Rarely Asked Questions—Issue 144 Accelerometer Tilt Measure over Temperature and in the Presence of Vibration

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Question:

My consumer grade accelerometer can theoretically measure <1°of tilt. Will this still be possible over temperature and in the presence of vibration?

Answer:

Most likely, the answer is no. Questions around definitive tilt accuracy values are always difficult to answer, as many environmental factors need to be accounted for when it comes to MEMS sensor performance. Typically, consumer grade accelerometers struggle to detect less than 1° of tilt in dynamic environments. To show this, a general-purpose, consumer grade accelerometer is compared with a next-generation, low noise, low drift, and low power MEMS accelerometer. The comparison looks at a number of error sources present in tilt applications and what errors can be compensated or removed.

Errors such as zero-*g* bias accuracy, zero-*g* bias shift due to soldering, zero-*g* bias shift due to PCB enclosure alignment, zero-*g* bias tempco, sensitivity accuracy and tempco, nonlinearity, and cross-axis sensitivity are observable and can be reduced through the postassembly calibration processes. Other error terms such as hysteresis, zero-*g* bias shift over life, sensitivity shift over life, zero-*g* shift due to humidity, and PCB bend and twist due to temperature variations over time can't be addressed in calibration or else they require some level of in-situ servicing to be reduced. For this comparison it is assumed that cross-axis sensitivity, nonlinearity, and sensitivity are compensated, as they require much less effort to minimize compared to tempco offset drift and vibration rectification.

Table 1 shows an estimate of the consumer grade ADXL345 accelerometer's ideal performance specifications and the corresponding tilt errors. When trying to achieve the best possible tilt accuracy, it is imperative to apply some form of temperature stabilization or compensation. For this example, a constant temperature of 25°C is assumed. The largest error contributors that can't be fully compensated out are offset over temperature, bias drift, and noise. Bandwidth can be lowered to reduce the noise as inclination applications typically require bandwidths below 1 kHz.

Table 1. ADXL345 Error Source Estimates

Sensor Parameter	Exemplary Performance	Condition/Note	Typical g	Application Error Tilt °
Noise	X/Y axis 290 $\mu g/\sqrt{Hz}$	Bandwidth at 6.25 Hz	0.9 mg	0.05°
Bias drift	Allan deviation	Short-term (for example, 10 days)	1 mg	0.057°
Initial offset	35 mg	No compensation	35 mg	2°
		With compensation	0 mg	0°
Error	No compensation	6.25 Hz bandwidth	36.9 mg	2.1°
Error	With compensation	6.25 Hz bandwidth	1.9 mg	0.1°

Table 2 shows the same criteria for the ADXL355. Short-term bias values were estimated from the root Allan variance plots in the ADXL355 data sheet. At 25°C, the compensated tilt accuracy is 0.1° for the general-purpose ADXL345 and for the industrial grade ADXL355 the tilt accuracy is 0.005°. Comparing the ADXL345 and ADXL355, it can be seen that larger error contributors like noise have been reduced significantly from 0.05° to 0.0045° and that bias drift has been reduced from 0.057° to 0.00057°. This shows the massive leap forward in MEMS capacitive accelerometer performance in terms of noise, temperature coefficient, offset, and bias drift, enabling much higher levels of inclination accuracy under dynamic conditions.

Table 2. ADXL355 Error Source Estimates

Sensor Parameter	Exemplary Performance	Condition/Note	Typical *g*	Application Error Tilt °
Noise	25 µ*g*/√Hz	Bandwidth at 6.25 Hz	78 µ*g*	0.0045°
Bias drift	Allan deviation	X/Y axis short-term (for example, 10 days)	<10 µ*g*	0.00057°
Initial offset	25 m*g*	No compensation	25 m*g*	1.43°
		With compensation	0 m*g*	0°
Total error	No compensation	6.25 Hz bandwidth	25 m*g*	1.43°
Total error	With compensation	6.25 Hz bandwidth	88 µ*g*	0.005°

The importance of selecting a higher grade accelerometer is crucial in achieving required performance, especially if your application demands <1° tilt accuracy. Application accuracy can vary depending on application conditions (large temperature fluctuations, vibration) and sensor selection (consumer grade vs. industrial or tactical grade). In this case, the ADXL345 will require extensive compensation and calibration effort to achieve <1° tilt accuracy, adding to the overall system effort and cost. Depending on the magnitude of vibrations in the end environment and temperature range, this may not even be possible. Over 25°C to 85°C, the tempco offset drift is 1.375°—already exceeding the requirement for less than 1° of tilt accuracy.

$$0.4\frac{\text{mg}}{C} \times \frac{1^{\circ}}{17.45\ \text{mg}} \times (85^{\circ}\text{C} - 25^{\circ}\text{C}) = 1.375^{\circ}$$

For the ADXL355 the tempco offset drift from 25°C to 85°C is

$$0.15\frac{\text{mg}}{C} \times \frac{1^{\circ}}{17.45\ \text{mg}} \times (85^{\circ}\text{C} - 25^{\circ}\text{C}) = 0.5^{\circ}$$

Vibration rectification error (VRE), as shown in Table 3, is the offset error introduced when accelerometers are exposed to broadband vibration. When an accelerometer is exposed to vibrations, VRE contributes significant error in tilt measurements when compared to 0 *g* offset over temperature and noise contributions. This is one of the key reasons it is left off data sheets, as it can very easily overshadow other key specifications.

Table 3. Errors Shown in Degrees of Tilt

	Maximum Tilt Error 0 *g* Offset vs. Temperature(°/°C)	Noise Density (°/√HZ)	Vibration Rectification (°/g^2r ms)
ADXL354	0.0085	0.0011	0.023[1]
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[1] *±2 g range in a 1 g orientation offset due to 2.5 g rms vibration.*

In environments with higher magnitude vibrations, it is essential to have a higher *g* range accelerometer in order to minimize clipping leading to offsets. Table 4 shows the ADXL35x family of accelerometers and their corresponding *g* range and bandwidths.

Table 4. ADXL354/ADXL355/ADXL356/ADXL357 Measurement Ranges

Part	Measurement Range (*g*)	Bandwidth (kHz)
ADXL354B	±2, ±4	1
ADXL354C	±2, ±8	1
ADXL355B	±2, ±4, ±8	1.5
ADXL356B	±10, ±20	1.5
ADXL356C	±10, ±40	1.5
ADXL357B	±10.24, ±20.48, ±40.96	1

Choosing a part from the ADXL35x family for tilt applications will provide high stability and repeatability, and this family is robust to temperature fluctuation and broadband vibration, as well as requires less compensation and calibration compared to a lower cost accelerometer. The hermetic package helps ensure that the end product conforms to its repeatability and stability specifications long after it leaves the factory. By providing repeatable tilt measurement under all conditions, Analog Devices' next-generation accelerometers enable minimal tilt error without extensive calibration in harsh environments, as well as minimizing the need for post-deployment calibration.

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