Improving the accuracy of inclination measurement with an accelerometer

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Tilt-measurement accuracy can easily be improved with a combined accelerometer and gyroscope. Frequently found in vehicles, single- or dual-axis accelerometers measure inclination of the electric park brakes (EPBs) that hold a vehicle stationary. For this, an x-/y- or z-axis low-g accelerometer is typically placed in a dedicated module of the EPB control unit.

Most modern vehicles also have ESC (electronic stability control), which prevents the vehicle from side slipping and rolling over. ECS typically combines a low-g accelerometer and gyroscope in a single chip, removing the need for a standalone EPB module, which avoids adding to the car's size, weight and cost. However, because a combo part is typically used for ESC, it's not necessarily optimised for tilt sensing, which makes it less accurate for this type measurement.

In a combo part, the x-axis is typically used for tilt measurement, whereas in EPB modules, traditional low-g accelerometers use the z-axis installed vertically in the engine compartment. The sensing axis should be placed perpendicular to gravity for better accuracy.

Evaluating accuracy

For tilt measurement of a vehicle, it's very important to evaluate the accuracy. Imagine a car parked on absolutely flat ground; the angle calculated by the accelerometer should be 0°. But if parked on a ramp, the inclination should be accurately detected so the braking system is appropriately actuated.

$$A_{OUT} = 1\,g \times \sin\theta$$

So,

$$\theta = \sin^{-1}(A_{OUT}/g)$$

where A_{OUT} is the output of the accelerometer in g, and θ is the inclination of the ramp in degrees.

Because sin θ is a nonlinear function, the relationship between A_{OUT} and θ is nonlinear and has best linearity near zero, which means it has the best measuring accuracy. As θ increases, the measuring accuracy degrades. That's why the sensing axis should be perpendicular to gravity, so the road slope grade is close to zero.

For tilt measurement of a vehicle, it's not necessary to consider the system with full ramp slope. In the real world, the vast majority of

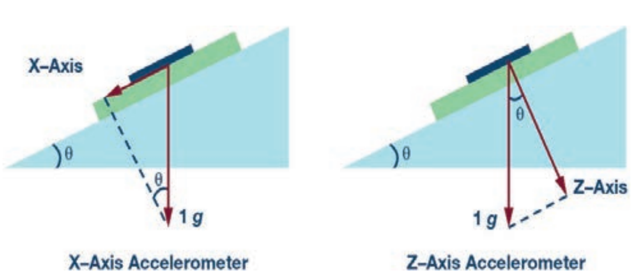

Figure 1: Installation of X-axis and Z-axis accelerometer

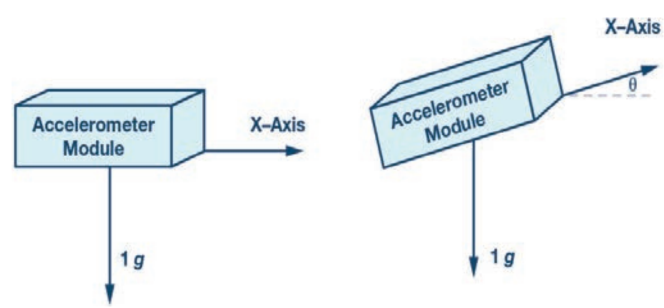

Figure 2: X-axis sensing tilt measurement

road slopes do not exceed 30°, so, for our design purposes, we only need to analyse the accuracy of contributions within the ±30° range.

Several contributions affect system-level measurement accuracy:

- Sensitivity error and initial absolute offset;
- Nonlinearity;
- Total offset variation from initial absolute offset;
- Noise.

Sensitivity error

Sensitivity is the slope of the transfer function measured of inputs-outputs, usually at +1g and -1g. Sensitivity error is the part-to-part sensitivity deviation; for example, some accelerometers' maximum sensitivity is 3%.

Initial absolute offset

The offset within the range is around 25°C; for example, 25°C ± 5°C, measured immediately after the module is made. The initial absolute offset denotes the standard deviation of the measured offset values across a large number of devices.

