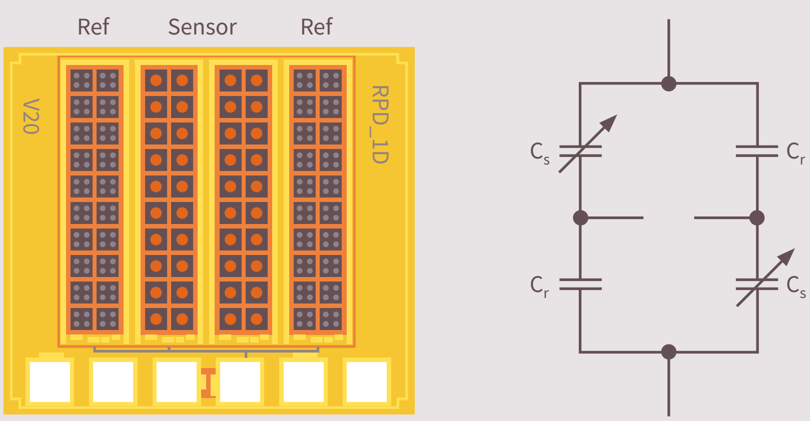


Figure 8: The cell structure of the capacitive sensor enables differential measurements with very low temperature drift

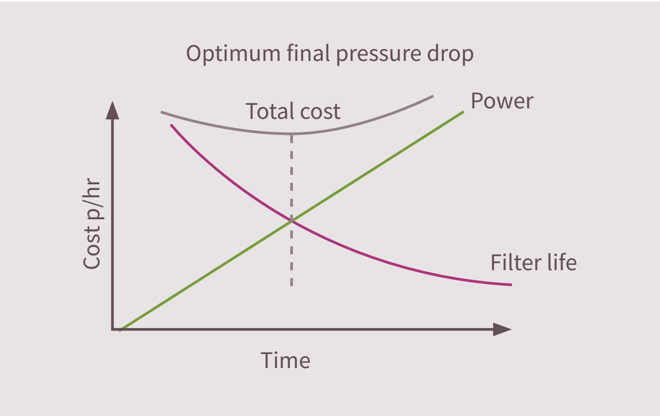
The sensing is done by detecting a change in the capacitance of the MEMS structure which requires much less power than the resistive measurement technique of piezo-resistive sensors. It means that the latter are best suited to mains-powered applications. The cell structure and capacitive bridge configuration developed are illustrated in figure 8. The capacitive barometric pressure sensor consists of four arrays of sensing and reference cells. The sensing cells have a flexible membrane that reacts to pressure change and provides the air pressure measurement. The reference cells have a stiff membrane that does not react to pressure changes and provides a stable measurement reference.

The benefit of this type of structure are:

› the pressure measurement can be differential, and both sensing and reference cells are exposed to the same temperature changes thereby negating temperature drift effects, which can be a significant problem for piezo-resistive sensors.

› it is up to 80% smaller than other waterproof pressure sensors enabling it to fit into a single, extremely compact, eight-pin, LGA package that measures just 2.0 × 2.5 × 1.1 mm.

This pressure sensor has very low power requirements (up to 50% less than piezo-resistive technologies) making it ideal for battery-powered devices as the average current consumption is 1.7 µA for pressure measurement (only 0.5 µA in standby mode). For flexible system designs, the sensor is configurable for different use cases to optimize the resolution in balance with the energy consumption as that is directly proportional to the measurement frequency. Different operation modes (high-precision, standard, low-power, and ultra-low-power) coordinate with different precision (± 0.002 hPa in high-precision mode) and measurement rates (single-shot and up to 128 Hz). For example, one-time measurement can be configured for high, single measurement accuracy, while the option to take several measurements per second addresses the needs of continuous monitoring. Operating in low-precision mode, for example, the current consumption is 2.1 µA with one measurement/second and less than 1 µA at standby mode. Operating with maximum precision, the sensor has a current consumption of about 38 µA.
An application example, where its low power consumption makes it ideal, is for an HVAC system with meters and meters of air ducting that includes filters in various locations. Strategically installed, air-flow monitors provide an alert to a drop in air flow caused by filters that need changing.



