Auto-Zero Calibration Technique for Pressure Sensors

A Technical Note

1.0 INTRODUCTION

This technical note describes how to implement Auto-Zero, a calibration technique for pressure sensors based on sampling the output at a known reference condition to allow for additional external correction of output errors including Offset Error, Thermal Effect on Offset (Offset Shift) and Offset Drift.

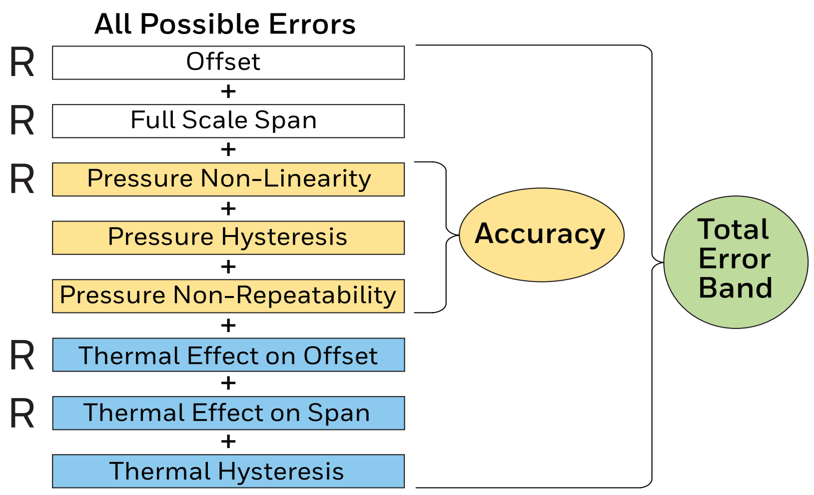
Because this technique is more difficult to achieve for absolute pressure sensor types (requiring a vacuum source or independent barometer to implement accurately), this technical note will primarily focus on gage and differential pressure types.

Please see Section 11.0 for a definition of terms used in this technical note.

2.0 BACKGROUND

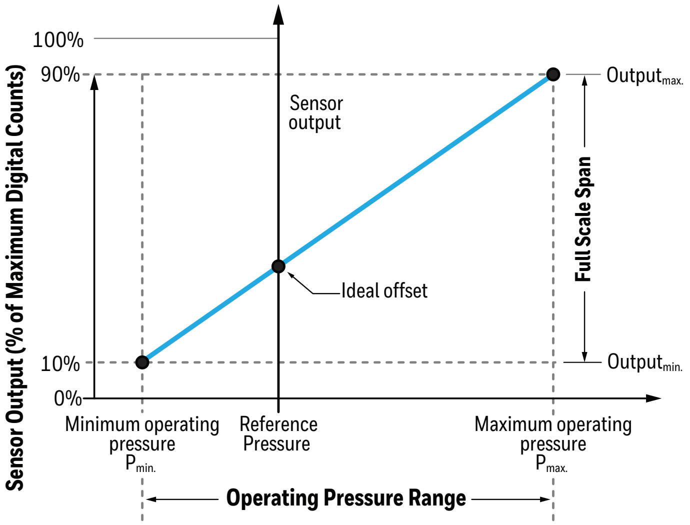
Most of the modern pressure sensors supplied today utilize integrated electronic methods to amplify the raw sensor element signal and minimize repeatable components of errors including those highlighted in Figure 1.

Figure 1. Total Error Band Explanation ("R" indicates repeatable errors)



