All Sensors ***Pressure Points*** are application tips to simplify designing with microelectromechanical systems (MEMS) pressure sensors and avoiding common pitfalls.

Pressure Point 12: Making MEMS Pressure Sensors Easier to Use (Part 1)

Pressure is one of the most common measurements. Based on their small size, low cost and high reliability, microelectromechanical systems (MEMS) pressure sensors that use the high-volume manufacturing techniques of the semiconductor industry are found in over 90% of today's applications.

It could be said that there are two types of pressure measurements: those that are made using a MEMS pressure sensor and those that will be. In either case, pressure sensors that are easier to use help designers of products for new or existing applications get their products to market faster. Pressure sensors with a digital output and an evaluation board have two aspects that make design-ins easier. Providing comparative data on two popular MEMS pressure sensors, this two-part white paper will show how pressure sensors with sigma-delta (ΔΣ) analog to digital converters (ADCs) (Part 1) and a sensor evaluation kit (Part 2) simplify design-ins.

Analog Pressure Output to Digital Input for Control

MEMS pressure sensors inherently provide a highly linear output that requires amplification and temperature compensation to work in most analog systems. For digital systems, conversion of such analog voltage signal to a digital code is also required. The core component for the interface between analog physical world and digital information domain is an analog to digital converter or ADC.

The ADC converts an input analog voltage signal into a digital code determined in relation to second known signal, the reference voltage. As a result, the sole purpose of ADC is to work as a comparator of an unknown signal to a known reference, with the results provided in digital code.

Due to the discrete nature of digital code, all ADCs apply quantization to the input signal to obtain a finite number of digital codes. Because analog signals have an infinite number of steps, an infinite amount of digital code would be required to represent 100% of the signal. As a result, limiting the input scale to some predetermined levels, and splitting it to small steps is required to represent the input signal with a close approximation. The common definition for minimum digital code step size for a specific ADC is resolution, and it is represented in bits. An ideal 1-bit ADC will generate a "1" when the input analog signal larger than 50% of the range, and a "0" if it is less. An 8-bit ADC has $2^8 = 256$ steps, thus it is possible to determine 100% / 256 = 0.390625% change of the range. If the range limits are between 0.0V and 10.0V, the ADC can resolve input analog signals with 39.0625 mV dc per 1 bit of digital code output.

Increased resolution reduces this minimal step size. In the example of 10.0V range ADC, 16-bit solution will provide 10.0V / 2^{16} = 10.0V / 65536 = 152.588 µV/bit.

The simplest ADC systems without any additional amplifiers or attenuators have an input range equal to the known reference voltage signal. Many modern ADCs have also integrated amplifiers and front-end circuits to allow multiple ranges from single known reference voltage.

Important Note on ADC Resolution

Resolution of the ADC is often confused and mistaken with accuracy, but actually these two parameters are almost unrelated. Higher resolution does not provide better accuracy; it only provides a smaller digital step size. Together with the input signal range, resolution provides the sensitivity of the ADC.

