Calibration Visualization and Automation Software for IEEE 1451.2 Compliant Smart Sensors

Rodger Alan Reinhart, President
Atmos Engineering,Inc.
443 Dearborn Park Road
Pescadero, CA 94060
Telephone: 650-879-1674
Fax 650-879-1675
E-mail: RodgerReinhart@atmos.com
Web: http://www.atmos.com

Abstract

A software program for the visualization of smart-sensor calibration data sets is described, with analysis and calibration of a digital-output pressure sensor used to demonstrate the features and benefits. The results of the analysis are IEEE 1451.2 formatted multinomial calibration and compensation coefficients.

Introduction

The calibration requirements of smart sensors, transducers and actuators require computation and visualization tools that work in three or more dimensions and allow rapid user interaction to optimize the calibration.

The calibration limit of a sensor is the sensor's short-term non-repeatability. For a silicon pressure sensor, short-term non-repeatability consists primarily of sensor output noise and thermal hysteresis. Thermal hysteresis is the dominant term and is typically 0.03% to 0.15% of full scale. Repeatable measurement errors are 100 to 500 times greater than non-repeatable errors, and consist primarily of non-linearity and thermal shifts in gain and offset.

The calibration process includes learning the shape of measurement errors vs applied temperature and pressure, encoding the error shape into a correction algorithm and storing the correction information into the sensor.

A software calibration and visualization package (CVS) developed by Atmos Engineering performs the computation and visualization tasks in the calibration process. Unique features of the CVS are:

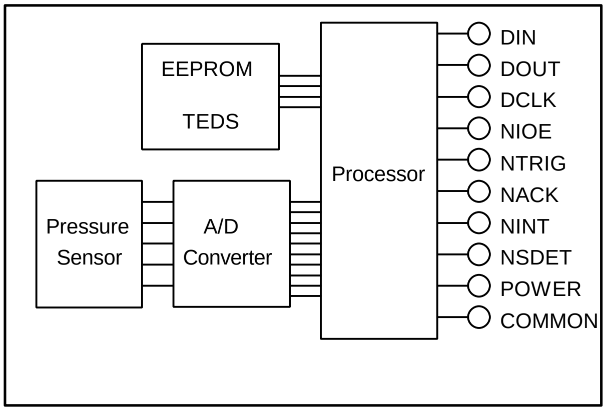
- Calibration data can be taken at any points throughout the working range. Evenly spaced data is not required.
- Data can be viewed in two or three dimensions.
- Multiple views of the same data set can be viewed concurrently.
- Data sets can be filtered to include or exclude data.
- Three-dimensional views are shaded surfaces that can be rotated to any viewing angle.
- Calibration order can be varied to determine the best-fit equation.
- IEEE1451.2-compatible multinomial coefficients are produced as output.

- High-order compensation can be performed with a small number of data points.
- High-order coefficients can be extracted in the presence of measurement noise and hysteresis.
- Custom computation algorithms are optimized for sensor calibration.
- Robust computation is insensitive to bad data points.
- Modeled sensor performance can be verified against actual sensor performance.
- Compensation is optimized based on characteristics of the correction device used. Finite resolution of compensation terms is included in the calculations.

Smart Transducer Sensor

A smart sensor or transducer consists of a sensor element, interface electronics, A/D converter and, optionally, D/A converter. Figure 1 shows a sensor module with an IEEE 1451.2 output, referred to as a smart transducer interface module (STIM)

Figure 1 STIM



The example STIM contains a pressure sensor, analog-to-digital converter, EEPROM memory, control processor and standard STIM digital and power signals. The module calibration information and characteristics are stored in the EEPROM memory. The data is stored in the transducer electronic data sheet (TEDS) format. The TEDS format is a hardware- and vendor-independent method of storing the information necessary to describe operating characteristics of a smart sensor, transducer or actuator.

Sensor Calibration and Compensation

Sensor calibration is divided into seven steps:

1. Verification and functional test
2. Pressure-temperature cycle with data collection
3. Calibration process verification
4. Data set modeling
5. Coefficient computation
6. Calibration verification
7. Coefficient programming

The CVS software performs steps three through six.