Two-point calibration

For tilt-measuring applications, the two main errors come from offset and sensitivity errors. To remove them, the output of acceleration should be calibrated, typically a one-time task for offset and sensitivity-of-tilt measurement. If the offset and sensitivity errors are considered, the relationship of accelerometer input vs output is:

$$A_{OUTPUT} = A_{OFFSET} + Gain \times A_{ACTUAL}$$

where A_{OUTPUT} is the offset error in g, gain is that of the accelerometer (ideal value of 1), and A_{ACTUAL} is the real acceleration applied on the accelerometer in g.

There are two basic calibration techniques, one of which is single-point. This calibration is done by applying 0g field on the accelerometer and then measuring the output. This type of calibration could just be used for calibrating offset error and gain error could not be calibrated. Then, the resulting output in the 0g field is subtracted from the real output value to remove the offset error.

This is an easy method for calibration but not for accuracy, because there's still sensitivity error.

Another way is 1g flip calibration, which uses two-point calibration at +1g and -1g. In each field of +1g and -1g the acceleration output is measured as follows:

$$A_{+1\,g} = A_{OFFSET} + Gain \times A_{ACTUAL}$$
$$A_{-1\,g} = A_{OFFSET} - Gain \times A_{ACTUAL}$$

where the offset A_{OFFSET} is in g.

From this two-point information, offset and gain can be resolved as follows:

$$A_{OFFSET} = 0.5 \times (A_{+1\,g} + A_{-1\,g})$$
$$Gain = 0.5 \times \frac{A_{+1\,g} - A_{-1\,g}}{2}$$

where the +1g and -1g measurements A+1g and A–1g are in g.

After this one-time calibration, the actual acceleration could be calculated by following this equation, each time removing the offset and sensitivity error:

$$A_{ACTUAL} = \frac{A_{OUT} - A_{OFFSET}}{Gain}$$

where A_{OFFSET} and A_{OUT} are in g.

Nonlinearity

The nonlinearity of a device is the maximum deviation of measured acceleration (A_{MEA}) and ideal linear output acceleration (A_{FIT}).

