Calibrate accelerometers for industrial apps

By Randy Carver
iSensor Application Engineer
E-mail: randy.carver@analog.com

Mark Looney
Staff Design Engineer
Multichip Products Business Unit
E-mail: mark.looney@analog.com

Analog Devices Inc.

The development of MEMS inertial-sensors technology has been driven by automotive safety systems; as such, it has been applied to several high-volume applications. The large volumes associated with automotive safety systems have enabled substantial investment in MEMS manufacturing technology, packaging concepts, quality assurance systems and innovative design approaches. This has resulted in cost-effective, reliable solutions that are finding niches in other market segments such as gaming consoles and mobile handset applications.

MEMS sensors are also finding their way into industrial applications including workplace safety systems. Equipment position sensing, impact detection and rollover prevention for lift trucks are some workplace safety systems that benefit from MEMS accelerometers. Workplace safety systems are designed to detect potentially dangerous operating conditions without affecting normal operation. One primary factor in this process is the accuracy of the sensing solution used. Like most technology solutions, MEMS accelerometers have cost and performance trade-offs.

For automotive and commercial applications, adequate performance at the lowest possible cost is sufficient. But industrial applications, such as workplace safety systems, require higher accuracy. In such cases, reliability, convenience and component costs of these solutions are critical.

Despite the introduction of higher integration and more accurate accelerometer products, system designers still need to understand how parts are calibrated; this allows them to decide whether to purchase this capability or develop their own calibration routines. This article outlines the calibration process for a dual-axis accelerometer and highlights its most common sources of error.

Why calibrate?

For many MEMS inertial sensor consumers, calibration provides an opportunity to trade system cost for improved accuracy in their sensing solutions (**Figure 1**). While the relationship in the graph is generic, the performance goals are generally driven by end-system performance requirements that add value for the customer.

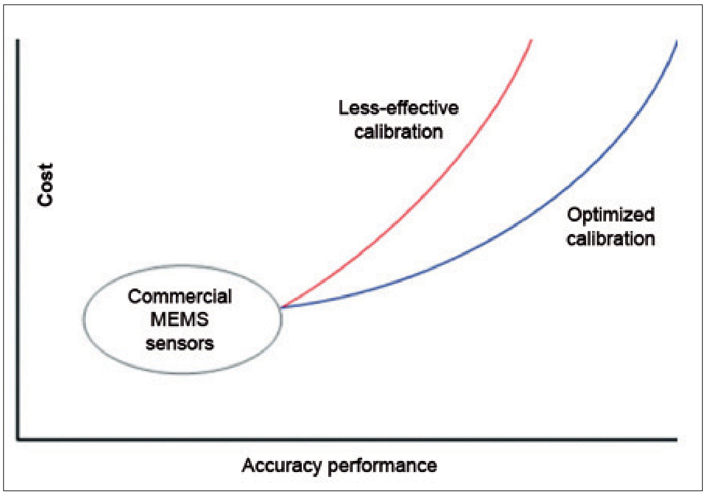

Figure 1: For MEMS inertial sensor consumers calibration provides an opportunity to trade system cost for improved accuracy of sensing solutions.

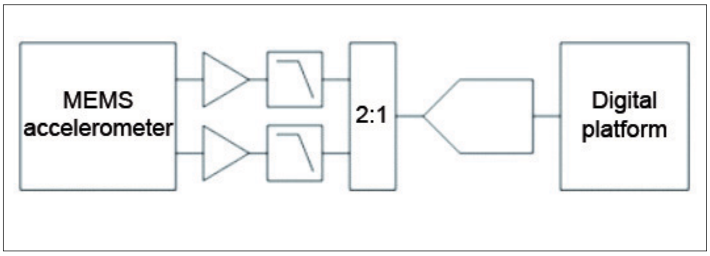

Figure 2: A typical circuit for providing calibrated accelerometer performance is shown.

For example, greater accuracy means the rollover prevention system does not need to overcompensate when determining the limits on a lift truck. Optimized accuracy levels can enable a crane to serve a larger area, or handle heavier loads, without the threat of tipping. The bottom line: optimizing performance in safety-sensing systems adds value to the overall solution.

