White paper

Innovative pressure transmitter signal conditioning with **Danfoss QDC™ excitation**

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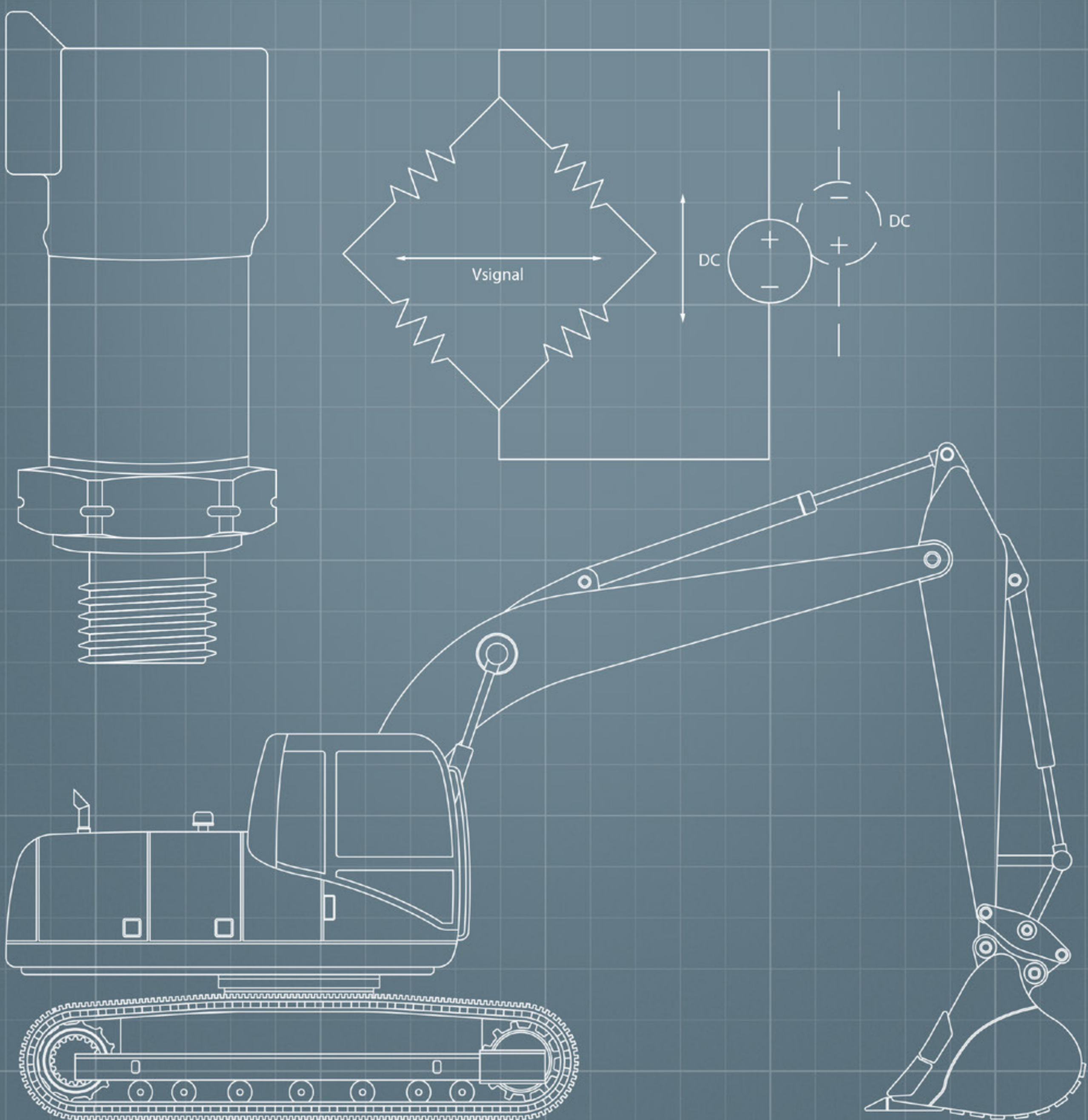

Executive summary

This is the third white paper in a series of three addressing how digitalization and the industrial evolution are impacting industrial sensors. The first white paper, Smart Sensor Connectivity of Tomorrow, unpacks what's driving digital sensors across major industries—today and in the future. And the second white paper, Communication protocols for wired digital sensor interfaces, explores how the new sensor system architecture allows us to find new ways of passing data along to a system.

Read them here

In high-pressure, heavy duty sensor applications—from mobile hydraulics to industrial engines— Micro Electro-Mechanical System (MEMS) and Thinfilm piezoresistive Wheatstone bridge technology is widely used. And within these sensors, pressure and load cell, strain gauge, and Wheatstone bridge-based measurement systems are often challenged by factors like zero-point drift, 1/f noise, and line noise—not to mention the rising restrictions around EMC and reliability.

That's why we set out to design the patented Danfoss Quasi-DC (QDC™), a new conditioning circuit that enables us to develop extremely stable, reliable, and high-quality pressure transmitters—in terms of both temperature and time. Furthermore, the goal was to achieve the utmost transmitter accuracy by minimizing the compensation effort with a mathematical high-order polynomial compensation—and minimize or even eliminate some of the part-to-part variations, especially in analog solutions.

In this white paper, we unpack the challenges that led our engineers to develop the new technology—and how the QDC™ excitation of MEMS and Thinfilm piezoresistive Wheatstone bridge has been proven to improve both the short- and long-term stability as well as the signal-to-noise ratio and immunity towards extreme electromagnetic disturbances.

You will **learn about**

1. Piezoresistive MEMS and Thinfilm pressure sensors
2. Challenges faced by MEMS and Thinfilm sensors
3. Danfoss patented QDC™ implementation
4. Tested and proven: High-performance meets high-quality with QDC™

1. Piezoresistive MEMS and Thinfilm pressure sensors

A pressure transmitter is typically implemented using three building blocks: a sensing element (i.e., MEMS or Thinfilm piezoresistive Wheatstone bridge), a conditioning circuit, and EMC filtering/protection circuitry. As industrial sensors have evolved alongside Industry 4.0, conditioning circuit technology has shifted from purely analog processing to digital processing—which led us to develop our new digital processing-based conditioning circuit.

Basics of MEMS and Thinfilm technology

An integrated MEMS or Thinfilm pressure sensor is based on the piezoresistive effects of strain gauges to detect strain when pressure is applied. The strain gauges connect to form a Wheatstone bridge circuit which maximizes the output of the sensor and reduces its sensitivity to errors (Figure 1).

The typical implementation of a MEMS pressure sensor is based on silicon with four p-doped piezoresistive resistor elements implanted in an n-doped substrate. Conversely, the typical implementation of a Thinfilm pressure sensor is based on piezoresistive resistor elements such as nichrome (NiCr) deposited on top of a silicon-dioxide-based isolation layer.

