AN4508
Application note

Parameters and calibration of a low-g 3-axis accelerometer

Introduction

This application note describes the parameters and calibration of a low-g 3-axis accelerometer. In general, the procedures described here may also be applied to 3-axis analog or digital accelerometers, depending on their respective specifications.

Section 1 of this application note introduces the terminology and parameters related to the accelerometer, while *Section 2* presents the accelerometer calibration techniques.

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1 Terminology

1.1 Accelerometer datasheet

The first step is to examine the accelerometer specifications and understand the meaning of each parameter.

Understanding the parameters

- Vdd - Power supply: This parameter defines the accelerometer operating DC power supply. Correct operation of the accelerometer using a power supply voltage outside of this range is not guaranteed. The parameters are provided by the accelerometer manufacturer under Vdd = +2.5 V at a room temperature of T = 25 °C. It is recommended to keep Vdd clean, with minimum ripple. One possible way to do this is to use an ultra-low-noise low-dropout regulator to power the accelerometer.
- Idd - Current consumption in normal mode: lower ODR corresponds to lower current consumption.
- ODR - Output data rate in normal mode: This parameter shows the possible output data rates in normal mode from which the user may select.
- BW - System bandwidth: This parameter defines the bandwidth of the system. When ODR = 100 Hz, BW is typically 50 Hz with a built-in low pass filter. The system recognizes any motion below 50 Hz. If the system has dynamic motion higher than 50 Hz, then the ODR needs to be increased to a higher setting in order to cover all useful system signals.
- Ton - Turn-on time: This parameter defines the time required before the accelerometer is ready to output measured acceleration data after exiting power-down mode.
- Top - operating temperature range: This parameter defines the operating temperature range. When the device is operated inside the specified range, proper behavior of the sensor is guaranteed.
- FS - Full-scale measurement range: For tilt sensing applications, a ±2.0 *g* range is sufficient because the Earth's gravity is ±1 *g* only. If the application requires measurement of higher *g* acceleration, the user can set the device to a higher full-scale range which results in lower sensitivity.
- So - Sensitivity: This parameter defines the value of 1 LSB with respect to m*g* in the digital representation.
- TCSo - Sensitivity change vs. temperature: This parameter defines how sensitivity changes with temperature. For example, at a ±2.0 *g* full-scale range, the sensitivity changes within ±0.01%/°C. Therefore, if the environmental temperature changes 40 °C, from 25 °C to 65 °C, then the sensitivity changes within the range of ±0.01% * 40 = ±0.4%, which means the sensitivity change over 40 °C is within 0.996 m*g*/LSB and 1.004 m*g*/LSB, which shows that the sensitivity is very stable versus temperature change. Thus, temperature compensation for sensitivity can be ignored.
- TyOff - Typical zero-*g* level offset accuracy: This parameter defines the zero-*g* accuracy at room temperature of 25 °C. For example, at a ±2.0 *g* full-scale range, the

zero-*g* accuracy of ±20 m*g* means that the zero-*g* output varies typically in the range of ±20 m*g* around the expected ideal value.