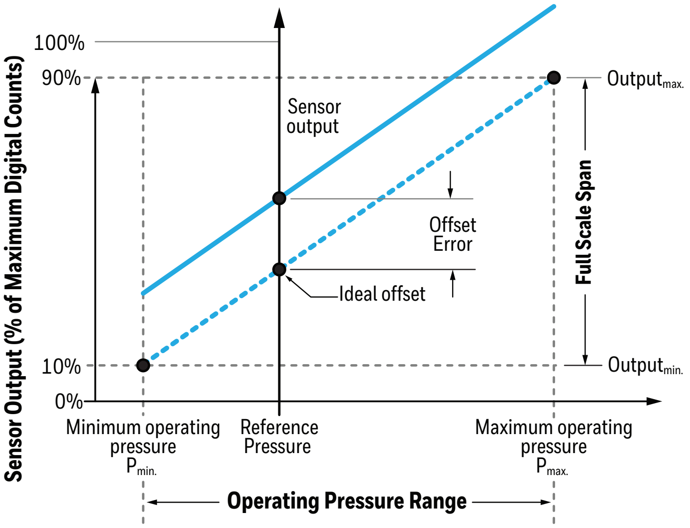
Factory calibration of these sensors applies temperature correction factors to compensate for the inherent, temperature-induced changes of the sensor signal, and minimize other repeatable sources of output error. In most embodiments, the integrated electronic method comes in the form of a sensor signal conditioning ASIC. This provides the sensor manufacturer with the ability to directly implement the factory calibration and achieve a near perfect sensor output signal. For example, the Ideal Transfer Function of a typical digital pressure sensor is shown in Figure 2.

Figure 2. Ideal Transfer Function of Digital Sensor (10% to 90% Calibration)



Mathematically, the Ideal Transfer Function is a straight line, independent of temperature, passing through the ideal Offset point with a slope equal to the ideal Full Scale Span over the operating pressure range. This basic linear function offers end users the advantage of applying a very simple algorithm to interpret the digital output and convert it to something meaningful for their applications. Any deviations in this Ideal Transfer Function, including those occurring over time and exposure to environmental conditions, manifest themselves as sensor errors. (Those errors, which contribute to Total Error Band and Accuracy, were shown in Figure 1.) By far, the largest component of this residual error in pressure sensors is the Offset Error as illustrated in Figure 3.

Figure 3. Transfer Function of Digital Sensor with Offset Error (10% to 90% Calibration)



3.0 ERROR SOURCES

Several factors may contribute to this Offset Error, including:

- Normal part-to-part variation related to factory calibration capability.
- End-user, installation-related, mechanically-induced mounting stress effects such as soldering the sensor to a circuit board.
- End-user applying adhesives to join the sensor to end application packaging.
- Inducing stress by means of connecting the sensor into the pneumatic system.
- Temperature variation, especially sensors with significant Sensitivity to temperature changes (large Thermal Effect on Offset).
- Drift due to aging and repeated exposure to changing environmental conditions (including temperature, humidity and pressure media).
- Power supply variation (i.e., ratiometricity errors).

All pressure sensors, no matter how expensive they are, no matter what materials they are made from, or how precisely and accurately they were originally calibrated in the factory, are susceptible to experiencing some level of change in Offset.

Fortunately, all these factors, which can affect the Offset, usually do not change the Full Scale Span or Sensitivity of the output. In other words, the Ideal Transfer Function being a straight line of the form $y = mx + b$, the slope of the signal is virtually unchanged so most of the error appears as a simple shift of the Offset point. This is another reason why Auto-Zero calibration techniques can be so powerful to implement in applications.

4.0 WHEN AND WHY TO AUTO-ZERO

It is highly recommended that the end-user periodically implement an Auto-Zero calibration technique to compensate and correct for these Offset Errors in order to return as closely to the Ideal Transfer Function as possible. How often the end-user needs to perform an Auto-Zero calibration technique is a function of the performance requirements of the end application. Even in applications where Auto-Zero in the field isn't feasible it is usually straightforward to implement an Auto-Zero in the factory for system assembly prior to installation in the application. Three typical examples of Auto-Zero timing and the corresponding benefits are:

1. Immediately after mounting the product in the factory for system assembly:

- Removes any Offset Error due to mounting stress.
- Removes any factory Offset calibration error.

2. At a fixed time interval while the sensor is being used:

- Removes any Offset Error due to mounting stress.
- Removes any factory Offset calibration error.
- Removes any time based Offset Drift.

3. If a temperature change is detected in the application:

- Removes any Offset Error due to mounting stress.
- Removes any factory Offset calibration error.
- Removes any time-based Offset Drift.
- Removes any factory Thermal Effect on Offset calibration error.

It should also be noted that because ultra-low pressure sensors are inherently more sensitive to pressure, they also are inherently more sensitive to stress changes and therefore changes in Offset. Therefore performing an Auto-Zero calibration on a device rated for use below 1 psi or 60 mbar is even more critical than doing so on a 15 psi or a 100 psi sensor. Performing an Auto-Zero on a 1 psi device may be critical to achieving the desired performance but may not be as critical when using a higher pressure range of sensor.