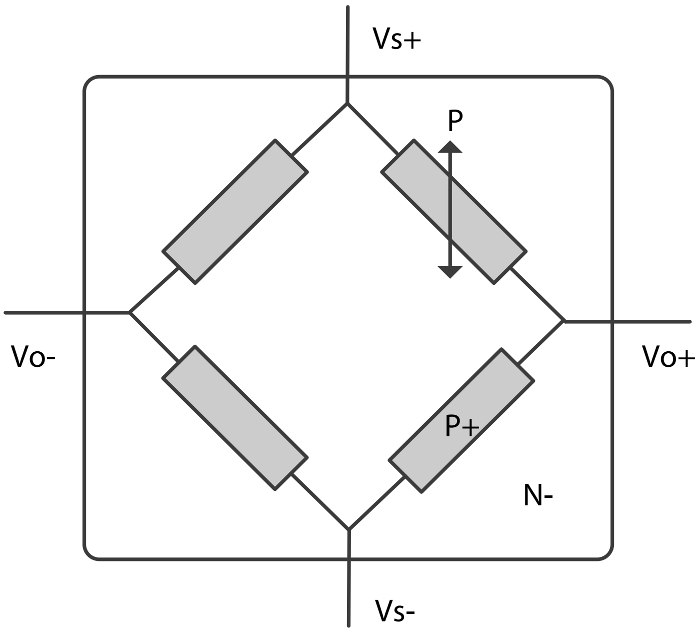

Figure 1: *A piezoresistive MEMS or Thinfilm sensor Wheatstone bridge*

Sensor output signal

The sensor signal from a MEMS chip in a pressure transmitter is typically in the range of 10mV/V for full-scale output—wheras the output from a Thinfilm-based sensor is typically 5–10 times lower.

Using traditional DC bridge excitation in a desired dynamic range of 70–80 dB, the DC error signals should be in the range of 1–5 µV and even lower for Thinfilm—a requirement that's quite difficult to fulfil in the specified temperature range.

2. Challenges faced by MEMS and Thinfilm sensors

While MEMS and Thinfilm technology is broadly used, there are many challenging factors that can contribute to less reliable sensor performance—and ultimately, less reliable application performance. Here, we examine these challenges in closer detail, from zero-point drift and leakage currents to corrosion and EMI disturbances.

Sensor temperature dependency and linearity

The MEMS pressure sensor is temperature-dependent and inherently non-linear (Figure 2). Furthermore, the mechanics, oil-filling, and protection membrane affect the temperature dependency and contribute to non-linearity—creating a signficant need for compensation.

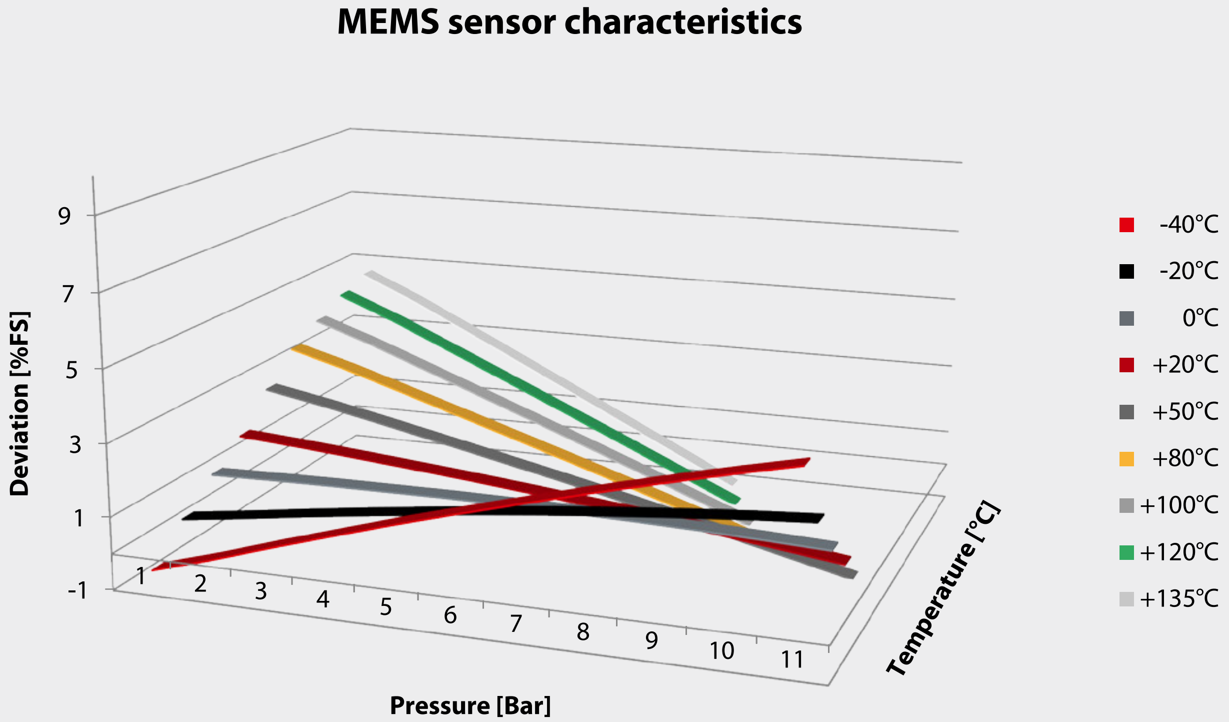

Figure 2: *Typical MEMS uncompensated characteristics showing full-scale output (FS) error.*

Generally, the Thinfilm pressure sensor is more linear—but has significant zero and span temperature dependency.

MEMS sensor substrate leakage

For a DC-excited MEMS pressure chip, the substrate is connected to the positive bridge excitation voltage—resulting in zero volts between the bridge top strain gauge and the substrate. The p-doped strain gauge and the n-doped substrate is in fact a diode—and diodes tend to cause leakage currents especially if they are not reverse-biased with more than 0.6 V. The leakage current is furthermore temperature dependent.

MEMS field-shield leakage

Having the MEMS sensor submerged in oil, the strain gauges must be shielded against additional charges due to the polarization of the oil. The MEMS chip is therefore protected by a field-shield— typically a metal layer covering the surface of the MEMS chip and connected to the bridge positive supply. This is quite similar to a Shottky diode, which is known to have significant leakage currents.

MEMS negative case (chassis) potential

The silicon strain-gauges and substrate form, to some extent, a p-channel enhancement MOSFET. A high negative case potential at the chassis with respect to the MEMS sensor can partly turn this parasitic MOSFET on—especially if the coverage of the field-shield is insufficient. The parasitic MOSFET will partially change the resistance value of the strain-gauge leading to primarily zero-point changes (Figure 3).