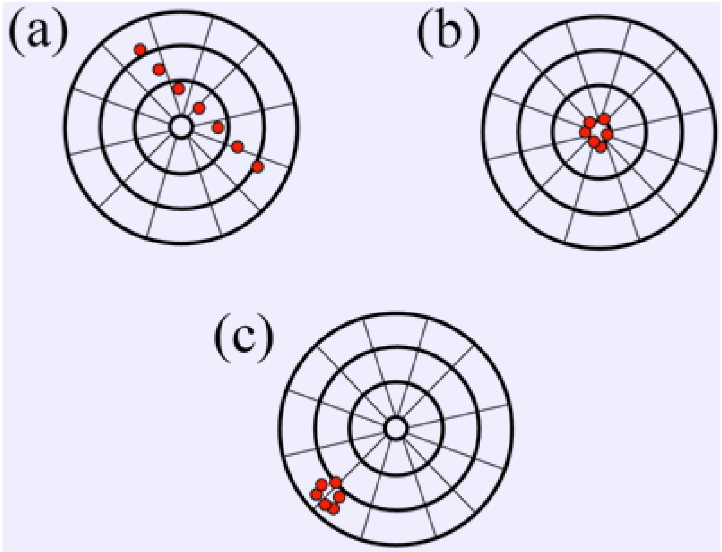

Figure 1. Accuracy versus resolution representation

Case **(a)** represents low resolution and low accuracy, with samples all over the place. The true signal value cannot readily be observed. Improvement on both resolution and accuracy will get sample distribution such as case **(b)**. This is high resolution *with* high accuracy. With high resolution and low system accuracy, the results will be case **(c)**. This is why calibration often more important than resolution for high-precision equipment, since even if it has high precision, it does not necessarily provide good accuracy.

There are many cases when 24-bit ADC provides worse accuracy than better 16-bit device. So, resolution provides a theoretical sensitivity level, in terms of the smallest digital code difference, while accuracy is derived from a complex mix of many actual ADC design parameters, such as front-end stability, temperature coefficients of amplifiers/voltage references, calibration and compensation correction and noise isolation from other components of the system.

An example, using 0-10 V range 8-bit and 16-bit theoretical ADCs, converts a 5.000 V analog signal into digital code, but this time with one extra variable. In case A, the voltage reference (known voltage against which ADC compare input signal) is precisely 10.0000 V, while in the second case B, there is 100 mV error in the voltage reference, so the true reference voltage is 10.1000 V.

Parameter	8-bit “A” ADC	8-bit “B” ADC	16-bit “A” ADC	16-bit “B” ADC
Input signal, $\mathbf{V_{IN}}$	5.0000 V	5.0000 V	5.0000 V	5.0000 V
1 bit step size	0.0391 V	0.0391 V	0.0001525 V	0.0001525 V
Reference signal, $\mathbf{V_{REF}}$	10.0000 V	10.1000 V	10.0000 V	10.1000 V
Reference error	0	0.1000 V	0	0.1000 V
Conversion result	$2^8 * (\mathbf{V_{IN}} / \mathbf{V_{REF}})$	$2^8 * (\mathbf{V_{IN}} / \mathbf{V_{REF}})$	$2^{16} * (\mathbf{V_{IN}} / \mathbf{V_{REF}})$	$2^{16} * (\mathbf{V_{IN}} / \mathbf{V_{REF}})$
Output digital code	0×80 or 1000 0000’b	0×7E or 0111 1110’b	0×8000	0×7EBB
Output error	0	2 bits or 0.1562 V	0	650 bits or 0.09912 V

Table 1. Reference error impact on 8-bit and 16-bit ADC

As this example shows, the error in the reference signal causes output digital code error, unrelated to how many bits of resolution are available. There are multiple sources of errors, many of which reside in the analog domain, and are affected by input signal properties, operation temperature, proximity to other devices on the board, power delivery quality and even mechanical stress to the board.

It is important to keep the reference voltage only slightly higher than maximum expected input signal level. To illustrate this condition, imagine the use of an 8-bit ADC from the example above with 10.0000 VDC reference voltage, when input signal levels are 0 to 0.1V. This is only 1% of the actual ADC range, since (0.1 V_{IN} / 10.0 V_{REF}) * 100% = 1%. This essentially makes an 8-bit with such a reference range useless, since the output code resolution is just 2.56 bits, providing next transfer function:

8-bit ADC Input voltage (V_{REF} = 10.000 V)	8-bit ADC Output code	Ideal error
0.000 V	0×00	0
0.010 V	0×00	100%, cannot detect signal
0.020 V	0×00	100%, cannot detect signal
0.030 V	0×00	100%, cannot detect signal
0.040 V	0×01 (Threshold level = 0.0391 V)	-2.34%
0.050 V	0×01 (Threshold level = 0.0391 V)	-21.88%
0.060 V	0×01 (Threshold level = 0.0391 V)	-34.90%
0.070 V	0×01 (Threshold level = 0.0391 V)	-44.20%
0.080 V	0×02 (Threshold level = 0.0782 V)	-2.34%
0.090 V	0×02 (Threshold level = 0.0782 V)	-13.19%
0.100 V	0×02 (Threshold level = 0.0782 V)	-21.88%