5.0 PRESSURE OUTPUT EQUATIONS AND AUTO-ZERO FUNCTION

1. The Ideal Transfer Function for the output of a pressure sensor is given by Equation 1:

Equation 1:

$$\text{Output} = \frac{\text{Output}_{\text{max.}} - \text{Output}_{\text{min.}}}{P_{\text{max.}} - P_{\text{min.}}} * (\text{Pressure} - P_{\text{min.}}) + \text{Output}_{\text{min.}}$$

where:
Output = Pressure reading from the sensor [Volts, %2^{16} counts, %Vs, etc.]
$\text{Output}_{\text{min.}}$ = Ideal output at minimum pressure [Volts, %2^{16} counts, %Vs, etc.]
$\text{Output}_{\text{max.}}$ = Ideal output at maximum pressure [Volts, %2^{16} counts, %Vs, etc.]
$P_{\text{min.}}$ = Minimum operating pressure [bar, mbar, psi, kPa, etc.]
$P_{\text{max.}}$ = Maximum operating pressure [bar, mbar, psi, kPa, etc.]

2. Rearranging Equation 1 to solve for pressure, we can calculate the Measured Pressure value as read directly from the sensor:

Equation 2:

$$\text{Pressure} = \frac{(\text{Output} - \text{Output}_{\text{min.}}) * (P_{\text{max.}} - P_{\text{min.}})}{\text{Output}_{\text{max.}} - \text{Output}_{\text{min.}}} + P_{\text{min.}}$$

3. The Auto-Zero value can then be calculated using this Measured Pressure value recorded (and optionally averaged) during the application of any known (or assumed, such as 0 psi g) Reference Pressure condition as follows:

Equation 3:

$$\text{AutoZero} = \text{Measured Pressure} - \text{Known Reference Pressure}$$

4. Once this "AutoZero" value has been calculated and stored, the final Auto-Zero Corrected Pressure value, or Corrected Pressure, may then simply be calculated every time a new Measured Pressure value is read under normal operating conditions:

Equation 4:

$$\text{Corrected Pressure} = \text{Measured Pressure} - \text{AutoZero}$$

This Corrected Pressure value gives a result which is as accurate and close to the Ideal Transfer Function as possible because the Auto-Zero correction has effectively compensated for Offset Errors.

6.0 IMPLEMENTING AUTO-ZERO CALIBRATION TECHNIQUES

In most applications, the pressure sensor is considered the primary reference and is perhaps the only pressure measurement in the entire system. Therefore, one of the most important factors to consider when using any re-calibration method is that there must be a known Reference Pressure condition that can be applied to the sensor. It is highly unlikely the end user can apply a specific known non-zero pressure to the sensor. It is much more likely there would be the ability to apply or detect when the system is at a zero (or very near zero) Reference Pressure condition.