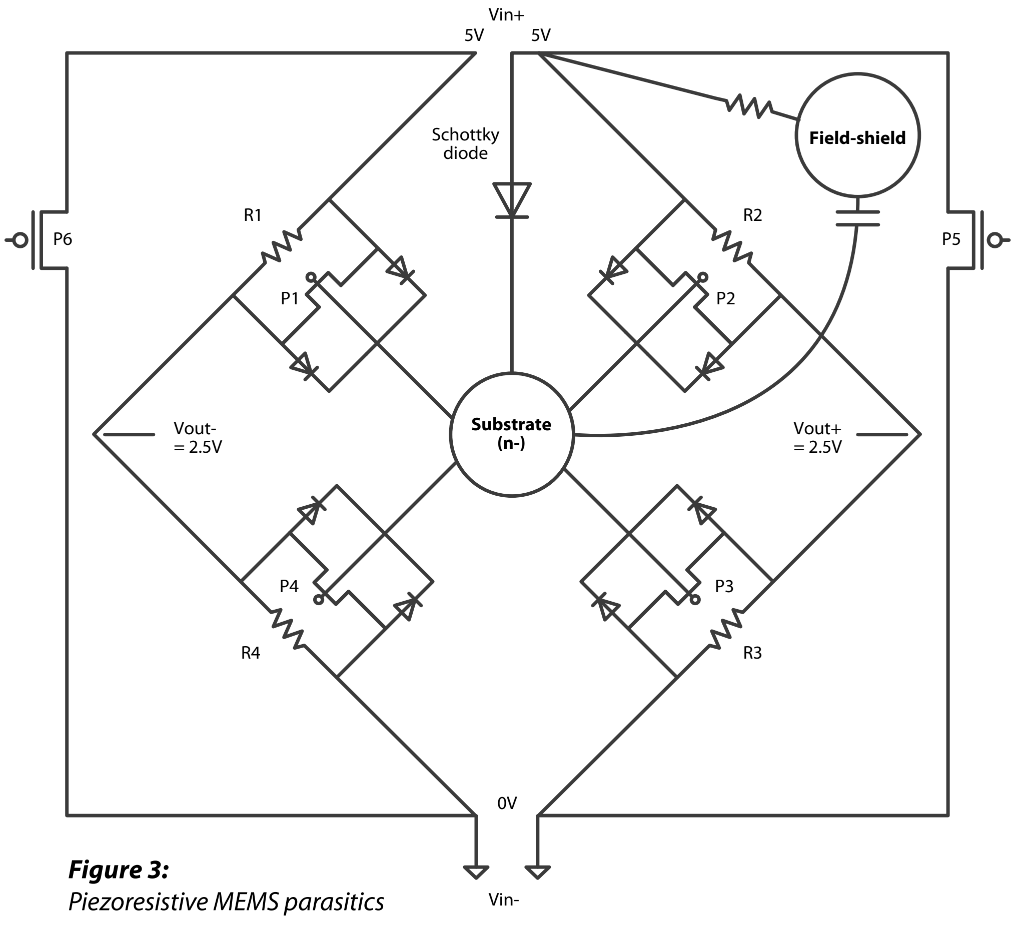

Figure 3:
Piezoresistive MEMS parasitics

MEMS and Thinfilm sensor bridge to chassis capacitive coupling

Although the strain-gauges are isolated (with MEMS having the substrate and glass below and with Thinfilm having a thin layer of silicon oxide below) the strain-gauges will have some parasitic capacitance to the chassis—Thinfilm having an order of magnitude higher than MEMS due to the very thin isolation layer.

With specifically conducted common-mode electromagnetic interference (EMI), some coupling via the parasitic capacitive couple will happen. If the signal chain is not perfectly balanced, this can cause EMI problems.

Thermoelectric effect (parasitic thermocouples)

The signal path between the sensor and the conditioning circuit consists of several different materials, and each time materials are joined, a potential DC voltage can be generated (due to temperature difference). This is known as the Seebeck effect.

Firstly, the circuit path is implemented symmetrically for inherent compensation. However, if a temperature gradient throughout the circuitry exists, a significant voltage can be generated. For example, Copper-Copper joints with one part oxidized have been known to generate several 100 µV/°C (Ref.1).
Thus, although the transmitter is zero-point compensated as part of the production flow, the DC error signal can change over time, e.g., because of moisture ingress.

Electromigration of wirebonds

The interconnection between the electronics and the pressure sensor is typically implemented using aluminum-based wirebonds. Under DC current stress, the wirebond life is limited by current density/direction and temperature.

Electrolytic corrosion Thinfilm

The resistor elements of a Thinfilm pressure sensor are metal-based (e.g., NiCr) and although protective methods such as passivation layers and more robust thin-film materials are used, they can be prone to corrosion when exposed to moisture and DC potentials (Figure 4).

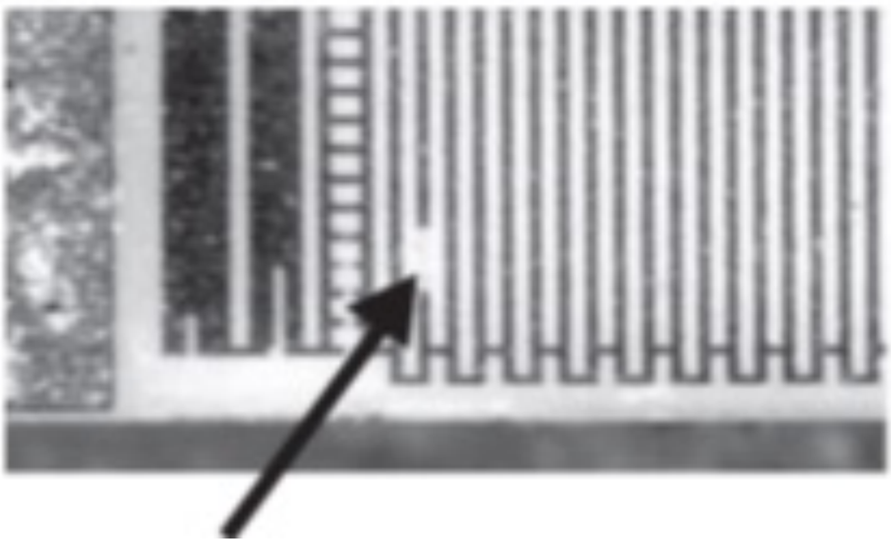

Figure 4: *Electrolytic corrosion of a metal-based meander*

Ref. 1: *Thermal EMF and Offset Voltage (April 2010) Thermal EMF and Offset Voltage - NI Switches Help - National Instruments*

Input amplifier

Offset voltage, bias, and offset current

All amplifiers, whether they are chopper stabilized or not, have error signals such as offset voltage, bias, and offset current at the input. Despite compensating for those parasitics during transmitter compensation, solder flux residues can cause problems later in the sensor's service life due to moisture ingress.

1/f noise (flicker noise) and thermal noise (white noise)

Noise is generated in all semiconductor devices (including MEMS) and passive components such as resistors (Figure 5). In general, noise is determined by the resistance level, current level, and temperature. Specifically for DC coupled systems, the 1/f—or flicker noise—plays an important role in determining the pressure transmitter signal-to-noise ratio.