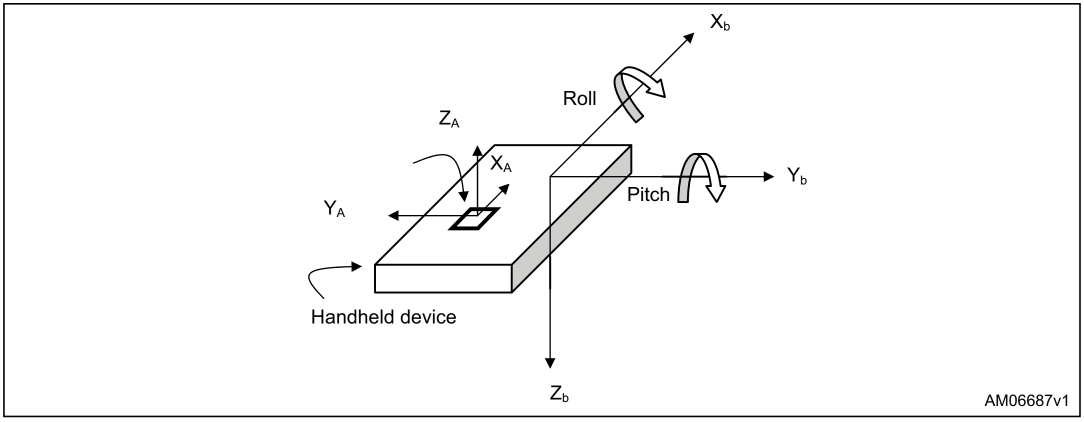
- TCOff - Zero-*g* level change vs. temperature: This parameter defines how much the zero-*g* level is affected by temperature variations.
- An - Acceleration noise density: This parameter defines the standard resolution the user can obtain from the accelerometer (once the desired BW is selected).

  1 σ resolution = $A_n(\mu g/\sqrt{Hz}) \cdot \sqrt{BW(Hz)}$. The higher BW leads to lower resolution.
- NL - Non linearity: This parameter defines the maximum error between the outputs and the best-fit straight line. For example, at ±2.0 *g* full-scale range, the non-linearity of 0.5% of FS means the largest error is 0.5% * 4000 m*g* = 2 m*g*, which corresponds to 0.1°. When the application requires measurements around the 0 *g* condition (as with tilt measurement), the non-linearity effect is negligible and can be ignored.
- CrossAx - Cross-axis sensitivity: The cross-axis effect arises due to natural misalignment of die positioning on the package substrate. Even if negligible in most applications, for very accurate tilt measurement the cross-axis sensitivity effect can be easily compensated for by following the procedure in *Section 2: Calibrating the accelerometer*. Moreover, when the device is placed on the final application board, the accelerometer calibration compensates both the device cross-axis sensitivity, and the misalignment between the accelerometer sensing axes and the board axes.

1.2 Definitions

Assume that the accelerometer is installed in a handheld device, such as a cell phone, a PDA or simply on a PCB board as shown in *Figure 1*.

Figure 1. Accelerometer inside a handheld device



X_b, Y_b and Z_b are the handheld device body axes with a forward-right-down configuration.

X_A, Y_A and Z_A are the accelerometer sensing axes, respectively. Note that the sign of Y_A and Z_A from the sensor measurements need to be reversed to have the sensing axes in the same direction as the device body axes.

Pitch and roll angles are referenced to the local horizontal plane, which is perpendicular to the Earth's gravity.

- Pitch (α) is defined as the angle between the X_b axis and the horizontal plane. Assume that the pitch angle resolution is 0.1°, then it goes from 0° to +179.9° when rotating around the Y_b axis with the X_b axis moving upwards from a flat level, and then keeps moving from a vertical position (+90°) back to a flat level again. The pitch angle goes from 0° to -180° when the X_b axis is moving downwards from a flat level, and then keeps moving from a vertical position (-90°) back to a flat level again. For example, in *Figure 2*, Y_b is fixed, X_b is rotating from Pitch = 0° to +30°, +90°, +150° and +179.9° for a positive direction.

- Roll (β) is defined as the angle between the Y_b axis and the horizontal plane. Assume that the roll angle resolution is 0.1°, then it goes from 0° to +179.9° when rotating around the X_b axis with the Y_b axis moving downwards from a flat level, and then keeps moving from a vertical position (+90°) back to a flat level again. The roll angle goes from 0° to -180° when the Y_b axis is moving upwards from a flat level, and then keeps moving from a vertical position (-90°) back to a flat level again. For example, in *Figure 3*, X_b is fixed, Y_b is rotating from roll = 0° to +30°, +90°, +150° and +179.9° for a positive direction.