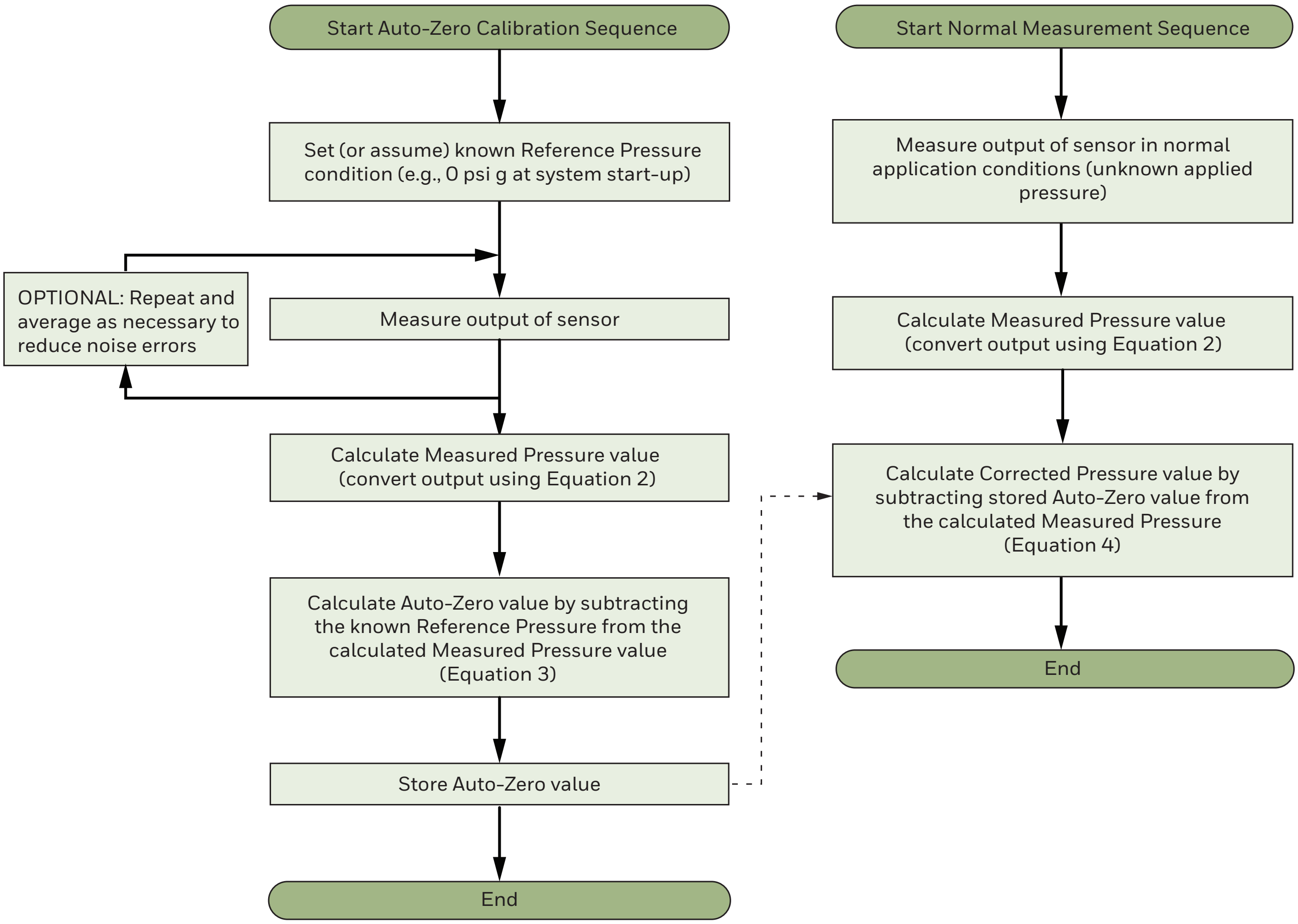
While this known and stable Reference Pressure condition is being applied to the sensor, the end user can measure the output of the sensor and detect if the Offset has changed (Offset Shift and Offset Drift), determine how much it has changed and correct for it digitally in the system. For this reason, the following correction procedure is termed an “Auto-Zero” calibration technique even though any known or assumed pressure may be used to compensate for changes in Offset.

In many applications, a zero condition doesn’t naturally occur, therefore a valve may need to be used to connect/disconnect pressure from the sensor’s port(s) to create a known Reference Pressure condition.

The flowchart in Figure 4 depicts how Auto-Zero calibration and correction techniques may be implemented in the end user application.

An example of software code which can be used to perform these basic algorithms is also given in Figure 6.

Figure 4. How to Implement Auto-Zero Calibration and Correction



Example of Auto-Zero Calculations

In the following example, the Corrected Pressure has been calculated for the following differential pressure sensor:

- -1 psi ($P_{min.}$) to 1 psi ($P_{max.}$) range
- 10% to 90% 16-bit digital calibration ($Output_{min.}$ 6554 or 0h1999 to $Output_{max.}$ 58982 or 0hE666)
- Raw output of 76% 16-bit (49807 or 0hC28F counts) after previously obtaining an Auto-Zero calibration measurement (with no pressure applied) of 52% 16-bit (34079 or 0h851E counts)

1. Because the Auto-Zero calibration measurement was obtained at a time when no pressure was applied (0 psi g at each port, or equivalently exactly the same pressure applied to both ports) we can assume that:

Equation 1: Known Reference Pressure = 0 psi g

2. With an output of 52% 16-bit (34079 counts or 0h851E) during the Auto-Zero calculation condition, we can use Equation 2 to convert this to a pressure output:

Equation 2:

$$\text{Measured Pressure (at Auto-Zero Condition)} = \left\{ \frac{(52 - 10) * (1 - -1)}{90 - 10} \right\} + (-1) = 0.05 \text{ psi g}$$

$$\text{Or equivalently using raw decimal counts} = \left\{ \frac{(34079 - 6554) * (1 - -1)}{58982 - 6554} \right\} + (-1) = 0.05 \text{ psi g}$$

3. Therefore, using Equation 3 the Auto-Zero value is simply given by:

Equation 3: AutoZero = Measured Pressure (at Auto-Zero condition) - Known Reference Pressure
= 0.05 - 0 psi g = 0.05 psi g

4. Now, using this calculated Auto-Zero value, the raw output of 76% 16-bit (49807 counts or 0hC28F) can be converted to a Corrected Pressure value using Equations 2 and 4:

Equation 4:

$$\begin{aligned} \text{Corrected Pressure} &= \text{Measured Pressure} - \text{AutoZero} \\ &= \left\{ \frac{(76 - 10) * (1 - -1)}{90 - 10} \right\} + (-1) - 0.05 \text{ psi g} \\ &= 0.65 - 0.05 \text{ psi g} \\ &= 0.60 \text{ psi g} \end{aligned}$$

This example shows that the Auto-Zero calibration method has removed an error (in this case 0.05 psi g or 2% of 16-bits) in the raw sensor output which would otherwise have given a higher Measured Pressure (0.65 psi g or 76% of 16-bits) compared with the more accurate Corrected Pressure (0.60 psi g or 74% of 16-bits).

7.0 DUAL PORT SENSORS

Dual ported sensors do not necessarily require that the system pressure is zero to be able to implement an Auto-Zero but rather that both ports are at exactly the same pressure. In addition to venting both ports to atmosphere, this can also be achieved by using a valve to shunt the pressure between the ports so that both ports see the same "system" pressure. This creates the same pressure on both sides of the pressure sensor die which results in the same condition as having both ports at zero pressure.

8.0 FREQUENCY OF AUTO-ZERO CALIBRATION

Careful consideration must be given to decide when best to implement the Auto-Zero calibration technique in the end application.
In general, the methods employed during the product's life fall into two categories, either time-based or opportunity based.

8.1 Time-Based Approach

This approach takes advantage of a system having periodic, repeated measurement cycles which are triggered by a timer function. An Auto-Zero calibration sequence can be inserted into each pressure measurement cycle. The timer-activated sequence consists of switching the pressure that is applied to the sensor from the measurement pressure to a Reference Pressure by using a two-way solenoid actuator.

Consider the example of measuring the liquid level in a tank or reservoir by measuring the pressure of the liquid at the bottom of the tank. The user wants to measure this pressure at a known time interval in the application. At each time interval, the system commands the solenoid to switch to the Reference Pressure, read the Reference Pressure output and store the Auto-Zero value. The system then commands the solenoid to switch to the application/measurement pressure to read the measurement pressure. The earlier stored compensation factor (the Auto-Zero value) is then subtracted from the Measured Pressure value. A time-based approach is most common in a continuous use application (system that run 24 hours per day). Examples include building control applications, HVAC damper control (night time, weekend), fluid metering, and air filter monitoring.

8.2 Opportunity-Based Approach

Certain types of applications are often ideally suited for Auto-Zeroing techniques because a condition or conditions exist when the measurement pressure is zero (or known) and can be used as the Reference Pressure. In these types of systems, the pressure is typically zero at some point in time, usually at system power-up. Additionally, for extremely high Accuracy applications, temperature may be monitored in order to determine when thermal equilibrium is reached suitable for Auto-Zero calibration to be performed. Example applications include air filter monitoring, laboratory equipment, weighing scales, oil pressure, washing machines, coffee machines, anesthesia machines, CPAP, and medical ventilators.

Finally, another opportunity when a known Reference Pressure may exist is during customer sensor installation in the factory for assembly of the system. In this situation, the measurement pressure can be known to be zero as the system is first powered up or remains unconnected and vented to atmospheric pressure. This can then be used as the Reference Pressure condition for the Auto-Zero calibration technique previously described above.