The cost increase associated with calibration includes both direct material costs (ADC, microcomputer, extra PCB complexity and labor) and investment costs (calibration fixtures and R&D engineering) that can be amortized over the anticipated volume of systems produced. The goal of any calibration process is to achieve valuable performance levels while managing associated costs.

The difference between a well-executed calibration process and a less-effective one is shown in the performance vs. cost curves in Figure 1. Diligence in identifying and mitigating risk will determine what a given level of performance improvement will cost. It only takes one mistake to move from blue to red!

Developing a MEMS calibration solution entails four steps:

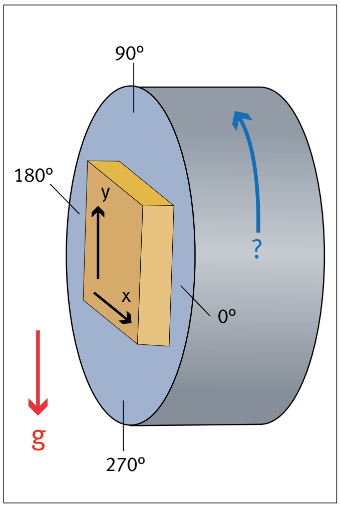

Figure 3: Gravity is a reliable source of stimulus for low-g accelerometer calibration, most simply implemented using a four-point tumble test as shown.

1. Establish performance goals.
2. Determine calibration requirements.
3. Design calibration process.
4. Implement correction formulas.

Performance goals

Establishing the performance goals for an accelerometer calibration sets the tone for the entire development process. These goals will guide the sensor selection. They will also guide the analysis process that will determine the behaviors that need correction, and ultimately, the complexity of the calibration process. This is critical because the temptation to ask for more than what is necessary can cause cost overruns and schedule delays.

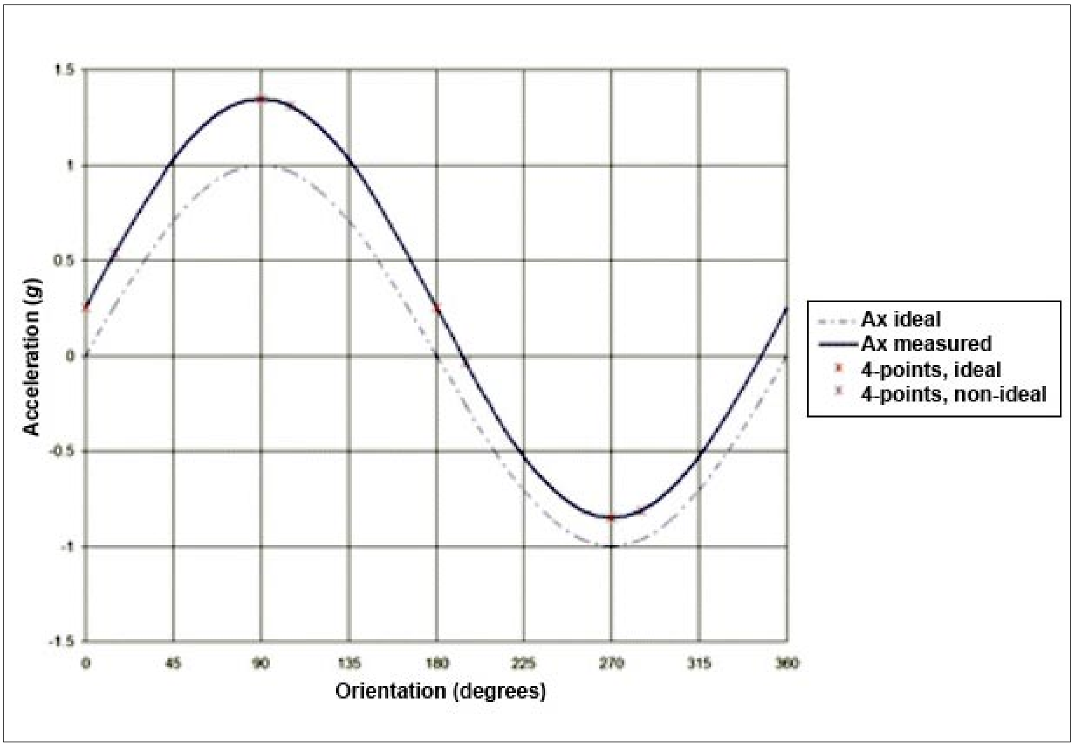

Figure 4: As the DUT is rotated, the X-axis sensor's output will be a sinusoidal function, with respect to the incline angle, as shown.