Calibration Data Set

A calibration data set consists of uncompensated sensor output sampled throughout the operating range. The pressure sensor data set contains the following values stored for each data point:

Digitized pressure signal	VP
Digitized temperature signal	VT
Reference pressure	PREF
Reference temperature	TREF
Module output pressure	POUT

A data set typically contains 100 to 1500 data points sampled throughout the operating pressure and temperature range.

Software Architecture

The CVS software is written in an object-oriented, array-based modeling language that provides libraries of host-independent graphics and math functions.

Numerous plots of the calibration data are available. The menus and display screens configure themselves based on the type of data set loaded.

The plots can be printed to the system printer or stored as a file. The compensation coefficients are written to a TEDS file.

For a single channel pressure sensor, the following plots are available:

Two-Dimensional VP Plots

VP offset vs temperature
VP offset vs VT
VP output vs PREF
VP output vs TREF
VP output vs data points

Two-Dimensional VT Plots

VT vs data points
VT vs TREF

Thermometer Calibration

TREF vs VT

Two-Dimensional Verification Plots

POUT offset vs PREF
POUT vs TREF-
Measurement error vs PREF
Measurement error vs TREF

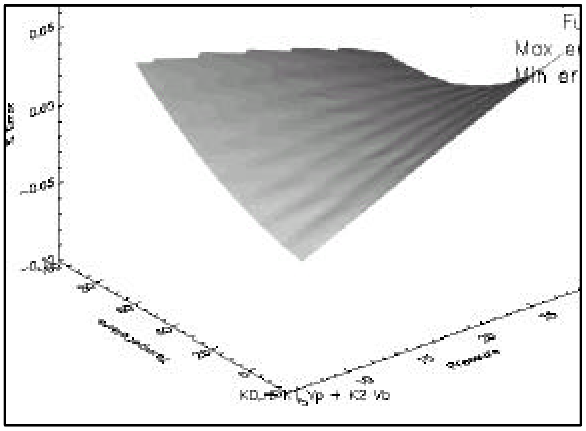
Three-Dimensional Plots

3d View of VP
Calibration error surface
Pressure measurement error surface

Calibration Error Surface

A calibration error surface is a three-dimensional surface. The x-axis and y-axis are reference pressure and reference temperature respectively. The z-axis is pressure measurement error. Pressure measurement error is the calibrated output minus the reference pressure.

Figure 2 Example Calibration Error Surface



CVS software allows real-time viewing and manipulation of the calibration error surface, and has controls to adjust the order of correction, angle of view, and filtering of the data set.

When a view parameter is changed, the software recalculates and redisplays the error surface. The complete calibration process is performed on each update, and correction coefficients are written to disk.

Calibration errors are displayed as a solid shaded-surface. As the compensation order is increased, repeatable errors become smaller until the error surface becomes a flat plane. The thickness of the plane is the combined measurement noise and hysteresis present in the data set. If the error surface does not become a plane the compensation equation is not a "good" model of the sensor errors and a different correction equation should be used.

An alternative to changing the correction equation is to divide the working range into zones with each zone having a unique set of correction coefficients. The P1451.2 standard supports this type of piece-wise surface.

Pressure Sensor Calibration

Figures 3 through 5 are calibration error surfaces for a 16 psia pressure sensor, Atmos module number 2510-BARO. This device is specified at 0.25% of full-scale total error band over the -40 C to 85 C temperature range.

Figure 3 shows the calibration error surface for the example pressure sensor. The compensation equation used contains an offset and gain term. The resulting error surface shows the 10% thermal errors in the sensor.

Figure 4 shows the calibration error surface with a second-order correction. Measurement error has been reduced to less than 1 percent of full scale.

Figure 5 shows the calibration error surface with the correction order increased to fourth order. The calibration error surface is flat to the sensor noise limit. The error histogram in the upper right hand corner of the plot shows a normally distributed residual error indicating that the fit equation matches the sensor characteristics. Measurement error has been reduced to under 0.08% percent of full scale.

For a typical silicon sensor, performance improvement is seen up to the seventh order. The CVS software is capable of accurately calculating coefficients up to the twelfth order. Correction above the sixth order is seldom required, and if necessary may point to non-linearity in the A/D converter or other component.