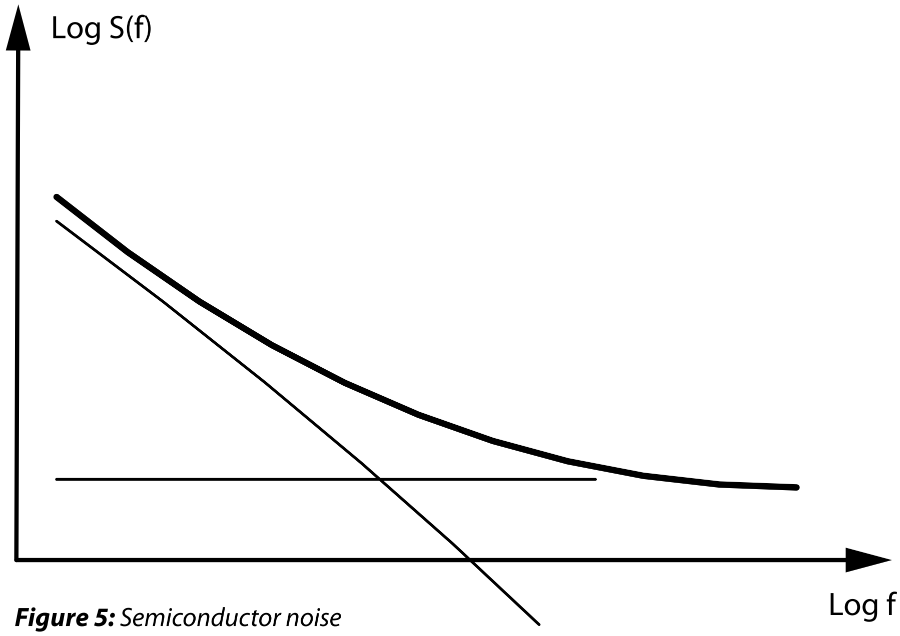

Figure 5: *Semiconductor noise*

Furthermore, both noise sources are temperature dependent, increasing proportionally with temperature.

3. Danfoss patented QDC™ implementation

Driven by mitigating the many potential error/drift sources of traditionally excited pressure sensors, we developed our new signal conditioning technology based on digital signal processing (Figure 6).

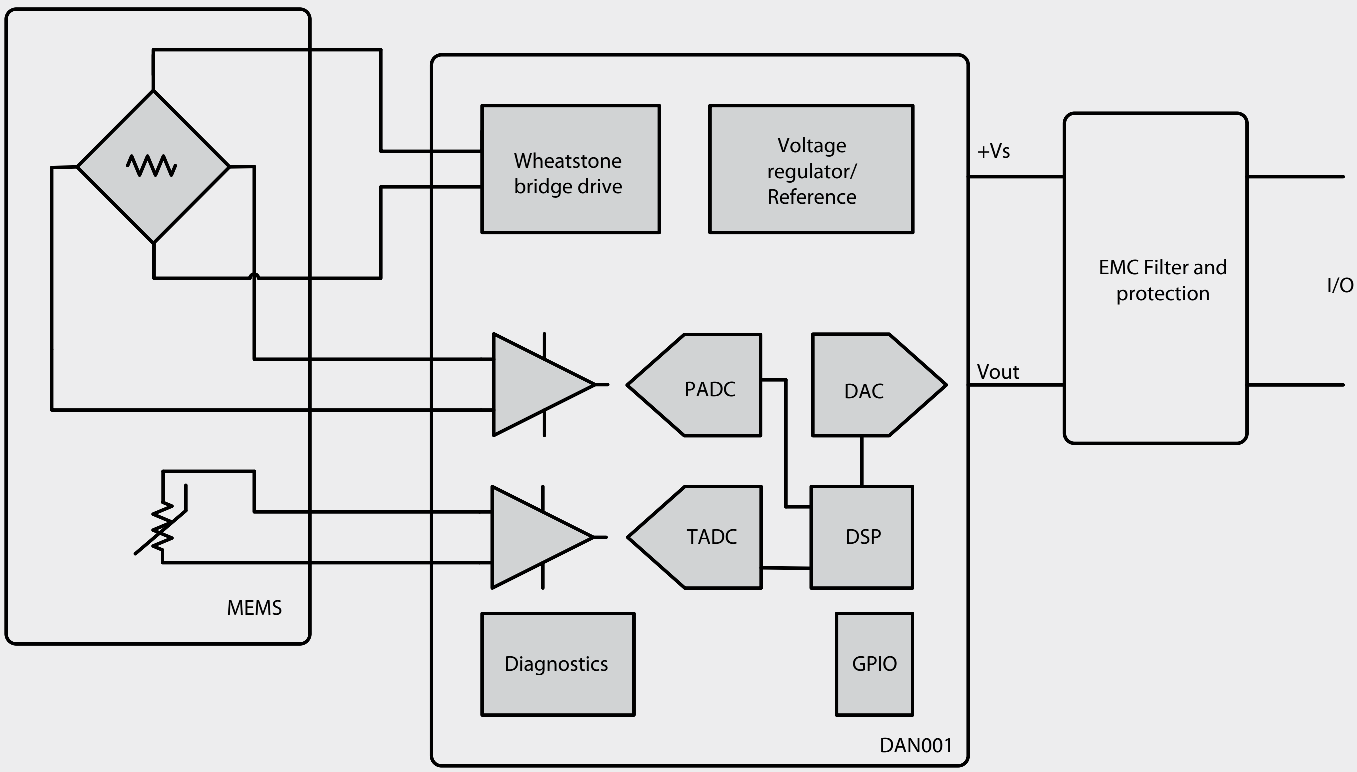

Figure 6: *The new Danfoss digital pressure transmitter*

The conditioning circuitry has two synchronous differential signal paths, one for pressure and one for temperature. The signals are amplified and consequently digitized using very high-resolution ADC's. Demodulation along with zero-point and span compensation is performed by a high-performance 32-bit digital processor before converting the digital signal back to analog using a high-resolution DAC.

QDC™ is a Danfoss protected trademark with registered patents covering the combinations QDC™ and MEMS (patent EP 2932218 B1, CN104870960 B) as well as QDC™ and Thinfilm (patent US9909944 B2, CN105393099 B).

QDC™ measurement principle

The basic idea behind using QDC™ bridge excitation is to implement a lock-in amplifier based on modulation and demodulation. In contrast to DC excitation, the QDC™ excitation pressure signal is an amplitude-modulated signal with the amplitude being proportional to the pressure. The detection is based on correlation, resulting in attenuation of any uncorrelated signal—such as DC signals (Figure 7).

Plus, using QDC™ over AC eliminated any phase shift or delay of the sensor output signal due to capacitive loading.