This requires the developer to understand early on how the accelerometer sensing system will affect the final system's performance goals. This early investment in time may seem inconvenient but it will lead to better performance and create opportunities for further innovation. This discussion highlights areas for consideration when the calibration must achieve a composite error of 1 percent.

Figure 2 shows a typical circuit for providing calibrated accelerometer performance. Error analysis determines the impact each component will have on the overall system-accuracy goals. Each component will have behaviors that must be considered. In addition to the MEMS accelerometer, the amplifiers, ADC, mux and passive components will exhibit their own offset, gain, noise, linearity, power supply and temperature dependent behaviors that need to be carefully considered and added to the sensor's performance.

Sources of error

This section identifies the common threats to these performance goals and shows how to quickly determine their impact, while avoiding a detailed circuit analysis. For simplicity, this sensitivity analysis focuses on a sensor's performance. The contribution of the remaining circuit elements will be assumed to be minimal for this discussion. The ideal equation for any linear sensor, including a MEMS accelerometer is $y = mx$ where m = ideal sensitivity.

IEEE-STD-1293-1998 offers a comprehensive modeling approach for describing the error behaviors in a typical MEMS accelerometer. The following equation offers a simple relationship to describe the impact of many common errors: $y = m_1 \cdot x + b_e + NL(x) + \phi_N(BW)$ where $m_1 = m \cdot (1+e)$; e = scale error, dependence on tolerance, temperature and power supply; be = offset error, dependence on tolerance, temperature and power supply; NL(x) = Linearity error, function of signal strength; ϕ_N (BW) = Noise, function of bandwidth.

The sensor signal conditioning circuit contains several components that can influence this equation. Some common error sources in these components include the MEMS accelerometer, amplifier, passive components and ADC.

Each component will contribute to the sensitivity (gain), bias (offset), linearity, noise, power supply-dependent behaviors and temperature-dependent behaviors. As the point of discussion here is calibration, the focus will be on the sensor. The principles illustrated can be applied to the rest of the circuit as well.

Sample analysis

Taking a composite error goal of 1 percent, we can quickly review the specifications of an available MEMS sensor. Take for example the accelerometer evaluated in the **Table**. Here, the calibration procedure must account, primarily, for bias and sensitivity, which both exceed the 1 percent composite error goal.

A reliable source of stimulus for low-*g* accelerometer calibration is gravity. The simplest means of using gravity is through the use of the industry standard tumble test. Tumble tests are used in applying an external stimulus varying between +1*g* to the DUT.

This low stimulus level restricts the use of the tumble test to accelerometers with full-scale ranges of less than 20*g*, based on the need for the calibration stimulus to equal 5 percent or more of the full-scale range.

Beyond this range, linearity, resolution, noise and other range-dependent behaviors will become more influential and impede the process of achieving the desired accuracy levels. Restricting the full-scale range allows the basic four-point tumble test to be used for calibration, rather than the multipoint tumble test, which allows for the calculation of linearity errors.

In a simplified diagram of the four-point tumble test shown in **Figure 3**, the DUT is vertical. The X-axis of the DUT is oriented along the horizontal axis for 0° inclination. The X-axis output of the DUT is recorded. Then, the DUT is rotated 90°, 180° and 270° with the X-axis outputs recorded at each of the four measurement positions.

As the DUT is rotated, the X-axis sensor's output will be a sinusoidal function, with respect to the incline angle (**Figure 4**). The difference between the actual and ideal curves is due to the accelerometer's offset and sensitivity errors. By taking data at each 90° increment, these behaviors can be characterized and isolated.

MEMS accelerometer sensitivity analysis parameter performance notes
Sensitivity +950mV/*g* to +1,050V/*g* equates to 5%
Offset 30m*g* (typical)
100m*g* (maximum) 3% for 1*g* system
10% for 1*g* system

Table: With composite error goal of 1 percent, an accelerometer can be evaluated as shown. Here, the calibration procedure must account for bias and sensitivity which both exceed the composite error goal.