Figure 3

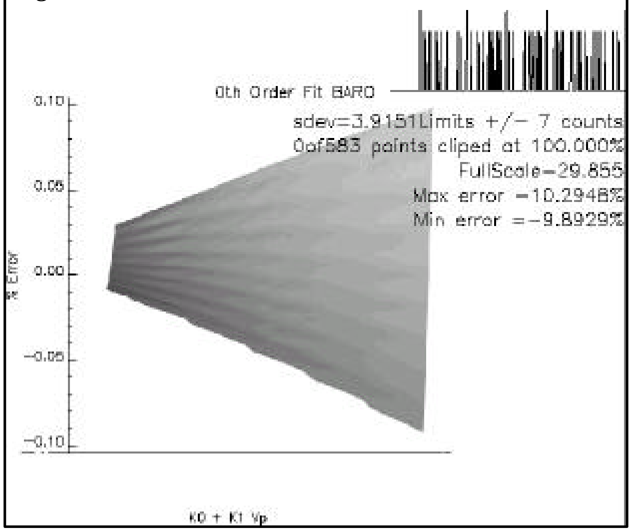


Figure 4

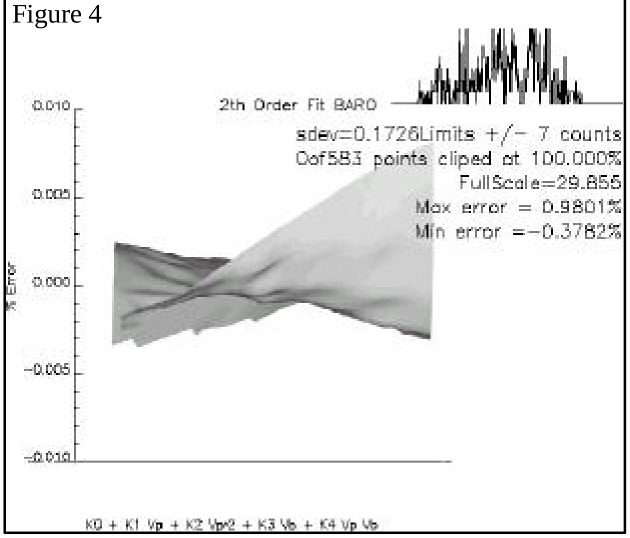
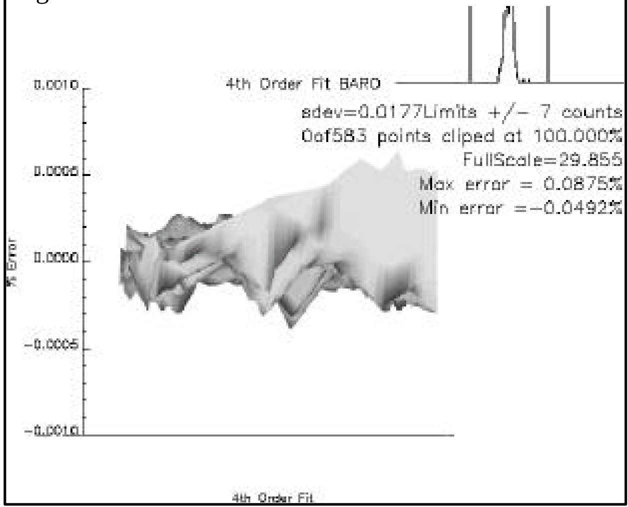


Figure 5



Correction Equation

The CVS software supports numerous correction equations. The equation used depends on the nature of the uncorrected output of the sensor. The most reliable compensation equations are based on the physics of the sensor element and interface electronics.

The IEEE1451.2 standard specifies a multinomial equation with the ability to specify different sets of coefficients over different portions of the operating range.

Equation 1 is an example of a fourth-order correction polynomial that is well suited for the compensation of silicon pressure sensors. Total measurement errors of under 0.1% of full scale can be achieved over the -40 C to +85 C temperature range.

The VP signal is the digitized pressure voltage from the pressure sensor element.

The VT signal is the digitized temperature feedback signal.

