Determination of Calibration Factors

Digital data acquisition system use analog-to-digital converters (ADCs) to convert analog voltages from sensors to digital, binary data. The most common ADCs used for vehicle safety testing have 12- or 16-bit resolution. A 12-bit ADC has 4096 binary steps (commonly referred to as counts or cnts) for its full scale input range while a 16-bit ADC has 65536 cnts.

To calculate the value of any given data sample in Engineering Units (e.g., Gs, Newtons, etc.), a *Zero Level* and a *Calibration Factor* must be known. A data sample value in Engineering Units (EU) is calculated as follows:

Equation 1.1

Data Value (in EU) = (Current Value [in ADC cnts] – Zero Level [in ADC cnts])*Calibration Factor [EU/cnt]

Zero Level

For vehicle safety testing, a *Zero Level* is often determined by averaging a number of data samples over a time period just prior to the test event. This average *Zero Level* in ADC cnts is determined for each data channel using software data processing.

It may be possible to use electronic circuits to attempt to assure that the ADC cnt level of every channel is at an exact value prior to every test (for example, at 2047 for the middle of a 12-bit ADC with a 0 to 4095 cnt input range). However, SAE J211 recommends that the best methodology is to use software to calculate the *Zero Level*.

There are very solid reasons for this recommended methodology. Sensor outputs tend to drift over time and an electronic circuit's ability to constantly keep the relative *Zero Level* at a fixed ADC cnt is impractical to achieve, especially when trying to differentiate dynamic test data from data just prior to the test. For instance, if an electronic circuit were constantly attempting to keep every data channel at exactly 2047 cnts as a test vehicle was being pulled into a barrier, at what point would the electronic circuit stop attempting to zero the channels and allow the dynamic test data to be recorded?

Calibration Factor

Calibration Factors for each data channel are determined using a number of different methodologies. It may be possible to use electronic circuits to accurately set the gain of a data channel and assume a fixed relationship between mV input and ADC cnts (and therefore a relationship between Engineering Units and ADC cnts using the sensor sensitivity in mV/EU). However, SAE J211 recommends that the best methodology is not to rely on set gains to determine the *Calibration Factor*. SAE J211 recommends that software be used to calculate the *Calibration Factor*.

Again, there are very solid reasons for this recommended methodology. If a system relies on set gains, it makes some very poor assumptions including:

- It assumes that the excitation source is constant and accurate for every test regardless of what sensors or cables are attached. Often the excitation voltage source in the data acquisition system is only accurately checked during yearly calibration cycles which, if this is the case, increases the chance of error. As described later in this document, an accurate *shunt calibration* will detect this failure mode.
- It assumes that the bridge of the sensor has not been damaged in any way since its last calibration. As described later in this document, an accurate *shunt calibration* circuit will detect this failure mode.
- It assumes that there are no other potential causes for gain errors in the data acquisition system. Gain is not only a function of the amplifier stages but is a combination of the amplifiers, bandwidth and anti-alias filters, offset nulling circuits, ADC accuracy, etc. As described later in this document, an accurate *voltage insertion calibration* circuit will allow precise end-to-end calibration of the data acquisition circuit.

One common way for using software to determine the *Calibration Factor* is to digitize a zero and a calibration sample just prior to and just after each test event (see Figure 1). Using software data processing, an average ADC cnt value is computed for the zero and for the calibration samples. The zero sample average is then subtracted from the calibration sample average and this delta ADC cnt value is used to determine the *Calibration Factor* for the channel. Often the pre- and post-test zero and calibration samples are compared as a diagnostic check.