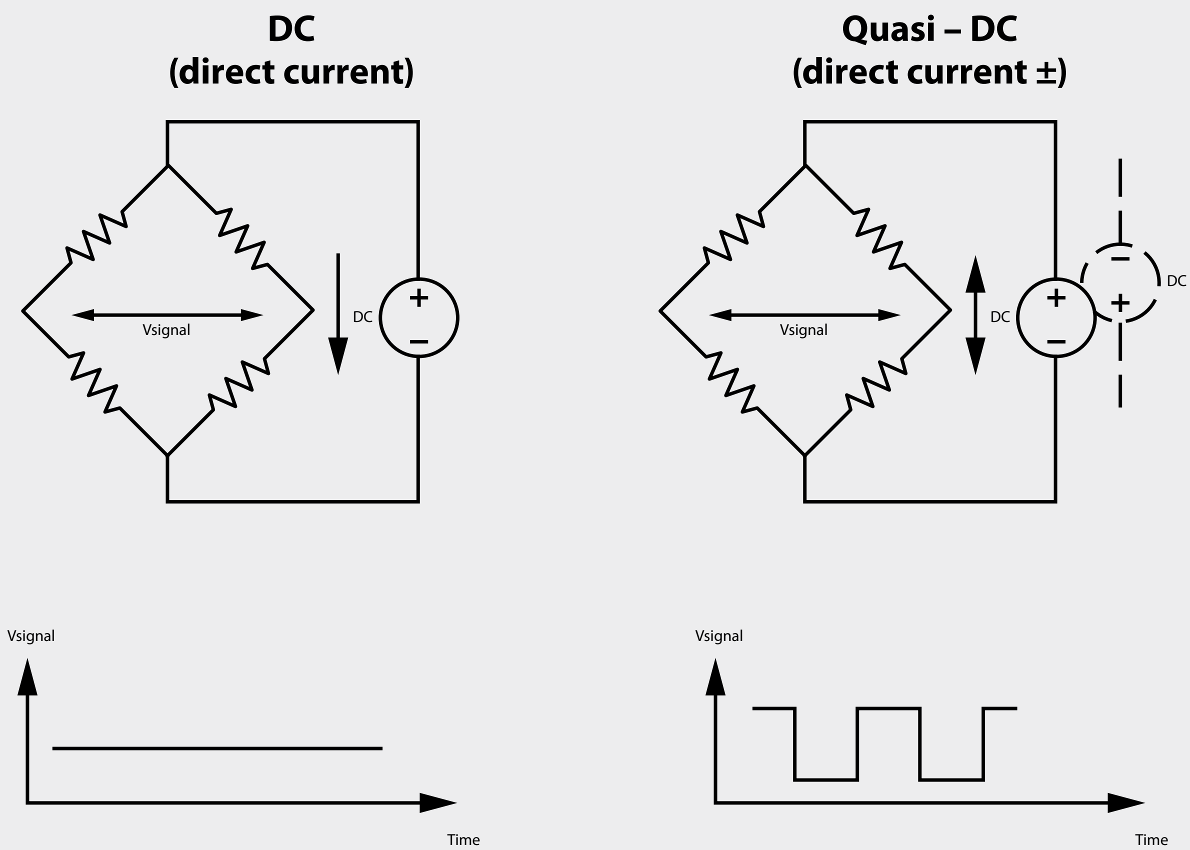

Figure 7: *On the left is traditional DC Wheatstone bridge excitation.*
On the right, the new, patented Danfoss QDC™ Wheatstone bridge excitation

Piezoresistive MEMS sensor, substrate voltage

A requirement of QDC™ excitation is that the substrate voltage of the piezoresistive MEMS sensor must have a higher voltage than that of the p-doped strain gauges; otherwise, the parasitic diode will conduct with one of the bridge excitation polarities—thus shorting the signal.

QDC™ demodulation and digital filtering

The sampling of pressure and temperature is performed immediately before changing the polarity of the bridge excitation—and the bridge output amplitude is simply determined by the difference between two consecutive samples (Danfoss implemented QDC™ is based on three samples resulting in a higher order filtering).

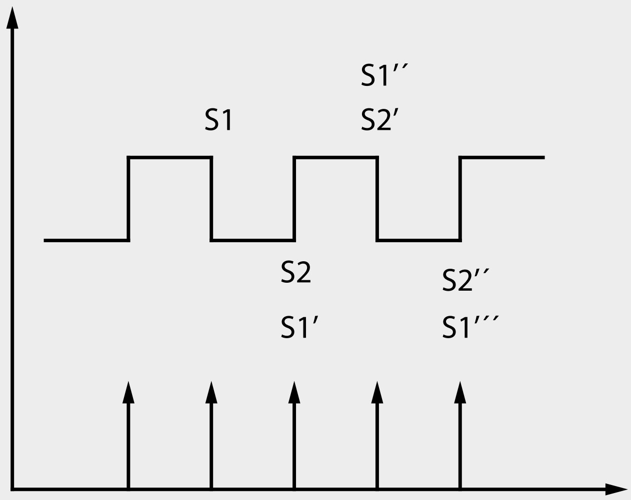

Figure 8: *Sampling and filtering of pressure and temperature with QDC™*

$$p = \frac{S1 - S2}{2} = \frac{(V_{bridge+} + V_{offset}) - (V_{bridge-} + V_{offset})}{2} = \frac{V_{bridge+} - V_{bridge-}}{2} = V_{bridge}$$

Equation 1: *Auto-zeroing filter*

QDC™ Auto-zeroing filter

Auto-zeroing is a 2-tap finite impulse response (FIR) filter (Figure 9) with coefficients 0.5, 0.5, resulting in a gain of 1 at DC, f_s, $2f_s$ and so forth and 'infinite' attenuation at $f_s/2$, $3f_s/2$, $5f_s/2$ and so on (Figure 10).

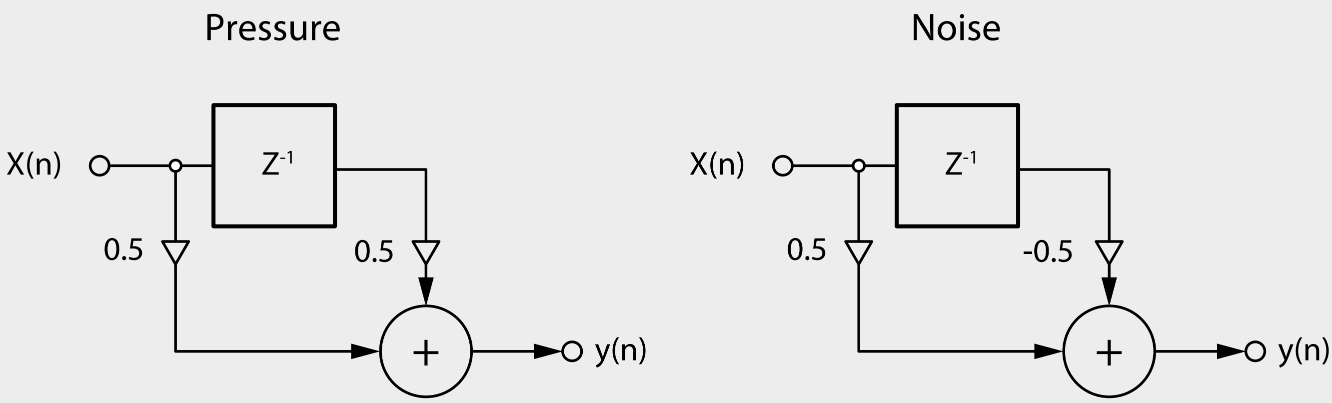

Figure 9: *Auto-zeroing FIR filter*

Any noise component that is uncorrelated to the bridge excitation frequency is filtered with the same 2-tap FIR filter, but with coefficient 0.5, -0.5 due to the demodulation. The result is 'infinite' attenuation at DC, f_s, $2*f_s$ and so forth and a gain of 1 at $f_s/2$, $3f_s/2$, $5f_s/2$ and so on (Figure 10).