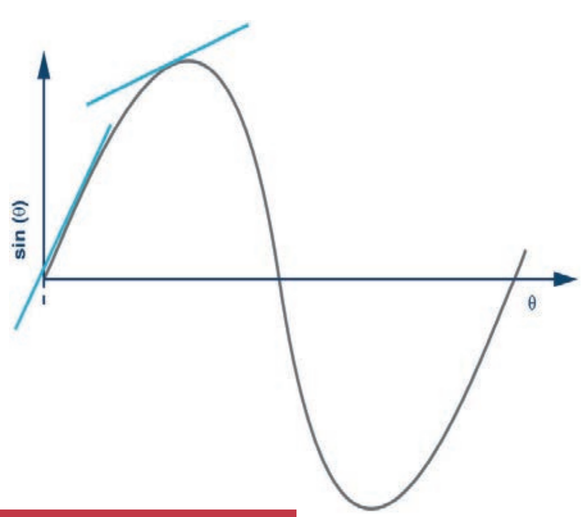

Figure 3: Sensitivity of sin θ to θ degrades as θ increases

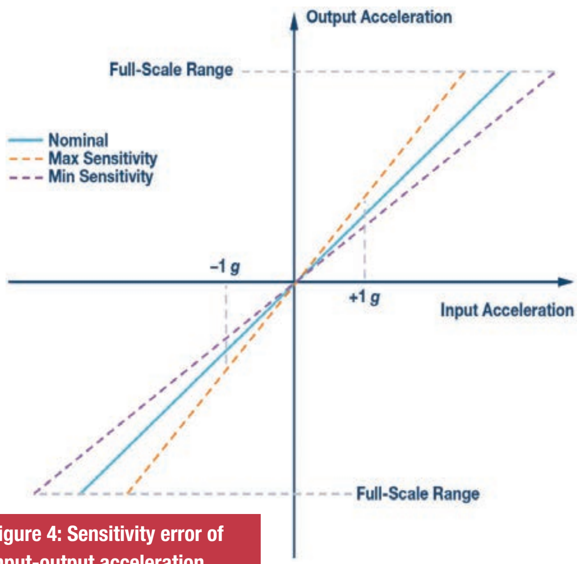

Figure 4: Sensitivity error of input-output acceleration

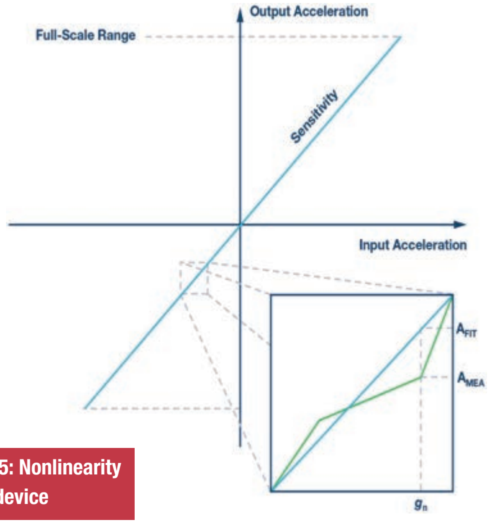

Figure 5: Nonlinearity of the device

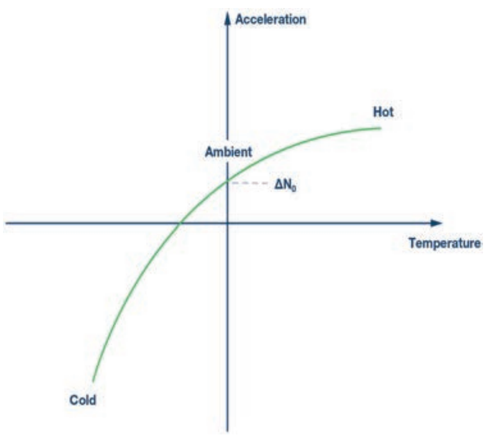

Figure 6: Step 1: Cancel out the offset at ambient

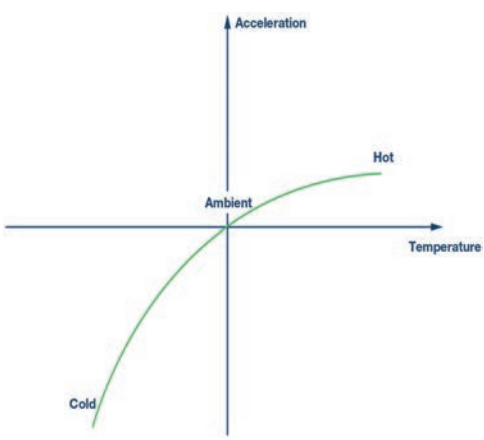

Figure 7: Step 2: Following cancellation of offset at ambient

The dataset of acceleration measurement should include the accelerometer's full-scale range, measured as Max($|A_{MEA} - A_{FIT}|$), where A_{MEA} is measured acceleration at a defined gn, and A_{FIT} is predicted acceleration at a defined g_n.

Most accelerometer or combo parts are nonlinear over a given input accelerometer range; for example, a range of 30mg ± 2g. For tilt measurement applications, the input ramp slope is within ±30°, which means the output acceleration range is within ±500mg (±1g × sin 30°); hence, nonlinearity within this range should be reassessed. Because the nonlinearity exists across the whole input range, it's difficult to accurately and quantitatively evaluate this error. However, because the data sheet for this part is usually very conservative for a nonlinearity of 30mg with an input range of ±2g, it would be more reasonable to use 10mg for error calculation within ±500mg.

Total offset variation from initial absolute offset

Total offset variation from initial absolute offset is the maximum offset deviation created by temperature, stress and ageing effects; it is measured relative to the initial absolute offset for a given device, and is the main contribution to the total error of accuracy.