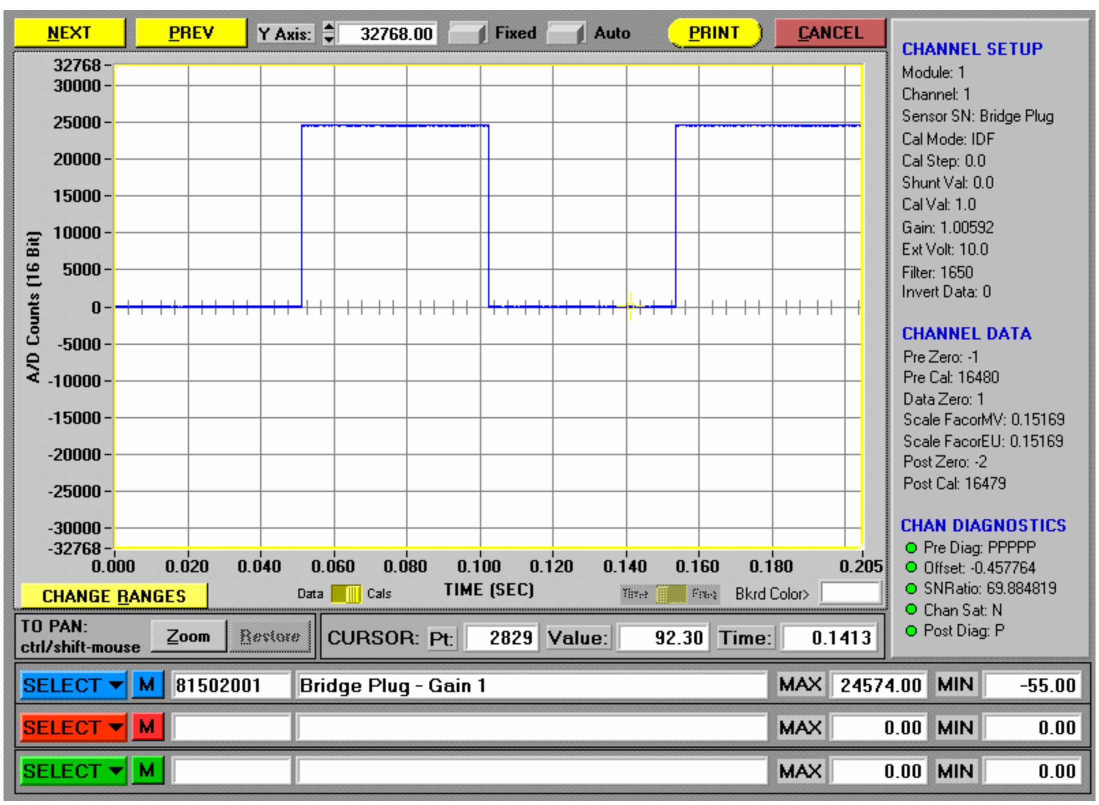

Figure 1: Pre- and Post-test Zero and Calibration Samples on a 16-bit ADC System

Shunt Calibration

A common and very accurate methodology for determining a data channel's *Calibration Factor* is to use shunt calibration. With this methodology, a known accurate resistor value is switched across the +Excitation and +Signal leads (and/or the –Excitation and +Signal leads) of the sensor (see Figure 2).