The transfer function in the frequency domain for the two filters is described by (Ref. 2):

$$H(f) = 20\ log\left[\cos\left(\pi\left(\frac{f}{fs}\right)\right)\right]$$

Equation 2: *Pressure filter transfer function*

$$H(f) = 20\ log\left[\sin\left(\pi\left(\frac{f}{fs}\right)\right)\right]$$

Equation 3: *Noise filter transfer function*

Ref. 2: *S.K. Mitra; Linear-Phase FIR Transfer Functions*

Sigma Delta ADC decimation comb filter

The digital filter of the SD ADC processes the 1-bit data stream from the modulator using a SINC3 comb filter. The transfer function in the frequency domain is described by:

$$H(f) = 20\ log\left[\frac{1}{OSR}\ \frac{\sin\left(OSR\ \pi\left(\frac{f}{fM}\right)\right)}{\sin\left(\pi\left(\frac{f}{fM}\right)\right)}\right]^3$$

Equation 4: *ADC SINC3 comb filter transfer*

The oversampling rate (OSR) is the ratio of the modulator frequency f_M to the sample frequency f_s.

Resulting digital filtering

The complete signal chain of digital filtering is then a result of the auto-zeroing FIR filter and the ADC SINC3 comb filter.

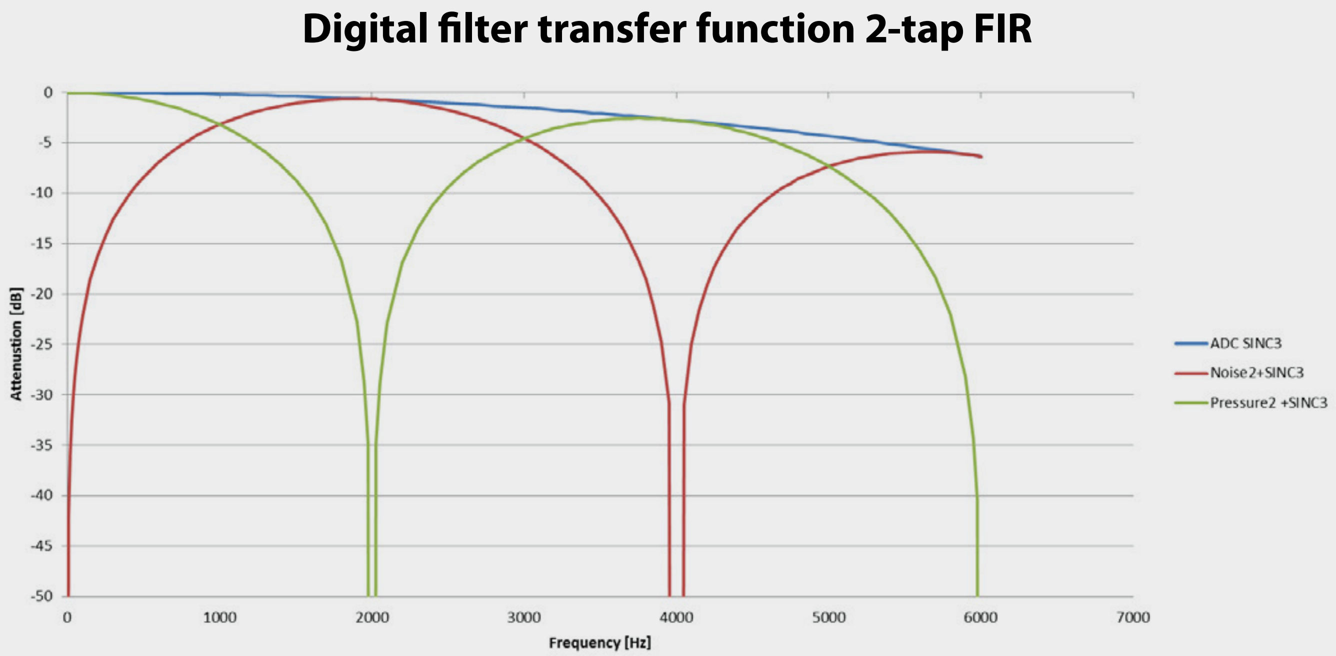

Figure 10: *Digital filter transfer function*

QDC™ response time

The QDC™ response time, including the latency time of the digital sampled system, is in the worst case three samples of 256 µs (i.e., 768 µs)—still less than the 1 ms system response time required.

QDC™ DC error filtering

Any DC signal—such as offset/bias of the input amplifier, parasitic thermocouples, etc.—that is uncorrelated with the excitation frequency will be filtered with 'infinite' attenuation of the 'Noise+SINC3' filter transfer function (refer to the red curve in Figure 10).

QDC™ and substrate/ field-shield leakage current

Using a DC voltage for the substrate and field-shield biasing any DC leakage currents will be attenuated by the auto-zeroing FIR filter.

QDC™ and negative case potential

Using DC voltage biasing of the field-shield will minimize the effect of negative case potential. The gate-source threshold voltage of the parasitic enhancement MOSFET is increased, requiring a much higher charge transfer due to oil polarization for partly turning the MOSFET on. Any DC leakage currents will be eliminated by the auto-zeroing FIR filter.

QDC™ and electromagnetic fields 50/60Hz 'line noise'

Any 50/60 Hz signal that is uncorrelated with the excitation frequency will be attenuated approximately 30 dB by the auto-zeroing FIR filter transfer function (refer to the red curve in Figure 10).

QDC™ and 1/f noise (flicker noise)/ thermal noise (white noise)

Due to the demodulation, the 1/f and thermal noise is uncorrelated to the pressure signal, hence the auto-zeroing FIR filter will result in significant noise reduction (the red curve in Figure 11). The 1/f noise is practically eliminated, and the thermal noise is reduced by a factor of approximately 2 due the bandwidth limiting effect.