Figure 2. Pitch definition

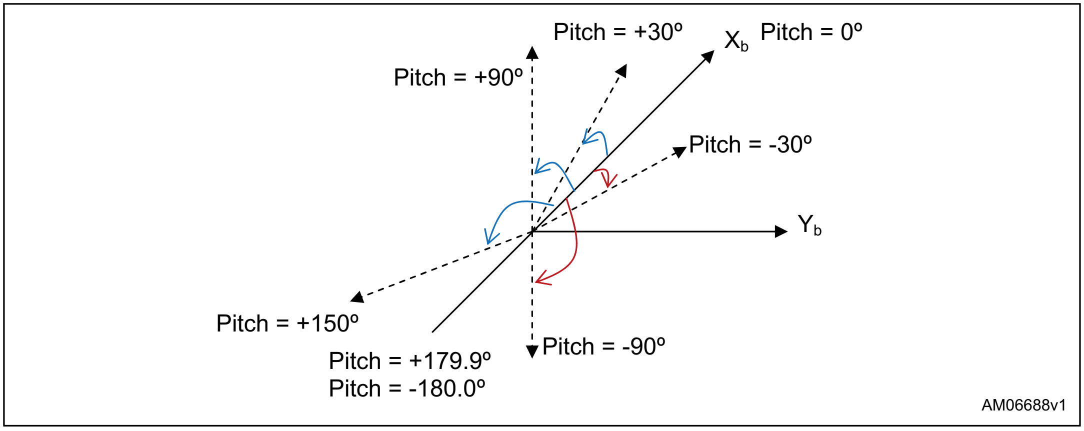
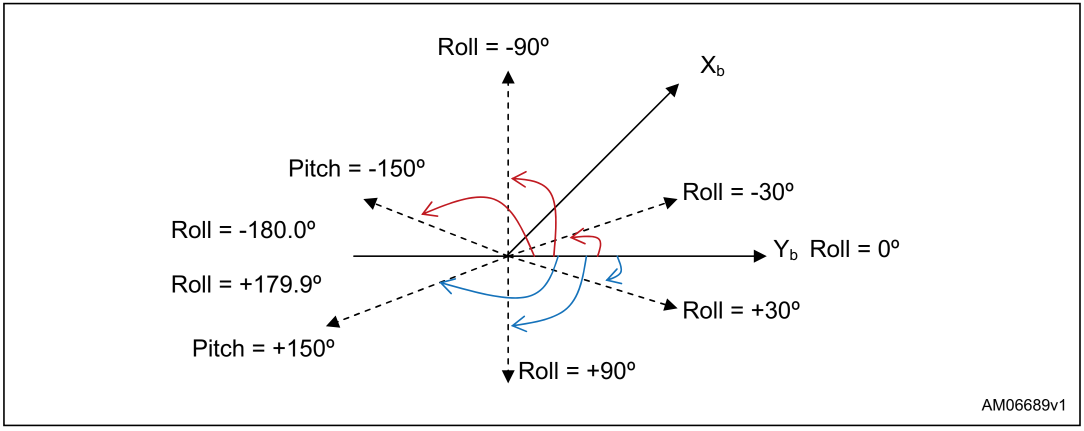


Figure 3. Roll definition



Assume A_x, A_y, A_z is the accelerometer raw measurement in the format of LSBs. *Table 1* shows the sign definition of the raw sensor data at 6 stationary positions with respect to the known Earth gravity vector. For example, in *Figure 1*, X_b and Y_b are level and Z_b is pointing down. Therefore, $A_x = A_y = 0$, $A_z = +1$ *g*.

Table 1. Sign definition of sensor raw measurements

Stationary position	Accelerometer (signed integer)		
	A_x	A_y	A_z
Z_b down	0	0	+1 *g*
Z_b up	0	0	-1 *g*
Y_b down	0	+1 *g*	0
Y_b up	0	-1 *g*	0
X_b down	+1 *g*	0	0
X_b up	-1 *g*	0	0

2 Calibrating the accelerometer

Section 1 describes the accelerometer parameters, the next step is to calibrate the accelerometer.