The offset of the overall sinusoid can be calculated by averaging the 0° and 180° points. Subtracting the 270° data point from the 90° data point provides a measure of the accelerometer output for the 1*g* stimulus provided by gravity.

These relationships depend on perfect alignment at the 0°, 90°, 180° and 270° positions. They also depend on perfect vertical alignment for assurance of a full 1*g* stimulus. m_1 = ½ [AX(90°) – AX(270°)], be = ½ [AX(0°) + AX(180°)]. Correction factors: Scale: KS = m/m1, Offset: KO = –be

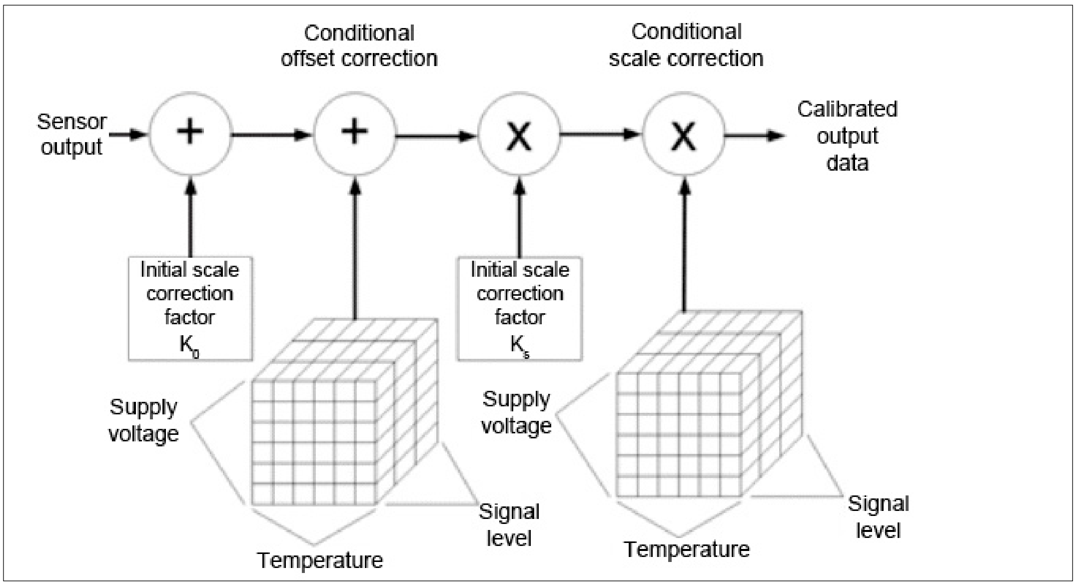

Figure 5: If conditions cause greater variation than the system performance goals will allow, the four-point tumble characterization must be performed over multiple conditions.

Measurement sensitivity

Since "perfection" is neither practical nor affordable, it is important to understand the sensitivity to each potential error that can be introduced by the calibration system itself. Determining the impact of each error influence will help mitigate risk against critical performance criteria.

Initial alignment angle—Absolute angle refers to the starting position. This error in start position will impact the sensitivity, but not the offset. The impact of this behavior can be isolated from other sensitivities and can be described by the following equation: ϕ = 1 – sin (90° + θE) <⇒> θE = 90 – a sin(1 – <eps>). For a sensitivity error of 1 percent, the initial alignment error must be less than 8°. If the sensitivity error is more aggressive, say 0.1 percent, the initial alignment error must be less than 0.8°. The absolute angle has an equal but opposite effect on the acceleration measurements at 0° and 180°, so this alignment error does not affect the offset. This is one advantage of using a four-point measurement approach. Once the actual offset is known, the initial alignment error can be calculated: θ_E = a sin (A_X (0°) – b_e)

If the sensitivity accuracy goals require this, the calculated alignment error can be plugged back into the error equations mentioned and used to scale the correction factors accordingly. This relationship relieves the pressure of having the initial starting point at exactly 0°.

The relative alignment error is defined as the deviation from the ideal 90° step size between each measurement step. The offset calibration will experience greater sensitivity to this error. The offset error introduced by the alignment error can be calculated using: Δb_e = sin(<theta$_R$).

For an offset accuracy goal of 1 percent, or 10m*g* for a 1*g*-range application, the alignment must be better than 0.57°. For an offset accuracy goal of 0.1 percent, or 1 m*g*, the relative alignment must be better than 0.057°. Although the initial alignment angle can be readily accounted for, the relative angle sensitivity requires strict positional control for high-accuracy calibration.