9.0 EXAMPLE OF RESULTS OBTAINED WITH AUTO-ZERO CALIBRATION

The graphs in Figure 5 give an example of the type of results which can be obtained with Auto-Zero calibration. In this example, a group of pressure sensors had its Offset Error at 25°C (see Figure 5.A.) removed by performing the Auto-Zero calibration technique at 25°C (see Figure 5.B.).

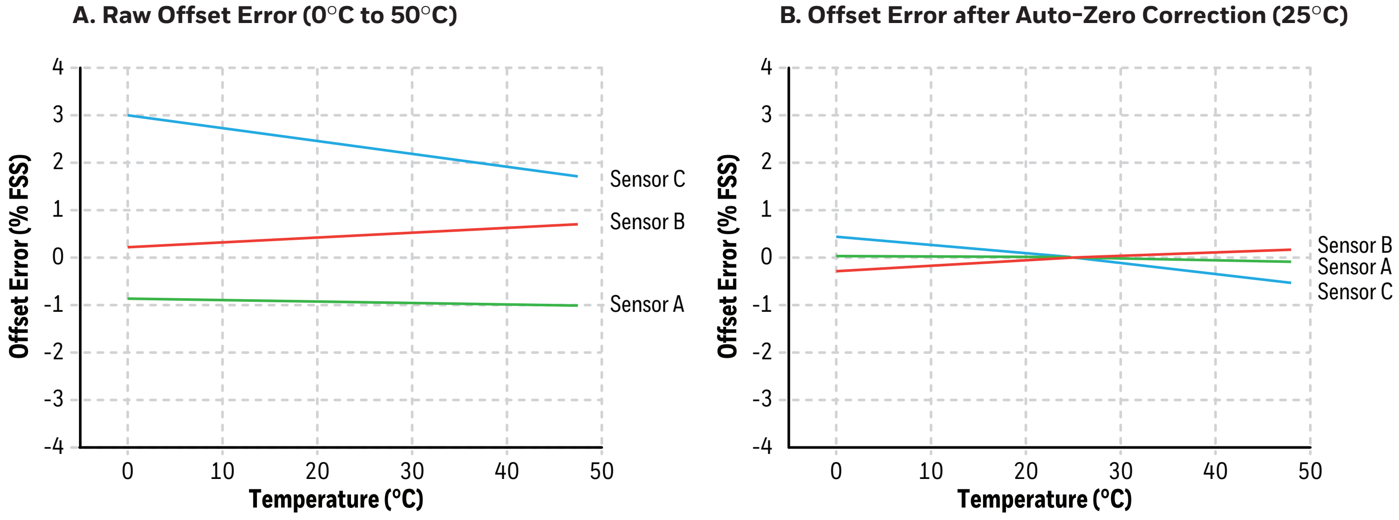
Notice that the Thermal Effect on Offset errors is unchanged (because the correction was performed only at 25°C); however, because the Offset Error was the main contributor to the Total Error Band it is clear to see from the difference between Figures 5.C. and 5.D. that the Total Error Band after Auto-Zero can result in much lower errors, that is, more accurate sensors.

It should also be noted that if the Auto-Zero calibration were performed at another temperature within the Compensated Temperature Range (e.g.,50°C) instead of at 25°C, then the errors at that specific temperature would be further minimized.

The graphs in Figure 5 illustrate the impact that an Auto-Zero calibration at 25ºC can have on the Offset error over temperature and correspondingly to the Total Error Band.

