

# Calibration

## System Considerations for Calibration

The most important function of a data acquisition system is to ensure integrity of the measurements produced. The data collected must be an accurate representation, to the highest practical degree, of the physical values that are being measured. If, prior to a test, a data acquisition channel is not ready to produce "good" data, this condition must be detected and reported, so that corrective action can be taken. The problem may be caused by such items as a faulty transducer, input wiring problems or a failed component in the signal path.

Calibration can help accomplish the goal of assuring reliable data by verifying the integrity of the signal path and also helps to reduce system costs by placing the burden of absolute accuracy on relatively few components.

The transfer functions of many transducers, i.e., the relationship between the physical values being measured and the output voltages or currents, cannot be included in the calibration cycle of a data acquisition system. This is because the physical value—such as temperature—must be changed to perform the desired measurements. Calibration factors for such sensors are derived from manufacturers' data sheets, Transducer Electronic Data Sheets (TEDS), standard tables, or the characteristics of individual transducers as determined by a calibration laboratory. These values are then entered into the computer or uploaded from a Virtual TEDS (VTEDS) file. Some transducer subsystems, such as multiplexed pressure sensors, actually are calibrated while attached to the system—by injecting precision pressures into the subsystem. Many data acquisition systems are able to detect open or short-circuited transducers or wiring. For example, an "open" thermocouple can be detected by passing a current through the thermocouple wiring and using the data acquisition system to measure the resulting voltage. This arrangement provides a measure of the source resistance to the thermocouple circuit.

## Voltage Injection

With the voltage-injection method, a known voltage is inserted into the input of a channel and the digitized response from the ADC is monitored. If three voltage points are chosen, e.g., near + and - full scale and zero volts, the transfer function of the channel can be easily computed. In addition, if this transfer function falls outside prescribed limits, a warning can be generated.

## Bridge Transducer Verification

For bridge-type transducers, shunt calibration generally is used. This type of calibration is performed by taking at least two sets of readings, one set with and one set without a shunt resistor connected across one leg of the bridge. It is recommended that a number of readings be taken in each state and the results averaged to minimize the effects of noise. In addition, a check should be incorporated to measure the range of a set of values, thus providing an indication of the noise level and perhaps identifying installation or system problems. If the data acquisition system uses a programmable relay to connect the shunt resistor, this calibration can be performed automatically.

If bridge balance is provided, an additional level of transducer verification may be performed. Assuming that the bridge balance circuitry operates by injecting current into the bridge, the resulting voltage shift provides a measure of the bridge resistance.

Ideally, the excitation voltage should be sensed at the bridge. This allows the actual voltage at the transducer to be measured, and the effects of wiring resistance nullified. The signal conditioner should be able to measure the excitation voltage to calculate the transfer function of the bridge as well as verify that the correct excitation voltage is present.

While the approximate resistance of bridge-type transducers can be determined, the actual transfer function of that type of a transducer, such as a strain gage, can only be determined from manufacturer's data or by changing the physical value—strain, in this case.

### **Reference Voltage**

All calibration voltages must be referenced to some highly accurate standard, such as provided by NIST (National Institute for Science and Technology, formerly the National Bureau of Standards—NBS). This requires periodic calibration of the data acquisition system components, so that any inaccuracies can be corrected. Instead of adjusting the gain and offset for all channels, it is desirable to reference all calibration measurements back to one point in the system. Thus, if this system reference is used as the basis for all calibration, only that component need be calibrated periodically. The data acquisition system should provide a means for busing this system reference voltage to the voltage injection relays for each signal conditioning channel.

### **Calibration Archiving**

Often, it is not sufficient to simply archive the data from a test. Responding to regulatory requirements, customer specifications or a desire for more data security, it may be necessary to archive the calibration information along with this data. This approach allows the accuracy of the data to be verified at a future date. With the calibration procedures discussed here, the additional archiving can be performed quite simply. The data acquisition system can produce a complete calibration record, taken just prior to the test. The "raw" uncalibrated data may also be archived.