Digital filter transfer function 2-tap FIR; Noise bandwidth

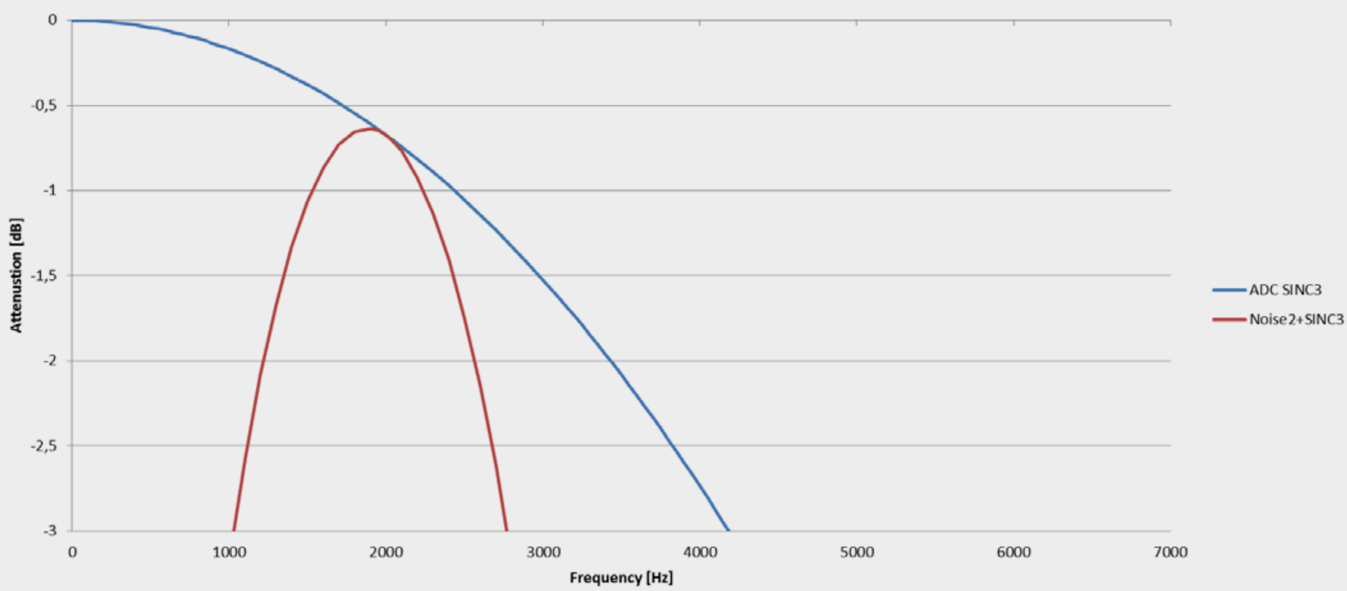

Figure 11: *Noise bandwidth*

QDC™ and Piezoresistive MEMS sensor, EMC

The reverse biasing of the parasitic diode will enhance the depletion layer, thus minimizing the capacitance between the strain-gauges and the substrate—a well-known and utilized phenomenon with Varactor diodes (Figure 12).

Minimizing the capacitance will have a direct impact on EMI—especially with conducted common mode signal, e.g., frequency converter switching noise. With the voltages selected, QDC™ has a factor two or more reduction of the capacitive coupling leading to improved EMI immunity.

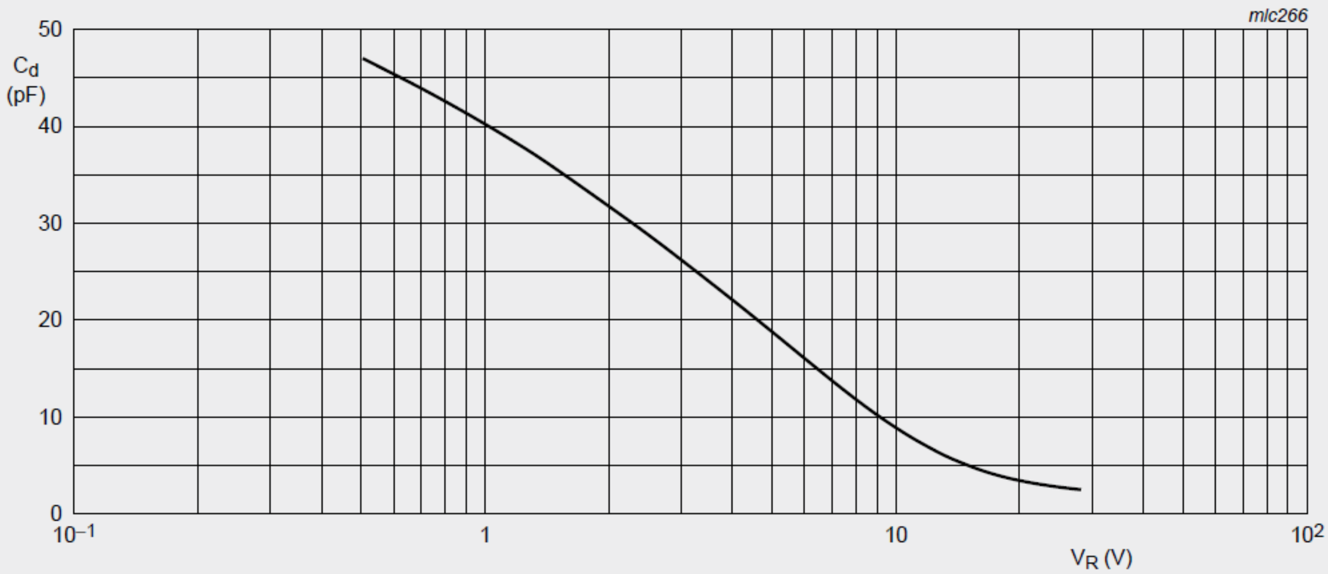

Figure 12: *Typical Varactor diode reverse voltage characteristics*

QDC™ and Electromigration

Without a DC current and utilizing only QDC™, changing the current direction with approximately 2kHz will significantly increase wirebond life by minimizing electromigration. Supporting research indicates the result is three orders of magnitude increase of the wirebond life (Ref. 3).

Ref. 3: *Metal Electromigration Damage Healing Under Bidirectional Current Stress, IEEE Electron device letters, vol 14, vol 12, December 1993*

QDC™ and Electrolytic corrosion

Similarly, QDC™ excitation will significantly inhibit electrolytic corrosion. An extreme/forced test clearly indicates the advantage for Thinfilm sensors (water droplet direct on non-passivated NiCr Thinfilm) (Figure 13).