Table 2. Low-level signal measurement with 8-bit ADC and high V_{REF}

Obviously, such a system is not suitable for such a low signal measurement and needs either a higher resolution ADC or signal amplification circuitry to bring the input close to the full-scale ADC range (which is 10.000 V, due to the used voltage reference V_{REF}).

However, smarter solution is often possible. The output resolution and accuracy can be increased by reducing the reference voltage to match the input signal voltage closer. An ADC may allow external voltage reference use, and allow low voltage reference levels. Reducing the reference voltage is functionally equivalent to amplifying the input signal, however, no amplifier or additional hardware-level components are required. Therefore, reducing the reference voltage is often used to increase the resolution at the input, keeping in mind LSB voltage larger than errors from design and own ADC implementation. (**LSB size** – minimal voltage step size for each code, equal to **Reference voltage / 2^N**.)

Care needs to be exercised, since the voltage reference cannot be decreased too much, as other effects such as thermal noise of the inputs, gain and offset errors, non-linearity and thermoelectric voltages becoming an issue, and these contributors are independent of the reference voltage.

Looking at the same example with reduced V_{REF} to **0.1500 V** allows the use of most of the reduced input range and obtains much better sensitivity over the test 0.000V – 0.100 V signal. An interactive sensitivity calculator is presented in the form and table below, with V_{REF} as a known reference voltage.

V_{ADC} sensitivity calculator

V_{REF}, reference voltage	0.1500 V
ADC resolution, **2^N**	N = 8 bits
LSB size, calculated	585.93750 **µV**

The same test values are used in the table below, but this time with a low reference voltage.

8-bit ADC Input voltage (V_{REF} = 0.150 V)	8-bit ADC Output code	Ideal error
0.000 V	0×00	0
0.010 V	0×11 (0.00996 V)	
0.020 V	0×22 (0.01992 V)	
0.030 V	0×33 (0.02988 V)	
0.040 V	0×44 (0.03984 V)	
0.050 V	0×55 (0.04980 V)	
0.060 V	0×66 (0.05977 V)	-0.39%
0.070 V	0×77 (0.06972 V)	
0.080 V	0×88 (0.07969 V)	
0.090 V	0×99 (0.08965 V)	
0.100 V	0xAA (0.09961 V)	

Table 3. Low-level signal measurement with 8-bit ADC and reduced VREF

With a 0.15V input reference voltage, the design can use even an 8-bit ADC with better than 1% accuracy in an ideal case. So, choosing correct reference level and range is very important for optimal performance of the analog to digital conversion system.

If the reference level cannot be reduced to match input signal range, it is necessary to amplify low level signals so a similar increase of the voltage resolution can be achieved. The alternative is to use a more expensive, higher resolution ADC. In the same example system with $\mathbf{V_{REF}}$ = 10.000 V as above, at least a 16-bit ADC would be required to achieve the same theoretical accuracy.

16-bit ADC Input voltage (V_{REF} = 10.000 V)	16-bit ADC Output code	Ideal error
0.000 V	0×0000	0
0.010 V	0×0041 (0.00992 V)	-0.82%
0.020 V	0×0083 (0.01999 V)	-0.05%
0.030 V	0×00C4 (0.02991 V)	-0.31%
0.040 V	0×0106 (0.03998 V)	-0.05%
0.050 V	0×0147 (0.04990 V)	-0.21%
0.060 V	0×0189 (0.05997 V)	-0.05%
0.070 V	0×01CA (0.06989 V)	-0.16%
0.080 V	0×020C (0.07996 V)	-0.05%
0.090 V	0×024D (0.08987 V)	-0.14%
0.100 V	0×028F (0.09995 V)	-0.05%

Table 4. Low-level signal measurement with more expensive 16-bit ADC and high V_{REF}

These resolution-depending errors are quantization limits of an ideal linear ADC. With real hardware, any gain, nonlinearity and offset errors must be added. This is the reason why all common multimeters have multiple ranges, instead of one combined 0V – 1000V range. Multimeters with an autorange feature still have the same design, but perform an automatic selection of the best range depending on input signal.