Please note that all accelerometers from ST have been factory-calibrated. For most applications, such as screen portrait/landscape rotation and laptop lid open/close detection, accelerometer calibration is not necessary. This means that users can use the zero-*g* level and sensitivity parameters from the datasheet directly to convert raw measurements A_x, A_y and A_z to normalized measurements A_{x1}, A_{y1} and A_{z1}. For applications that require better than 1° tilt-measurement accuracy, such as automobile alert systems, tilt-compensated electronic compasses and level monitoring systems, accelerometer calibration is recommended.

The relationship between the normalized A_{x1}, A_{y1} and A_{z1} and the accelerometer raw measurements A_x, A_y and A_z can be expressed as,

Equation 1

$$\begin{bmatrix}A_{x1}\\ A_{y1}\\ A_{z1}\end{bmatrix} = [A\_m]_{3x3}\begin{bmatrix}1/A\_SC_x & 0 & 0\\ 0 & 1/A\_SC_y & 0\\ 0 & 0 & 1/A\_SC_z\end{bmatrix}\cdot\begin{bmatrix}A_x - A\_OS_x\\ A_y - A\_OS_y\\ A_z - A\_OS_z\end{bmatrix}$$

$$= \begin{bmatrix}ACC_{11} & ACC_{12} & ACC_{13}\\ ACC_{21} & ACC_{22} & ACC_{23}\\ ACC_{31} & ACC_{32} & ACC_{33}\end{bmatrix}\cdot\begin{bmatrix}A_x\\ A_y\\ A_z\end{bmatrix} + \begin{bmatrix}ACC_{10}\\ ACC_{20}\\ ACC_{30}\end{bmatrix}$$

where [A_m] is the 3 x 3 misalignment matrix between the accelerometer sensing axes and the device body axes, A_SC_i (i = x, y, z) is the sensitivity (or scale factor) and A_OS_i is the zero-*g* level (or offset).

The goal of accelerometer calibration is to determine 12 parameters from ACC_{10} to ACC_{33}, so that with any given raw measurements at arbitrary positions, the normalized values A_{x1}, A_{y1} and A_{z1} can be obtained, resulting in:

Equation 2

$$|A| = \sqrt{A_{x1}^2 + A_{y1}^2 + A_{z1}^2} = 1$$

Calibration can be performed at 6 stationary positions as shown in *Table 1*. Collect 5 to 10 seconds of accelerometer raw data with ODR = 100 Hz at each position with known A_{x1}, A_{y1} and A_{z1}. Then apply the least square method to obtain the 12 accelerometer calibration parameters. Refer to *Appendix A* for additional details.

Appendix A Least square method

Let's consider accelerometer calibration at the 6 stationary positions shown in *Table 1*. *Equation 1* can be rewritten as:

Equation 3

$$\begin{bmatrix} A_{x1} & A_{y1} & A_{z1} \end{bmatrix} = \begin{bmatrix} A_x & A_y & A_z & 1 \end{bmatrix} \cdot \begin{bmatrix} ACC_{11} & ACC_{21} & ACC_{31} \\ ACC_{12} & ACC_{22} & ACC_{32} \\ ACC_{13} & ACC_{23} & ACC_{33} \\ ACC_{10} & ACC_{20} & ACC_{30} \end{bmatrix}$$

Or

Equation 4

$$Y = w \cdot X$$

where:

- Matrix X is the 12 calibration parameters that need to be determined
- Matrix w is sensor raw data LSBs collected at 6 stationary positions
- Matrix Y is the known normalized Earth gravity vector

For example,

- At Z_b down position (P1 position), $\begin{bmatrix} A_{x1} & A_{y1} & A_{z1} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$, and assume that at Z_b down position, n1 sets of accelerometer raw data A_x, A_y and A_z have been collected. Then,

Equation 5

$$Y_1 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}_{n1x3}$$
$$w_1 = \begin{bmatrix} A_{xP1} & A_{yP1} & A_{zP1} & 1 \end{bmatrix}_{n1x4}$$

where:

Matrix Y_1 has the same row of [0 0 1].