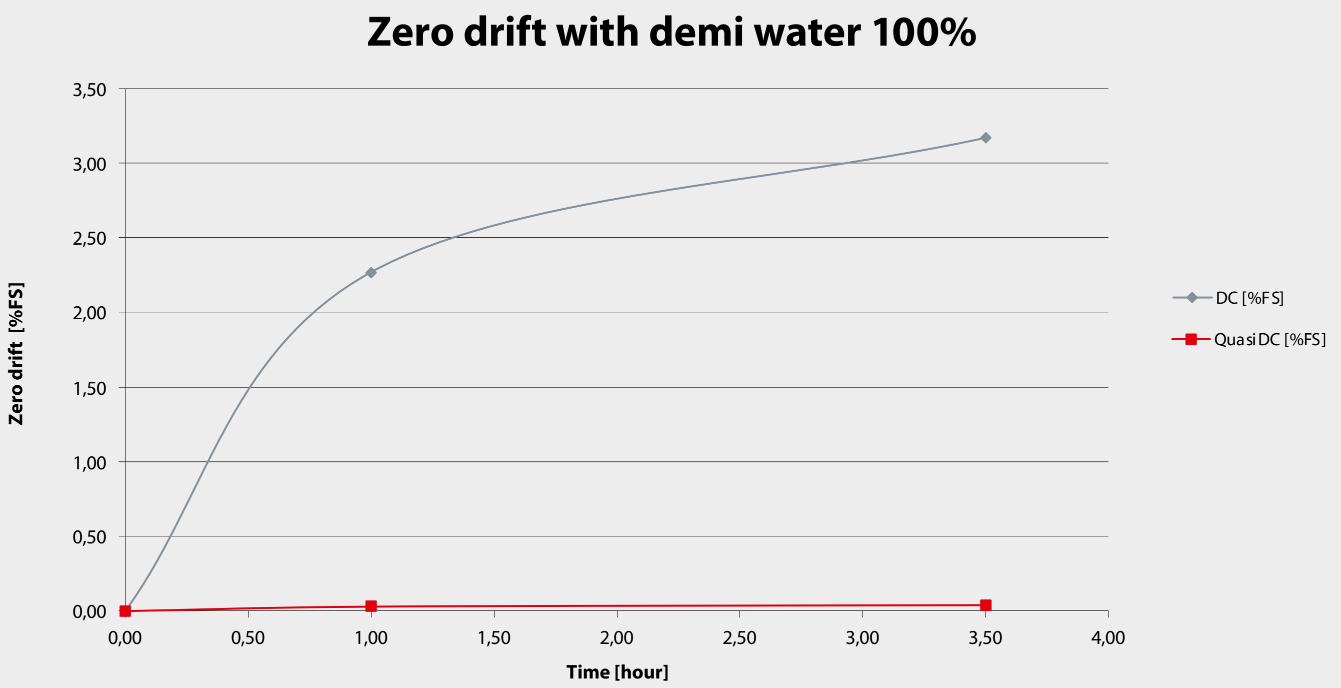

Figure 13: *Zero-point drift, forced humidity test QDC™ versus DC*

Mathematical polynomial compensation

To compensate for sensor zero-point and span temperature dependencies, the sensor output signal from the auto-zeroing FIR filter is compensated using a second-order polynomial with coefficients calculated based on the actual measured sensor temperature and previous MEMS or Thinfilm sensor characterization.

For each measured sensor temperature, the coefficients for the pressure compensation are calculated using a third-order polynomial

$$P(p,T) = \begin{bmatrix} A_0 & A_1 & A_2 & A_3 \\ B_0 & B_1 & B_2 & B_3 \\ C_0 & C_1 & C_2 & C_3 \end{bmatrix} \cdot \begin{bmatrix} T^3 \\ T^2 \\ T \\ 1 \end{bmatrix} \cdot \begin{bmatrix} p^2 \\ p \\ 1 \end{bmatrix} = \overline{\overline{Coeff}} \cdot \bar{T} \cdot \bar{p},$$

where $\overline{\overline{Coeff}}$ is the matrix of compensation coefficients.

Equation 5: *Mathematical polynomial compensation*

Calculations and conversions are performed every 256 µs.

This method has proven to be very effective in delivering excellent overall accuracy—and it allows us to significantly optimize our manufacturing process.

4. Tested and proven: High-performance meets high-quality with QDC™

Pressure sensors for harsh industrial applications must deliver long-term stability and reliability. With the many challenges faces by standard analog signal processing—combined with the increasing demand for future-proof solutions—we developed QDC™ digital signal conditioning that unites high-quality with high-performance.

Actual HTOL measurement result

We verified the exceptional stability of this new digital pressure transmitter using extremely comprehensive testing—including the high-temperature operating life (HTOL) test (Figure 14).

Sensor output drift over time under extreme operating temperatures

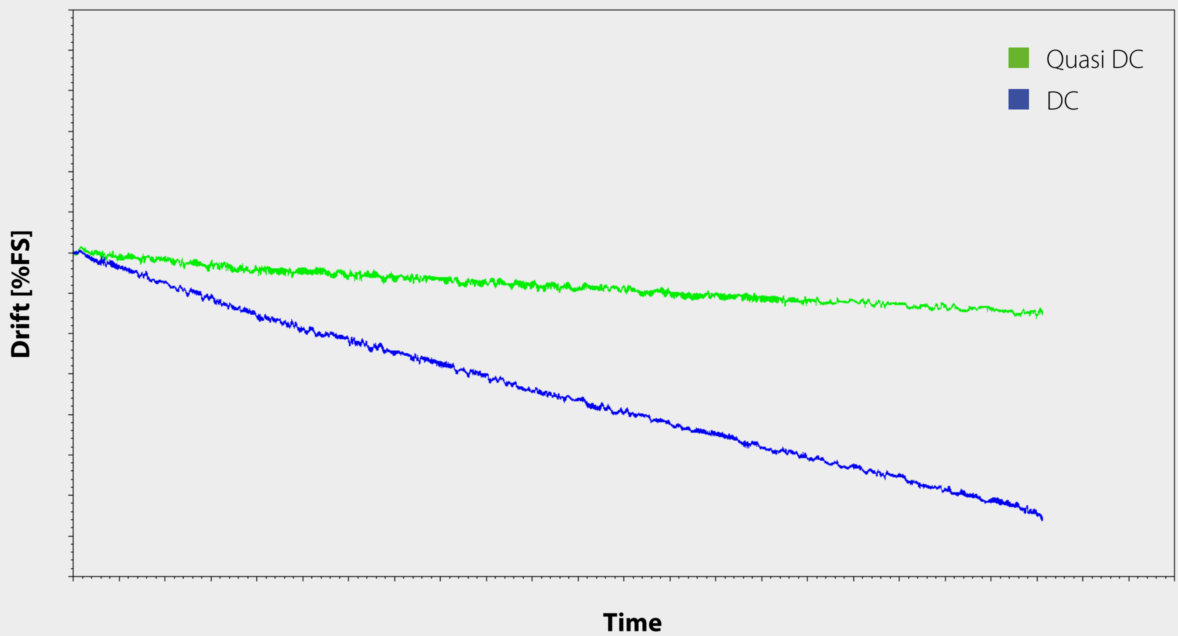

Figure 14: *Sensor long-term drift at elevated temperature*

The HTOL test is performed using the same MEMS transmitter hardware implementation, some with QDC™ excitation and some with DC excitation of the sensor bridge.

The test result in Figure 15 reflects both the performance and positive enhancement of QDC™ excitation on already excellent HTOL of our sensors.

Future-ready performance

Our engineers are dedicated to merging decades of expertise with the new technologies offered by Industry 4.0—all of which is driven by a passion for developing the industry's most reliable and high-performance sensing solutions.

With the QDC™ conditioning circuit, our pressure transmitters are now even more stable—and significantly reduce drift over time for long-lasting, future-ready accuracy.

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