These application challenges are well recognized by leading ADC manufacturers that spend a significant amount of R&D resources to reduce the impact of all these error contributors on overall output accuracy by using better packaging, isolation, and better stability parts in the design. As result, knowledge and design features also improved performance, so added digital resolution is useful in many applications. Resolution is relatively cheap to add, but it is important to understand that it is not the resolution alone that makes a higher accuracy ADC.

Most modern ADCs have low voltage power supply requirements, matching typical +3.3V or +5V digital systems supply rails. As result, the reference voltages also have typical levels at 2.500, 2.048, 3.000, 4.096 VDC. To measure signal levels higher than these values, attenuation and front-end scaling is required. Lower voltage levels are helpful for compact battery-powered devices and allow simple interfacing with a typical CMOS microcontroller, digital signal processor (DSP) or digital bus. Many ΔΣ ADCs and feature-rich SAR ADCs have integrated on-chip voltage reference sources, front-end amplifiers, switching, even temperature sensors as well, essentially making nearly complete measurement system on compact single chip package.

There are different types of ADC designs depends on target application requirements and operation principle. Table below presents some most common types, their basic performance parameters and their strong/weak sides.

ADC Type	Flash	Delta-Sigma ΔΣ	Integrating (slope)	Successive approximation (SAR)
Operation principle	Parallel comparator array	Oversampling with digital filtering	Integration vs known reference charges	Binary search comparison
Speed	Very fast (up to few GHz)	Slow (Hz) to Fast (few MHz)	Very slow (mHz) to Medium (kHz)	Medium (kHz) – Fast (few MHz)
Resolution	Low, <14bit	Medium to very high, 12-32 bit	Can be very high, 32 bits	8 – 20 bit
Power	Very high	Low	Low-High	Low-Medium
Noise immunity	Low	Medium-High	High	Medium
Design complexity	High	Low	High	Low
Implementation cost	High	Low	Medium to very high for precision	Low

Table 5. Types of ADC designs and performance limitations

Correct ADC type choice is key importance for best results in specific applications. Common pressure sensor applications operate with low bandwidth due to relatively large volumes of measured flow/mass, typical choice are ADC types like SAR, Delta-Sigma and less often Integrating type. Other designs, for example high-speed oscilloscope need to use flash or pipeline ADCs with high bandwidth.

ADC of same type also may have very different packages, and different levels of integration. Larger packages often can have integrated reference blocks, temperature sensors, input channel multiplexers, programmable current sources for sensor excitation. Often ADC block is also integrated part of bigger system on chip (SOC) system to further save space, however accuracy and resolution of such converters often inferior to discrete ADC designs. Resolution of ADC inside SOCs is usually 12-16 bit with just few exceptions on specialized instrumentation solutions.

Sensors with an Integral ADC

To simplify the use of an analog sensor in digital systems, some sensor manufacturers offer sensors with an integral ADC. A comparison of test results is shown later in this report. Table 6 shows the sensors from All Sensors Corporation (ASC) and another supplier and Table 7 shows their key specifications. This includes the effective number of bits (ENOB) resolution and the total error band (TEB), which typically provides the most important “accuracy” for many applications.