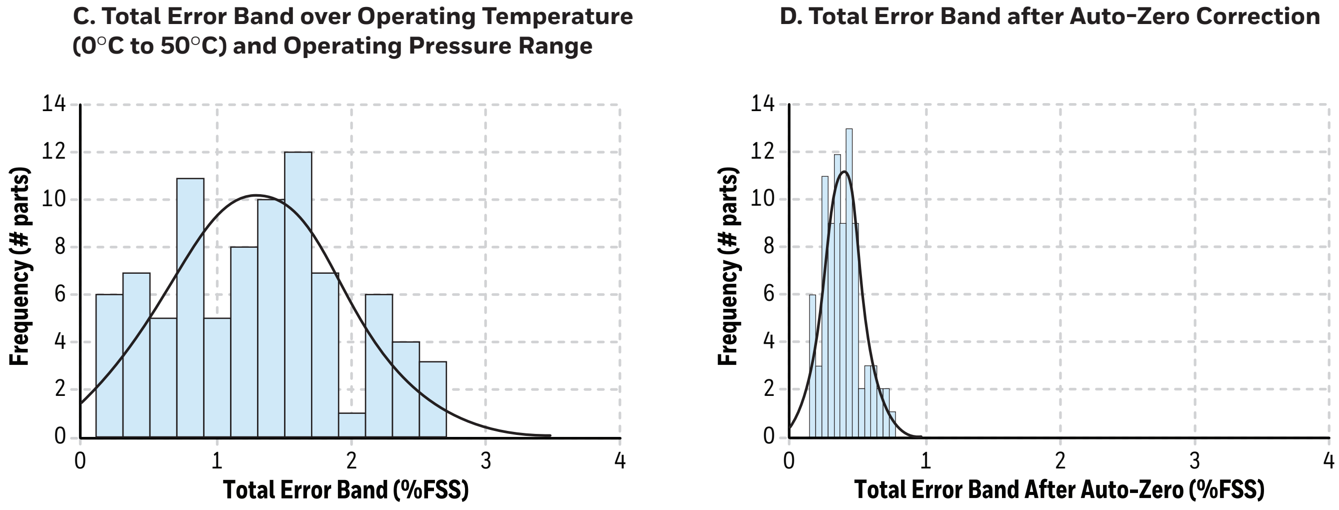
Graphs 5.A. and 5.B. include the Offset data from just three of the sensors over the 0ºC to 50ºC Compensated Temperature Range while graphs 5.C. and 5.D. show the Total Error Band before and after Auto-Zero correction, respectively, for the entire batch of sensors over the full compensated pressure and temperature range.

Figure 5. Auto-Zero Calibration Examples



A. Raw Offset Error (0°C to 50°C)

B. Offset Error after Auto-Zero Correction (25°C)



C. Total Error Band over Operating Temperature (0°C to 50°C) and Operating Pressure Range

D. Total Error Band after Auto-Zero Correction

10.0 Example of Software Code Utilizing Auto-Zero Techniques

Figure 6. Pseudo Code for Auto-Zero

```
//*****************************************************************************************************************
// This is an example of simplified C pseudo code to calculate and pass back an AutoZero pressure value

// In this example it is assumed that “calculateAutoZero” is called when the users’ system is in a reference pressure condition. In theory this
// reference condition can be any pressure within the operating range that is known and can be held steady for a period of time. In most
// instances this pressure will be atmospheric pressure -- or 0 gage pressure.
//
// The AutoZero does not need to be performed with every reading, just at periodic intervals like startup and/or any other time when the
// system is in a state where this could be performed.
//*****************************************************************************************************************
float calculateAutozero(int numToAvg, float referencePressure)   // Pass in the number of readings to average and the reference system pressure
{
    float   Avg  =  0.0;
    float   Total  =  0.0;
    float   measuredPressure;
    float   AutoZero  =  0.0;

    for    (int i = 0; i < numToAvg; i++)                            // loop to the number of samples to average
    {
            measuredPressure  =  getPressureFromSensor ();            // this is a user written function to get the Pressure Output from the sensor
                                                                      // in pressure form (bar, mbar, PSI, etc. . . )

            Total  = Total  +  measuredPressure;                      // keep a total of the pressure readings
    }

Avg  =  Total  /  numToAvg;                                           // calculate the average pressure reading

AutoZero  =  Avg  -  referencePressure;                               //  calculate the AutoZero value as the average value  -  reference value
                                                                      //  the AutoZero value represents the difference between the sensor
                                                                      //  actually reads, and the known pressure the sensor is seeing
                                                                      //  the AutoZero value will then be subtracted from all future pressure readings
                                                                      //  to give the Corrected Pressure value
    return AutoZero;
}

//*****************************************************************************************************************
// This is an example of simplified C pseudo code to show how the autozero corrected pressure is calculated
//
// In this example it is assumed that the user has a function to read pressure values from the sensor, has performed the autozero
// procedure of the above function, and has the autozero value “AutoZero” stored for use.  In this example the autozero value is passed as a
// value, but it could be a global variable.
//
// This function would need to be called after EVERY value read from the sensor to ensure the pressure value used in the application is
// as accurate as possible.
//*****************************************************************************************************************
float calculateCorrectedPressure (float measuredPressure, float AutoZero)
{
    float   correctedPressure = 0.0;
    correctedPressure  =  measuredPressure  - AutoZero;               // calculate the corrected pressure value as the autozero pressure value subtracted
                                                                      // from the measured pressure from the sensor
    return correctedPressure;
}
```