Matrix w_1 contains raw data in the format of LSBs.

- At Z_b up position (P2 position), $\begin{bmatrix} A_{x1} & A_{y1} & A_{z1} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -1 \end{bmatrix}$, and assume that at Z_b up position, n2 sets of accelerometer raw data A_x, A_y and A_z have been collected. Then,

Equation 6

$$Y_2 = \begin{bmatrix} 0 & 0 & -1 \end{bmatrix}_{n2x3}$$
$$w_2 = \begin{bmatrix} A_{xP2} & A_{yP2} & A_{zP2} & 1 \end{bmatrix}_{n2x4}$$

- At Y_b down position (P3 position), $\begin{bmatrix} A_{x1} & A_{y1} & A_{z1} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}$, and assume that at Y_b down position, n3 sets of accelerometer raw data A_x, A_y and A_z have been collected. Then,

Equation 7

$$Y_3 = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}_{n3x3}$$
$$w_3 = \begin{bmatrix} A_{xP3} & A_{yP3} & A_{zP3} & 1 \end{bmatrix}_{n3x4}$$

- At Y_b up position (P4 position), $\begin{bmatrix} A_{x1} & A_{y1} & A_{z1} \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \end{bmatrix}$, and assume that at Y_b up position, n4 sets of accelerometer raw data A_x, A_y and A_z have been collected. Then,

Equation 8

$$Y_4 = \begin{bmatrix} 0 & -1 & 0 \end{bmatrix}_{n4 \times 3}$$
$$w_4 = \begin{bmatrix} A_{xP4} & A_{yP4} & A_{zP4} & 1 \end{bmatrix}_{n4 \times 4}$$

- At X_b down position (P5 position), $\begin{bmatrix} A_{x1} & A_{y1} & A_{z1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$, and assume that at Xb down position, n5 sets of accelerometer raw data A_x, A_y and A_z have been collected. Then,

Equation 9

$$Y_5 = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}_{n5 \times 3}$$
$$w_5 = \begin{bmatrix} A_{xP5} & A_{yP5} & A_{zP5} & 1 \end{bmatrix}_{n5 \times 4}$$

- At X_b up position (P6 position), $\begin{bmatrix} A_{x1} & A_{y1} & A_{z1} \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \end{bmatrix}$, and assume that at X_b up position, n6 sets of accelerometer raw data A_x, A_y and A_z have been collected. Then,

Equation 10

$$Y_6 = \begin{bmatrix} -1 & 0 & 0 \end{bmatrix}_{n6 \times 3}$$
$$w_6 = \begin{bmatrix} A_{xP6} & A_{yP6} & A_{zP6} & 1 \end{bmatrix}_{n6 \times 4}$$

Combine *Equation 5* to *10* and let n = n1 + n2 + n3 + n4 + n5 + n6, then *Equation 4* becomes:

Equation 11

$$Y_{n \times 3} = w_{n \times 4} \cdot X_{4 \times 3}$$

where:

Equation 12

$$Y = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \\ Y_5 \\ Y_6 \end{bmatrix}_{n \times 3}$$
$$w = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \\ w_6 \end{bmatrix}_{n \times 4}$$

Therefore, the calibration parameter matrix X can be determined by the least square method as:

Equation 13

$$X = \left[w^T \cdot w\right]^{-1} \cdot w^T \cdot Y$$

where:

Equation 14

$$w^T \quad \text{means matrix transpose}$$

$$\left[w^T \cdot w\right]^{-1} \quad \text{means matrix inverse}$$

Revision history

Table 2. Document revision history

Date	Revision	Changes
10-Jun-2014	1	Initial release.

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