**One of the leading airbag manufacturers demonstrated the importance of built-in diagnostics in front-end modules. They wanted their test system to notify them immediately if a transducer failed or if a problem with the sensor wiring occurred. With built-in diagnostics, designed by KineticSystems, these types of error conditions (excitation alarms, open/short conditions, etc.) can be reported immediately and also logged into the datafile.**

## **Standard Calibration Procedure**

For optimum accuracy it is recommended that the user perform a calibration of the channels to be used prior to acquiring data. The calibration procedure should be performed following a minimum equipment warm-up of approximately half an hour. Each channel or group of channels which share common active input circuitry should be calibrated following warm-up

and prior to acquiring data.

It is recommended that the following calibration procedure be followed. Calibrator loading effects should be taken into account in determining the number of channels connected to the reference at any one time. Overloading the capability of the calibrator reference voltage can have adverse effects on acquired data.

The calibration measurement should be made with the calibrator range ( $k$ ) set per note 3 below for each channel ( $j$ ).

1. Acquire N-samples with grounded inputs selected ...  $X_i^j(0)_i = 1, N$ .
2. Acquire N-samples with +CAL inputs selected ...  $X_i^{jk}(+CAL)_i = 1, N$ .
3. Acquire N-samples with -CAL inputs selected ...  $X_i^{jk}(-CAL)_i = 1, N$ .

Notes:

1. Be sure to allow adequate settling time between switching input levels *especially if lowpass filters are present* in the analog path. The time for a simple RC filter to settle to one lsb of a 16-bit ADC is 10.38 time constants or  $1.66/f_c$  where  $f_c$  is the filter cutoff frequency. Filters with sharper roll-off typically require proportionally longer settling times.
2. It is recommended that at least N=20 samples be acquired for each input level.
3. The calibrator voltage should be set to give an output voltage that is near full scale on the ADC.

From this calibration data a slope ( $m_j$ ) and an offset ( $b_j$ ) are computed for each channel ( $j$ ). These quantities are then used to convert the measured ADC counts for channel  $j$  to volts.

### Determining the offset $b_j$ and slope $m_j$

The offset  $b_j$  for channel  $j$  is computed from the N *calibration* measurements  $X_i^j(0)$  with the input switched to ground as follows:

$$b_j = \frac{1}{N} \sum_{i=1}^N X_i^j(0)$$

The slope  $m_j^k$  for channel  $j$  is computed from the N measurements  $X_i^{jk}(+CAL)$  with calibrator range  $k$  (+CAL) selected and the N measurements  $X_i^{jk}(-CAL)$  with calibrator range  $k$  (-CAL) selected as follows:

$$m_j^k = \frac{\frac{1}{N} [\sum_{i=1}^N X_i^{jk}(+CAL) - \sum_{i=1}^N X_i^{jk}(-CAL)]}{E_0^k(+CAL) - E_0^k(-CAL)}$$

Where:

- $X_i^{jk}$  is the  $i$ th measured ADC counts for channel  $j$  using calibrator range  $k$ .  
 $E_0^k$  is the published calibrator voltage value for range  $k$ .

## Applying the calibration to data

The input voltage to be measured  $V_j$  is computed from the acquired ADC count  $X_j$  by the following relation:

$$V_j = \frac{(X_j - b_j)}{m_j^k}$$

Where:

- $V_j$  is the *derived* analog input voltage for channel  $j$  in Volts.
- $X_j$  is the *measured* analog input for channel  $j$  in ADC counts
- $b_j$  is the offset for channel  $j$  as determined from the calibration run prior to taking data
- $M_j^k$  is the gain for channel  $j$  as determined from the calibration run prior to taking data

## Periodic System Calibration

KineticSystems recommends that the precision reference source used during pre-acquisition calibration is calibrated at approximately 6 month intervals or an interval that is appropriate to the user's situation. The calibration is accomplished by attaching a NIST traceable DVM on the test points provided on the module front panel and adjusting the output of the precision reference to 10.0 Volts.

## High Precision Calibration Procedure

For some low-level applications, for example thermocouples, accurate voltage measurements at millivolt signal levels may be required. Some signal conditioning modules implement a further level of calibration to achieve accuracies of a few microvolts. These accuracies are achieved by calibrating the internal calibrator and channel-to-channel thermal EMF differences between the actual signal input connector and the common switched ground used for calibration. These second-order correction factors are stored in EEPROM for each module when the module is calibrated at the factory. These correction factors can be read by the application software and applied at the time the data is read.