11.0 DEFINITION OF TERMS

- **Auto-Zero:** A compensation technique based on sampling output at a known reference condition, within the compensated temperature and pressure range of the product. Typically, a zero pressure reference such as atmospheric pressure (or equal pressure on both pressure ports for a differential product) is employed to allow the external correction of Offset error.
- **Offset:** The output signal obtained when the Reference Pressure is applied to all available pressure ports. Also known as “null Offset”, “null” or “zero”.
- **Offset Error:** The maximum deviation in measured Offset at reference temperature relative to the ideal (or target) Offset as determined from the Ideal Transfer Function.
- **Thermal Effect on Offset:** The maximum deviation in Offset due to changes in temperature over the Compensated Temperature Range, relative to Offset measured at reference temperature.
- **Offset Shift:** An ambiguous term sometimes used to describe a permanent change in the output of a sensor. Note that the term “Offset Shift” is also sometimes used to describe temporary output changes due to temperature fluctuation. To avoid confusion, the later should really be termed as Thermal Effect on Offset.
- **Drift:** Instability; the opposite of stability which is the ability of a sensor to retain its performance characteristics with time. Note that the term “Drift” should only be used to describe temporal (time based) changes.
- **Ideal Transfer Function:** Mathematically, the Ideal Transfer Function is a straight line, which is independent of temperature, passing through the ideal Offset with a slope equal to the ideal Full Scale Span over the operating pressure range. (See Figure 2.)
- **Full Scale Span (FSS):** The algebraic difference between output signal measured at the upper and lower limits of the operating pressure range. Also known as “span” or ambiguously as “full scale output”. (See Figure 2.)
- **Total Error Band (TEB):** The maximum deviation in output from the Ideal Transfer Function over the entire compensated temperature and pressure range. Includes all errors due to: Offset, Full Scale Span, pressure non-linearity, pressure hysteresis, non-repeatability, Thermal Effect on Offset, thermal effect on span and thermal hysteresis. (See Figure 1.)
- **Accuracy:** The maximum deviation in output from a best fit straight line (BFSL) fitted to output measured over the compensated pressure range at reference temperature. Includes all errors due to: pressure non-linearity, pressure hysteresis and non-repeatability.
- **Sensitivity (Slope):** The ratio of output signal change to the corresponding input pressure change. Sensitivity is determined by computing the ratio of Full Scale Span to the specified operating pressure range.
- **Measured Pressure:** The raw pressure value as obtained directly from the sensor after converting the output reading into pressure units using the Ideal Transfer Function. (See Equation 2.)
- **Reference Pressure:** The pressure used as a reference (or “zero”) point when measuring or calibrating sensor performance. Unless otherwise specified, this is vacuum (0 psi a) for an absolute pressure sensor and local ambient atmospheric pressure (0 psi g) for gage, compound and differential pressure sensors.
- **Corrected Pressure:** The Auto-Zero corrected pressure value which is compensated for Offset errors by subtracting a stored “AutoZero” value from the Measured Pressure. (See Equations 3 and 4, and Figure 4.)
- **Total Error Band After Auto-Zero:** The maximum deviation from the Ideal Transfer Function over the entire compensated pressure range at a constant temperature (within the Compensated Temperature Range) and supply voltage (within the calibrated supply voltage range) for a minimum of 24 hours after an auto-zero operation. Includes all errors due to Full Scale Span, pressure non-linearity, pressure hysteresis, and thermal effect on span.
- **Compensated Temperature Range:** The temperature range (or ranges) over which the product will produce an output proportional to pressure within the specified datasheet performance limits.

For further definitions please see individual product datasheets or the Honeywell Pressure Sensor Glossary of Terms.

Warranty/Remedy

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