Sensor	TEB
All Sensors DLHR-L10D	±0.75%
All Sensors DLHR-L02D	±0.75%
All Sensors DLHR-L01D	±1.00%
Supplier X Product 1	±2.0%
Supplier X Product 2	±1.0%

Table 6. Pressure sensors with digital front-end selected for test

Parameter	DLHR-L10D	DLHR-L02D	DLHR-L01D	Product 1	Product 2
Pressure range	Diff., ±10 inH^{2}O	Diff., ±2 inH^{2}O	Diff., ±1 inH^{2}O	Diff., ±20 inH^{2}O	Diff., ±2 inH^{2}O
Sensor die configuration	5-resistor bridge, 2×2mm proprietary die			4-resistor bridge, 2.5×2.5mm proprietary	
ADC Type	16/17/18-bit Δ-Σ			24-bit Δ-Σ	
DSP	YES			NO	
TEB	±0.75%	±0.75%	±1.00%	±1.0%	±2.0%
Output rate	15 to 270 SPS			20 SPS to 2000 SPS	
Typical ENOB min. speed	17 bits			18 bits	16 bits
	16 SPS			20 SPS	
INL				±15 ppm of FSR (ADC)	
Power requirements	Single, 1.68 – 3.63 VDC			Single, 2.3 – 5.5 VDC	
Onboard temperature sensor	Yes, 16 bits			Yes, 14 bits	
Temperature range	-25°C to +85°C			-40°C to +85°C	
Digital interface	I^{2}C, SPI			SPI	
One off reference price (DigiKey/Mouser)	\$53.04 USD			\$57.61 USD	

Table 7. Specification comparison of evaluated pressure sensors

Disregarding the output data resolution, the accuracy (TEB) specifications differ significantly. This confirms earlier theory, that the accuracy of the pressure sensor is a system measurement, not depending on ADC resolution.

The All Sensors Difference

Since it is not easy to compensate silicon die for good accuracy, linearity and stability, All Sensors chose to use two of the same sensor dies, route pressure to them in opposite directions, and measure the differential signal between the two.

Silicon die from the same wafer batch have very good correlation, so errors such as non-linearity, temperature dependence and offsets can be nulled from the output signal. Such an arrangement is similar to making a Wheatstone bridge from two on-die bridge sensors. This patented method \ provides active dual-die compensation for common-mode pressure sensor errors.

To provide better performance, especially for low pressure measurements, the die structure in All Sensors' chip uses a proprietary Collinear Beam^2 or COBEAM^2™ technology. COBEAM^2 technology is designed to provide better pressure sensitivity in a small package, which previously required boss structures and larger die topologies. The smaller die design without the boss structure significantly reduces both unwanted gravity and vibration sensitivity.

Summary & Conclusions

Years ago, a significant amount of knowledge was needed to implement a pressure measurement into the system, starting from sensor design, low-noise and a stable front end for the sensor, measurement system and compensation methods. Today, even students without any practical electronics design background can get digital output sensors, connect them to popular platform like a Linux-based Raspberry Pi or Arduino and get initial pressure measurements in a matter of hours, not weeks. The obtained value is already a calibrated and compensated value, ready to be used for further processing in an application.

Given the noise levels in the maximum practical application, pressure sensors with an 18-bit ADC provide equally acceptable results as a 24-bit ADC. In fact, 17-bit ENOB is only achievable with a low noise pressure sensor die, such as All Sensors CoBeam^2 Technology, which is superior to other low noise solutions. Furthermore, All Sensors DLH/R series pressure sensors are easy to use and require no external math by the user.

Signal conditioned silicon pressure sensors with a digital output have achieved pricing and packaging that make them acceptable for a wide number of applications. Their accuracy and digital compensation makes them attractive in variety of precision sensing projects including many industrial applications. These applications include flow metering, liquids level measurements, process monitoring, research, optical power detection and many more. With the new high resolution digital sensors, applications can now be addressed which were not possible before with the industry-standard 14-bit ADCs that provided a maximum 13-bit ENOB.

Reference

1. Based on "Evaluation of modern pressure sensors with digital interface," https://xdevs.com/article/pressure/