Two second-order corrections are involved in the precision calibration:

1. A gain correction term  $\epsilon_k$  that represents a second-order correction to the gain based on the hybrid calibrator range  $k$ . Note that the gain correction is most significant at high gains since the hybrid calibrator accuracy is most accurate at calibration levels of 100mV and above when compared to 16-bit ADC measurement accuracy of 0.003% .
2. An offset correction  $\delta_j$  that represents a second-order correction to the offset for channel  $j$  which represents slight thermal EMF differences due to different signal paths from the front connector to the input amplifier and the common switched input ground used during calibration to determine channel offsets. Note that the offset correction is only important at high gains when measuring low-level signals where  $\mu$ Volt offset differences can be resolved by the ADC.

When using the second-order correction terms, the measured input voltage is given by the expression:

$$V_j = \frac{(X_j - b'_j)}{m_j^k}$$

Where:

$V_j$  is the *derived* analog input voltage for channel  $j$  in Volts.

$X_j$  is the *measured* analog input for channel  $j$  in ADC counts

$b'_j$  is the offset for channel  $j$  as determined from the calibration run prior to taking data that includes a second order offset correction term.

$M_j^k$  is the gain for channel  $j$  using calibrator range  $k$  as determined from the calibration run prior to taking data

### Pre-acquisition Calibration

As noted earlier the equipment should be turned on and temperatures allowed to stabilize for a minimum of half an hour prior to performing the calibration and data collection. It is also recommended that temperature fluctuations be held to a minimum during warm-up, calibration and data acquisition.

The second order calibration is based on gain correction terms which not only correct for the precision of the hybrid calibrator, but also corrects for any deviation of the precision reference from 10.0 Volts. For these reasons the following considerations apply:

- Only the internal precision reference source in the module should be used with this calibration technique (not the common ADC reference source).
- The periodic calibration procedure no longer *requires* calibrating the precision reference source since the second order correction terms correct for any long term drift.
- A switched set of test points for measuring the calibrator output permit a common NIST traceable DVM to be used for a completely automatic periodic calibration.

### Determining the offset $b_j$ and slope $M_j^k$

Prior to collecting data, a calibration run should be performed to determine the offset  $b'_j$  and gain  $M_j^k$  for each data channel. These quantities are derived as follows:

$$b'_j = \frac{1}{N} \sum_{i=1}^N X_i^j(0) + m_j^k \cdot \delta_j \cdot 10^{-9}$$

Note: Since the offset correction  $\delta_j$  is small the published gain can be used in place of  $M_i^k$  in the above expression for the offset  $b'_j$  without loss of accuracy.

Where:

- $X_i^j(0)$  is the *ith* measured ADC counts for channel *j* with inputs switched to internal ground.
- $X_i^{jk}(\pm\text{CAL})$  is the *ith* measured ADC counts for channel *j* using calibrator range *k*.
- $E_0^k$  is the published calibrator voltage value for range *k*.
- $\epsilon_k$  is the 16-bit signed 2s complement integer “calibrator correction factor” stored in EEPROM for CAL range *k* scaled by  $10^6$  (e.g.  $\pm 2\text{mV}$ ,  $\pm 5\text{mV}$ ,  $\pm 10\text{mV}$ , ...) ranges.
- $\delta_j$  is the 16-bit signed 2s complement integer “offset correction factor” stored in EEPROM for channel *j* scaled by  $10^9$ .

## Periodic Calibration Procedure

The periodic high precision calibration differs from the general periodic calibration. It is no longer necessary to adjust the precision reference source voltage as any drift in the precision reference is reflected in the second-order gain corrections that are derived and stored in EEPROM during the periodic calibration.

It is recommended that the periodic *gain calibration* be performed at approximately 6 month intervals. It is expected that the *offset periodic calibration* need only be performed once over the life of the module. This calibration is performed at the factory during final testing.

When the system is configured with a common based cable between the calibrator test points and a NIST traceable DVM which is computer controlled, the periodic gain calibration can be performed automatically without operator intervention.