Off-axis tilt—Off-axis tilt error is the amount of change in the axis of rotation with respect to the horizon. If the rotational apparatus is perfectly vertical, then the axis of rotation is perfectly horizontal. Off-axis tilt will impact the sensitivity error in a manner that is similar to the initial alignment impact.

Gravitational acceleration variation—Caution is warranted here since the ideal 1*g* external stimulus may not exactly be 1*g*. It more accurately reflects twice the local gravity, which can vary from the ideal gravity based upon latitude, elevation above sea level, lunar-solar gravity fluctuations and large nearby masses.

Mechanical vibration—Vibration of any kind can translate into linear acceleration and introduce errors into the calibration process. Mechanical isolation, by using a granite block or air-isolated table structure, will help and digital filtering of the data can help remove some artifacts of vibration as well.

Accelerometer sensitivities—The two most common conditions that influence accelerometer behavior are power supply voltage and temperature. The four-point tumble can be used to characterize the accelerometer's behavior over anticipated supply and temperature ranges as well. The linear approximation approach requires that the four-point tumble data be taken at the extremes (minimum and maximum) for each parameter.

These data can be used to extrapolate incremental correction factors, based on accuracy requirements. If nonlinear behaviors are observed, more data points can be added while increasing the order of curve fitting.

Power supply—Some accuracy requirements will drive the need to characterize the influence of power supply variation. If these behaviors need calibration attention, the same four-point tumble test can be used at different supply levels to gather the data required for the appropriate curve-fitting operation.

The complexity of the curve fit depends on the accuracy goals and the nature of the errors themselves. The result will be a set of calibration coefficients for each power-supply condition.

Temperature—To maintain a 1 percent error due to thermal variation, the temperature coefficients for sensitivity and offset should be considered. In this case, we have Sensitivity = 0.3 percent (typical, 40°C to 125°C); Offset = 0.1mg/°C (typical).

For a quick estimate, these values can be doubled (2 assumption) and combined in the composite error for temperature:

$E_T = \sqrt{e_s^2 + eb^2}$. e_s = 0.006 (2x = Sensitivity contribution, eb = Offset contribution, $e_b = \sqrt{E_T^2 + E_b^2} = \sqrt{0.012 - 0.0062} = 0.008$ = 0.8%.

Composite error for temperatrure: If the maximum acceleration measurement level is 1*g*, then this ratio can be used to calculate how wide the temperature can vary, while maintaining the 1 percent composite thermal error goal:

ΔT = 1*g* x (0.008/(0.2m*g*/°C)) x)1000m*g*/*g*) = 40°C

Implementation

It is possible to apply correction factors calculated during this calibration process to many digital platforms. Examples include MCUs, DSPs, FGPAs and other programmable logic devices. The processing resources required for the correction formulas might influence processor selection, but in many industrial systems, processors have other requirements that may be more demanding. The math required for the correction is relatively simple: first, remove the offset/bias errors using an add operation and second, remove the scale errors using a multiply operation.

While in service, industrial systems experience changes in operating conditions that can influence the bias and sensitivity behavior in MEMS accelerometers. The most common conditions that influence these behaviors are power supply voltage and ambient temperature. Power supply voltages can change by up to 10 percent and each industrial system will have its own temperature range requirements.

If these conditions cause greater variation than the system performance goals will allow, then the four-point tumble characterization must be performed over multiple conditions to map the error behaviors and developer table of calibration coefficients. The final implementation of these coefficients will look like the diagram in **Figure 5**. Calibration tables in this case have three variables, including a set for an extra condition, which could be for frequency response or other conditions.

Conclusion

One of the most critical factors in deploying a calibrated accelerometer function is the establishment of valuable performance goals. Developers know that calibration is not free, but still opens great opportunity to add value, if the end goal is clearly established.

Developing performance goals expands thinking beyond "engineering capability" into the realm of schedule risk (lost revenue), performance risk (failed customer expectations) and cost overruns (lost market share). Even a basic understanding of performance impact, along with the required investment for achieving that performance through calibration, will equip engineers to make better integration decisions, as they ponder the everlasting question of make vs. purchase.