Among all these factors like temperature, stress, ageing, etc., variation vs temperature accounts for the largest percentage of total offset variation. Typically, variation-vs-temperature is a second-order curve, a rotated parabola. To eliminate this type of error, perform a three-point calibration at system level. For a given device, the output variation-drift vs temperature could be calibrated per the following steps:

Step 1:

The output response of the device is shifted by a value ΔN_0. The first step in the temperature calibration process is to cancel out the offset at ambient.

Step 2:

Next, the device is tested at hot, and this new information is used to generate a linear equation for offset correction.

Step 3:

A second-order component is added to the existing equation to correct for the remainder of the offset, assuming the second-order curve follows this equation:

$$A_{TEMP} = at^2 + bt + c$$

This is a second-order parabolic formula, with the rotation component been cancelled through steps 1 and 2. This second-order parabola renders three solutions of the following equation:

$$(Temp_{COLD}, \Delta N_2), (Temp_{AMB}, 0), (Temp_{HOT}, 0)$$

Then, we can determine the tempco parameters a, b, c.

All tempco information ΔN_0, ΔN_1, ΔN_2, a, b, c should be stored in the system's nonvolatile memory, and an on-board temperature sensor is needed. The system should calibrate the accelerometer routinely after each power-up to ensure the cancellation of the variant-drift vs temperature.