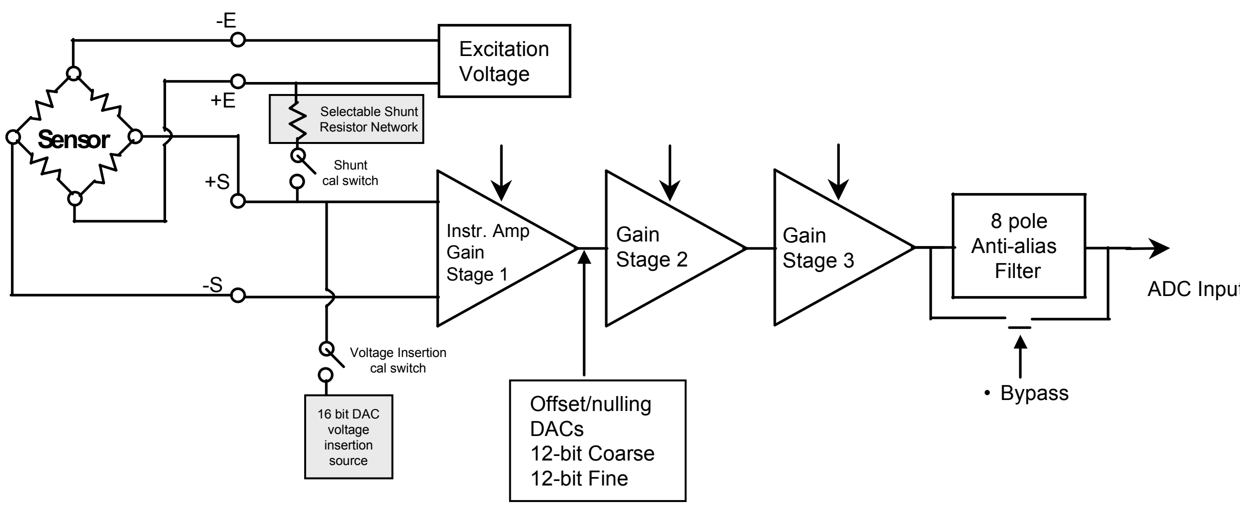

Figure 2: Block Diagram of Shunt and Voltage Insertion Calibration Circuit

This causes a delta change in the mV input to the data acquisition channel and therefore a delta change in the ADC cnts. Note that the switch used to insert the calibration resistor needs to have a low resistance so as not to affect the reading.

At the time of sensor calibration, a shunt calibration is performed using an accurate, fixed resistor chosen to cause a delta mV change equal to approximately 75% of the full scale range of the sensor. The sensor calibration data sheet will then record the exact resistor value used and the corresponding delta mV value. The delta mV value is converted into Engineering Units using the sensor's calibrated sensitivity. Therefore a calibrated relationship between a shunt resistor value and an Engineering Unit value is established (for instance 62.5 KΩ equates to 1514.85 Gs).

It is important to note that this relationship is ***independent*** *of the excitation voltage level and the set gain of the data channel*. For example, if an accelerometer is calibrated with an excitation voltage of 10.00 V but is only supplied 9.96 V during the actual test, its mV output per G will be slightly less than expected. If a calibrated shunt resistor is used to determine the *Calibration Factor* just prior to the test, the *Calibration Factor* will also be slightly lower than expected by the exact same proportion. The end result is that the test data in Engineering Units is extremely accurate. For the same reason, it does not matter if a set gain of 100 is actually 100.00 or 101.24.

Per SAE J211, the *Calibration Factor* for each data channel is determined using software when the shunt calibration methodology is employed. Generally, just before each test is performed, the sensor is connected to the excitation voltage source and allowed to warm up to its normal operating temperature. Then a zero sample is recorded. The shunt resistor is then inserted into the circuit and a calibration sample is recorded (as shown in Figure 1). Using software, the average zero and calibration sample levels are determined and a delta cnt value is calculated. The software now calculates the *Calibration Factor* for the data channel as per equation 1.2.

Equation 1.2

Calibration Factor [EU/cnt] = Engineering Unit value equivalent to the shunt resistor/delta cnts

There are advantages and disadvantages to this methodology.

Advantages:

- Assuming the shunt resistor is accurate and stable, a very accurate *Calibration Factor* is computed independent of the exact gain of the amplifier stages, the filters, the ADC, etc., or the excitation voltage level.
- Accurate calculation of the *Calibration Factor* relies on only one component in the data acquisition electronics (the shunt resistor) to remain accurate under all conditions between yearly system calibration cycles.
- Since shunt calibration uses the sensor wiring and bridge as part of the calibration circuit, the shunt calibration methodology performs a complete sensor-to-ADC systems check. Any major problems with the sensor, wiring, or data acquisition system can be detected before a valuable test is performed.
- Since the software is also aware of the expected sensor sensitivity in mV/V/EU, a diagnostic check can be performed to be sure that the mV deflection caused by the insertion of the shunt resistor matches the expected sensitivity. Equation 1.3 below shows how to determine the calculated Engineering Unit value, which can be compared to the theoretical Engineering Value associated with the shunt calibration resistor.

Equation 1.3

Calculated EU value = (mV delta caused by shunt resistor insertion)/(sensor sensitivity [mV/V/EU]*Excitation Voltage)

If the calculated Engineering Unit value does not match the theoretical Engineering Unit value within a certain percentage, then it can be assumed that there is something wrong with the sensor, wiring, or data acquisition system.

Disadvantages:

- The calculated versus theoretical diagnostic check described above is dependent on the set gain of the data acquisition system being exact. If it is not exact then the gain error will contribute to the difference between the calculated and theoretical Engineering Unit value. The software and user now has no way of knowing whether this error is due to the data acquisition system or to problems in the sensor bridge or wiring.

If an accurate voltage insertion calibration circuit is also used as described in the next section, the exact gain of the data acquisition system can be calculated before the shunt calibration check is done.