## Second-order Periodic Gain Calibration

The calibrator or gain correction terms  $\epsilon_k$  for the high precision calibration procedure are computed and stored in EEPROM based on factory measurements using a NIST traceable DVM. The recommended interval for this calibration is approximately 6 month intervals for applications requiring a high level of precision. The user should determine the calibration interval based on the individual situation.

The calibration procedure is to connect a NIST traceable DVM of suitable accuracy to the calibrator

output which is available on the front panel of the module. The module is then set up through software to select the desired calibrator output range  $k$  and +CAL output using the precision reference source internal to the module being calibrated and selecting the calibrator output to the front panel test points. The DVM reading  $D^k$  (+CAL) is recorded. A similar measurement  $D^k$ (-CAL) is made. The value of  $\epsilon_k$  is then computed for each calibrator range  $k$  and stored as a signed 16-bit integer in EEPROM as follows:

$$\epsilon_k = \frac{[D^k(+CAL) - E_0^k(+CAL)] - [D^k(-CAL) - E_0^k(-CAL)]}{[E_0^k(+CAL) - E_0^k(-CAL)]} \times 10^6$$

Where:

$D^k$  is the calibrator output voltage measured with an NIST traceable DVM for calibrator range  $k$ .

$E_0^k$  is the published calibrator voltage value for range  $k$  (e.g. 5mV, 10mV, 20mV, ...).

Note:

The value of  $\epsilon_k$  before scaling is a small number ( $\ll 1$ ). For the *ideal* calibrator  $\epsilon_k = 0$ . To store the value of  $\epsilon_k$  in a computer architecture independent representation we have chosen to store it as a scaled 16-bit 2s complement binary integer which has a range of  $\pm 32767$ . This gives the correction multiplier  $(1 + \epsilon_k)$  a range from 0.967233 to 1.032767 to an accuracy of  $1:10^6$  (0.0001%).

## Offset Correction

The offset calibration is expected to be considerably less sensitive to long term drift and is expected to be stable over the life of the module. This calibration is performed at the factory and the results stored in EEPROM. The calibration can also be performed in the field. For this calibration the input wiring *must* be disconnected and a special shorting connector installed in its place.

The offset correction terms  $\delta_i$  are computed and stored in EEPROM based on measurements of the differences in offsets for each channel between the offset measured with the inputs shorted using a special connector and when the common internal ground is selected that is used during a pre-acquisition calibration. These differences are scaled to nanovolts and stored as 2s complement binary integers in the EEPROM.

$$\delta_j = \left( \sum_{i=1}^N X_i^j(\text{Input-gnd}) - \sum_{i=1}^N X_i^j(\text{Internal-gnd}) \right) \frac{1}{Nm_j} \times 10^9$$

where:

$X_i^j(\text{Input-gnd})$  is the  $i$ th measured ADC counts for channel  $j$  with the inputs grounded.

$X_i^j(\text{Internal-gnd})$  is the  $i$ th measured ADC counts for channel  $j$  with inputs switched to internal ground.

$M_j$  is the channel gain. This can be the gain determined from a simple calibration or just the published channel gain since the error introduced by the latter is minimal.

## Programmable Calibration

Historically, the process of calibrating a channel has been a time-consuming process. With a short circuit at the input connector, a potentiometer would be adjusted until the channel output read zero volts. This sets the channel's zero offset. Then the gain would be adjusted similarly, with a known voltage applied to the input. This process would need to be repeated later if a different gain range was required. The only other approach was to use components in the signal path which were extremely accurate and exhibited the lowest drift possible.

With the advent of modern data acquisition systems, the whole process can be automated to the extent that is feasible. Rather than adjusting the channel for a 'perfect' gain and offset, a better approach is to measure and record in memory the transfer function of the channel and then compensate, generally in software, for any deviations from the ideal when the data is being reconstructed. Thus, under computer control, the ADC count corresponding to zero volts and a voltage near full scale can be measured and the transfer function calculated. An on-board, precision, programmable voltage source is often used to facilitate this measurement.

One obvious advantage to programmable calibration, in addition to dramatically shortening setup time, is reduced cost, since only the calibration source needs to have a high degree of absolute accuracy. Components used in the signal path need to be appropriately linear and have sufficient stability between calibration runs.