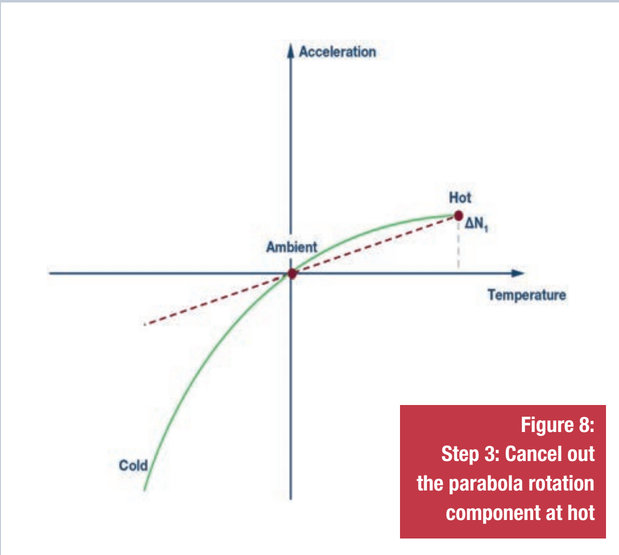

Figure 8: Step 3: Cancel out the parabola rotation component at hot

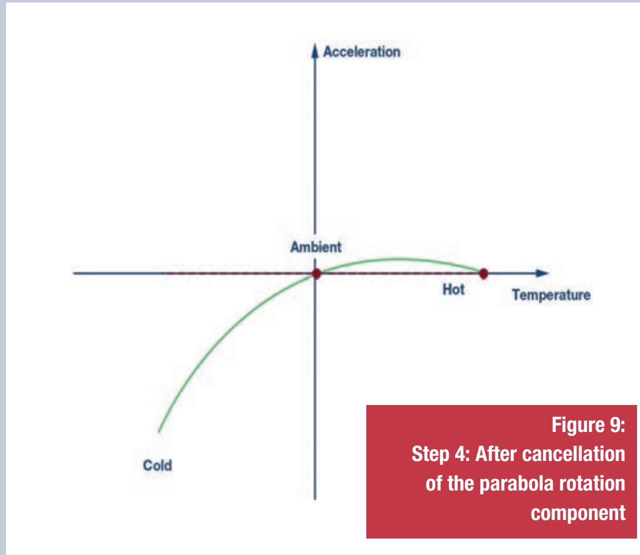

Figure 9: Step 4: After cancellation of the parabola rotation component

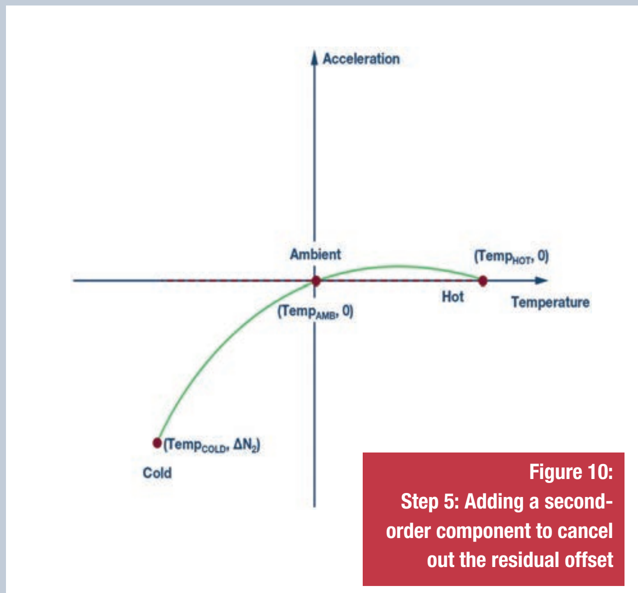

Figure 10: Step 5: Adding a second-order component to cancel out the residual offset

Noise

To perform tilt measurement based on a single sample of data may not be reliable. Even if the accelerometer had zero noise, tilt measurements are made whilst the car is on, so any or all vibrations caused by the engine, passing traffic or passengers moving inside the car must be mitigated. The best way to do this is to average the data for as long as possible without falling below the minimum data-rate requirements, reducing the rms noise.

Assuming we sample the noise, we get a per-sample variance of

$$\mathrm{Var}(z) = E[z^2] = \sigma^2$$

Averaging a random variable leads to the following variance:

$$\mathrm{Var}\left(\frac{1}{n}\sum_{i=1}^{n} z_i\right) = \frac{1}{n^2}\mathrm{Var}\left(\sum_{i=1}^{n} z_i\right) = \frac{1}{n^2}\sum_{i=1}^{n}\mathrm{Var}(z_i)$$

Since noise variance is constant at σ2,

$$N_{AVG} = \mathrm{Var}\left(\frac{1}{n}\sum_{i=1}^{n} z_i\right) = \frac{1}{n^2} n\,\sigma^2 = \frac{1}{n}\sigma^2$$

demonstrating that averaging n realisations of the same uncorrelated noise reduces noise power by a factor of n, and reduces rms noise by √n.

Because random noise is subject to Gaussian distribution, rms noise is equivalent to the standard deviation of Gaussian distribution. The minimum population within 6σ is 97%. For example, if averaging every 100ms of data at 1ksps, then max rms noise = 0.4mg, meaning that the calculation for peak noise at that point is only 2.4mg if we use 6σ as the distance from the mean.

The factors to multiply the rms value by depend on the statistical needs of the mission profile for the part. For example, if choosing six as a factor (peak-to-peak noise is 6 × RMS_Noise), the number of times the algorithm is run over the part's lifetime will impact the probability, exceeding the worst-case scenario of 6 × RMS_Noise. It can be summarised as:

$$E = M \times r$$

where E is the expected times exceeding worst-case over lifetime, M is the lifetime running times, and r is probability of exceeding the worst case. Based on this, we can evaluate a reasonable factor by multiplying the rms noise.

ADXC1500/ADXC1501

Taking ADI's ADXC1500/ADXC1501 (combined gyroscope and 2-axis/3-axis accelerometer) as an example, all the error contribution items are listed in Table 1 with or without >

Error Contribution	Before Calibration	After Calibration	Calibration Measures
Sensitivity error	30mg	0mg	Two-point calibration
Initial absolute offset	15mg	0mg	Two-point calibration
Nonlinearity	10mg over ±500mg	10mg over ±500mg	None
Total offset variation	50mg	10mg	Three-point calibration
Noise	24mg	2.4mg	100× averaging
Total error	129mg	22.4mg	
Accuracy	7.4° (worst case)	1.28° (worst case)	In degrees

Table 1: Error contributions with/without calibration

calibration measures. We can assume that total offset variation is the second curve and variation over temperature accounts for 80% of its total offset variation. Also, use six as the factor multiplied by the maximum rms noise.