Voltage Insertion Calibration

Another common methodology used to determine the *Calibration Factor* is to insert a very accurate voltage source at the front end of the data channel (at the +Signal input) and read the delta change at the back end of the system (at the ADC). This is done after all gain stages are set. The inserted voltage is usually set to provide an approximate 75% change of the full scale ADC range (for a 16-bit ADC, the desired change in cnts would be approximately 32768 x 0.75). To achieve accurate, 75% input with a wide range of gains, a high resolution, adjustable voltage insertion source is generally required (a 12- or 16-bit digital-to-analog converter or equivalent).

Therefore if an accurate inserted voltage causes a delta change in ADC cnts, this *Calibration Factor* in mV/cnt can be converted to EU/cnt using the sensor's calibrated sensitivity using the equation:

Equation 1.4

Calibration Factor [EU/cnt] = Calibration Factor [mV/cnt]/(Sensor Sensitivity [mV/V/EU]*Excitation Voltage [V])

As recommended by SAE J211, the *Calibration Factor* in mV/cnt is usually determined by using software to calculate the delta between the average zero and calibration sample levels (as shown in Figure 1) and then converting the *Calibration Factor* to EU/cnt as shown in equation 1.4.

There are advantages and disadvantages to this methodology.

Advantages:

- Assuming the inserted voltage is accurate, the complete data channel gain or scale factor is determined including the amplifier stages, the filters, the ADC, etc.
- Accurate calculation of the *Calibration Factor* relies on only one component in the data acquisition electronics (the voltage insertion source) to remain accurate under all conditions between yearly system calibration cycles.
- Since there is an expected gain or scale factor associated with each complete data channel, software can be used to check the calculated *Calibration Factor* to what is expected as a diagnostic check.

Disadvantages:

- Voltage insertion calibration does not check the sensor wiring or sensor electronics in any way. A sensor could have a bad bridge or a cut wire and the data acquisition system may not be aware of this condition.
- Voltage insertion calibration also does not check the excitation voltage source. The excitation voltage could be at 8.80 V instead of the expected 10.0 V and this condition would not be detected by the voltage insertion calibration methodology alone.

Calibration Factor Summary

There are other less common, yet still valid methodologies of determining the *Calibration Factor* for a data channel. One of these other methodologies, often referred to as shunt emulation, has the advantages of a strict shunt calibration with the ability to dynamically adjust the actual shunt level to exactly 75% of the sensor full scale range.

In all SAE J211 compliant methodologies, the *Calibration Factor* for each data channel is calculated using software, not by relying on set gains. This is done by recording a zero sample and then recording a calibration sample. If the calibration sample is produced by an accurate source, the resulting delta cnts seen at the data acquisition system's ADC can be used to determine the *Calibration Factor* in EU/cnt.

The calibration level can be produced manually using an accurate, external voltage source or by manually inserting a shunt calibration resistor. With modern electronics, it is possible and desirable to have the data acquisition system contain accurate, finely adjustable voltage sources and/or multiple shunt calibration resistor circuits that are switched in automatically during calibration before each test is performed.

Systems can be considered compliant with SAE J211 whether they perform the calibration manually or automatically as long as software is used to calculate the corresponding *Calibration Factor*. It is important to note that the application of the calibration reference (voltage or shunt) and determination of the *Calibration Factor* should be performed before every test since sensors, cables, temperatures, etc., are generally not constant.

Note that test laboratories may want to consider performing *both* a shunt and voltage insertion calibration methodology and check one against the other. Also note that although SAE J211 does not require the user to perform any diagnostic checks on the *Calibration Factor* before the test is run, doing so may well detect problems before test data is lost or collected incorrectly.

DTS TDAS Systems

All TDAS systems are fully SAE J211 compliant. They have very accurate voltage insertion and shunt calibration circuits to determine the exact *Calibration Factor* for every channel. This is done automatically on every channel before every test. With TDAS systems, the user can be sure that the *Calibration Factors* for all channels are accurate, do not rely on fixed gains, and are checked every time before every test. This provides the user with the highest confidence for critical testing. To our knowledge, TDAS systems are the only data acquisition systems for on-board crash testing that have these comprehensive and accurate circuits for determination of *Calibration Factors*.