Sensing the pressure drop across an air filter to determine when it needs to be changed also minimizes unnecessary power consumption by motors caused by dusty filters especially as energy consumption is a major cost in running an HVAC system. The diagram shows the optimal change-out point of an air filter, i.e., the point where the pressure drop increases electrical consumption and overtakes the cost of installing a new filter.

Figure 9: Shows pressure dropping as a result of dusty filters and the associated costs

As these monitors can be self-contained, battery-powered units with wireless connectivity, this is a much more cost-effective solution than using membrane-based sensors that need mains power and therefore incur the costs of power cable and cable installation. They are therefore also easier to retro-fit in existing installations.

These use the Venturi effect which is the reduction in fluid pressure (and increase in velocity) that results when a fluid flows through a constricted section of pipe and is an application of Bernoulli's equation. The flow is related to ΔP (P1-P2) by the equation:

$q = c_d \pi/4 D_2^2 [2(P_1 - P_2) / \rho(1 - d^4)]^{1/2}$

Where:
q is the flow in m^3/s
c_d is the discharge coefficient, the area ratio = A_2 / A_1
P_1 and P_2 are the respective pressure in N/m^2
ρ is the fluid density in kg/m^3
D_2 is the orifice, venturi or nozzle inside diameter (in m)
D_1 is the upstream and downstream pipe diameter (in m)
and $d = D_2 / D_1$ diameter ratio

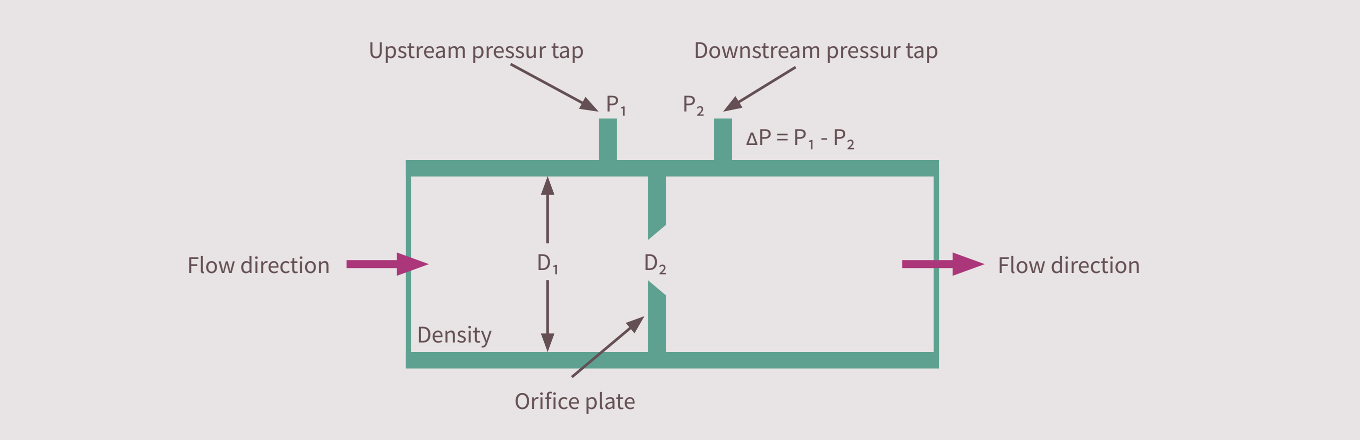


Figure 10: The Venturi effect. The static pressure in the upstream P_1 is higher than at P_2 because the cross-sectional area of D_1 is greater than D_2

In summary, this provides a very robust and waterproofed solution that is ideal for a variety of applications in harsh environments, especially dusty or damp/wet ones. Target applications are air flow monitoring and Predictive Maintenance in, for example, home appliances such vacuum cleaners, and HVAC systems.

Further details for system integration can be found in a barometric air pressure sensor here.

7. Conclusion

The new generation of sensors are much smaller than previous technologies. These MEMS (Micro Electro-Mechanical Systems) solutions enable electronics to be integrated with them to give them the ability to process data and make decisions. This enables smarter solutions to be created that ensures that equipment operates in an optimal efficient manner as well as ensuring that equipment is pre-emptively fixed or replaced before expensive, disruptive issues or failures occur.

Please contact Infineon to see how our sensors can add value to your equipment by ensuring that it operates at peak efficiency with a long lifetime creating better customer satisfaction.

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