This combination of a gyroscope and a tri-axis accelerometer enables many new applications, especially in automotive safety systems and industrial automation applications.

Minimising these large error sources is mission-critical to designing more reliable and accurate automotive safety systems, such as robust electronic stability control and rollover detection. These build on traditional chassis control systems already in the vehicle, including anti-lock braking, traction control and yaw control. EW

Products

Crystal Display Systems and Taicenn partner over product support

Displays, touchscreen and embedded specialist Crystal Display Systems (CDS) has partnered with embedded specialist Taicenn to promote and support its products in the UK and Europe. The support covers industrial and rugged embedded boxed PCs as well as industrial touch-panel PCs, and other industrial products such as rugged IP65 stainless steel keyboards, all designed specifically for systems and applications that require excellent performance, high-level reliability and stability, long supply period and technical support.

CDS's executives say that Taicenn is the best-kept secret in the embedded world for highest quality and reliability as well as new and innovative products with major blue-chip OEMs.

The CDS Taicenn range of panel PC displays incorporates the TBOX PCs with an industrial and reliable monitor into the smallest packages.

www.crystal-display.com

New automotive-grade current sensor ICs improves safety and efficiency

Allegro MicroSystems has announced a new family of automotive AEC-Q100-qualified, monolithic Hall-effect current sensor ICs. Small and energy-efficient, the ACS71240 family is ideal for electric vehicle chargers, DC/DC converters, as well as industrial motor and IoT applications.

The new devices offer next generation improvements over the popular Allegro ACS711 predecessor, including output signal immunity to stray magnetic fields (created by adjacent motors or current carrying wires); improved output signal accuracy (<±1.5% typical); and output signal immunity to noisy supply voltage rails.

The ACS71240 family also features an extremely fast, dedicated over-current fault output that has a typical response time of 1.5μs, improving system safety. This fault output provides a simple means of detecting short-circuit events that will prevent damage to MOSFETs or IGBTs in inverter, motor and other switching power electronics applications.

www.allegromicro.com

LATTICE SEMICONDUCTOR

Lattice sensAI delivers 10X performance boost for low-power IoT devices

Lattice Semiconductor announces major performance and design flow enhancements for its award-winning sensAI solutions stack. The Lattice sensAI stack provides a comprehensive hardware and software solution for implementing low power (1mW-1W), always-on artificial intelligence (AI) functionality in smart devices operating at the Edge.

IHS forecasts 40 billion devices will be operating at the network Edge by 2025. For reasons including latency, network bandwidth limitations and data privacy, OEMs designing always-on Edge devices want to minimise sending data to the Cloud for analytics. Lattice sensAI enables such OEMs to seamlessly update their existing designs with low-power AI inferencing optimised for their application requirements. Incorporating such local intelligence also lowers expenses related to Cloud-based analytics by only sending relevant data for further processing.

Enhancements include 10x performance boost over previous version, seamless user experience, expanding neural network and ML frameworks support, and more.

www.latticesemi.com

Pickering Interfaces wins Queen's Award for outstanding short-term growth

Pickering Interfaces has won the Queen's Award for Outstanding Short-Term Growth in overseas sales over the last three years.

"Pickering Interfaces exports 95% of its production overseas – 40% to North America, 35% to Europe and 20% to Asia. We received the Queens Award this year due to our 25% average growth during each of the three previous years," said Keith Moore (pictured), Pickering Interfaces's CEO.

Pickering Interfaces Ltd was founded in 1988 as part of the Pickering Group, which also celebrated its 50th anniversary in 2018.

Based in Clacton-on-Sea, Essex, the company designs and manufactures modular signal switching and instrumentation for use in electronic testing and simulation for a wide range of industries including automotive, aerospace and defence, energy, industrial, communications, medical and semiconductor. The company offers fast turnaround on a very large range of both catalogue and customised solutions.

www.pickeringtest.com