The temperature feedback signal can be extracted from the pressure element or can be generated by a separate temperature sensor.

$$
\begin{aligned}
P = \quad & K0 + K1 \times VP + K2 \times VP^{2} + K3 \times VP^{3} + K4 \times VP^{4} \\
& + K5 \times VT + K6 \times VP \times VT + K7 \times VP^{2} \times VT + K8 \times VP^{3} \times VT \\
& + K9 \times VT^{2} + K10 \times VP \times VT^{2} + K11 \times VP^{2} \times VT^{2} \\
& + K12 \times VT^{3} + K13 \times VP \times VT^{3} + K14 \times VT^{4}
\end{aligned}
$$

Equation 1 Fourth-Order Polynomial

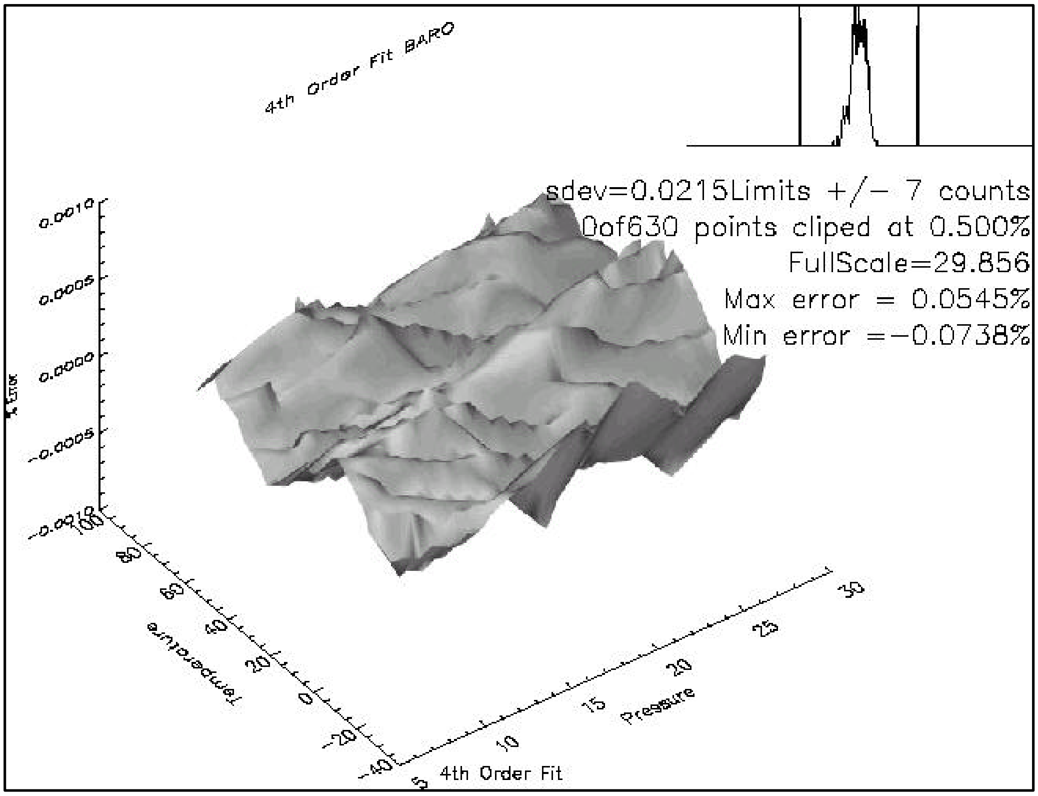


Figure 6 Fourth-Order Compensation Results

Thermal Hysteresis Measurement

Thermal hysteresis is the primary accuracy limit for a silicon pressure sensor. The CVS software has been designed to be insensitive to hysteresis in the data set. High-order coefficients typically correct for errors near or below the hysteresis limit. Classic curve fit techniques have difficulty discriminating between hysteresis and high-order sensor characteristics.

Figure 7 is a fourth-order compensation of a 30 PSIA full-scale sensor module. The sensing element is an oil-isolated element and a 16-bit A/D converter is used. The resulting error surface is flat to within 0.04 percent of full-scale and the residual error histogram in the upper right hand corner shows a hysteresis of 0.045% of full scale. The hysteresis is centered at zero error.

Thermal errors in this sensor have been attenuated from +/- 15 percent of full scale to 0.01% of full scale. The majority of the remaining error is measurement noise and thermal hysteresis.

Acknowledgements

Stan Woods, Hewlett Packard

Janusz Bryzek, Maxim Integrated Products

Lynne Bowman, Lynne Bowman Creative Services

Reference

1) IEEE Draft Standard for A Smart Transducer Interface for Sensors and Actuators , IEEE P1451.2 D3.05

Figure 7