AN5551

Application note

Precise and accurate tilt sensing in industrial applications

Introduction

This application note serves as a guide for the user in selecting the most appropriate ST sensor for angle measurement in static or dynamic environments.

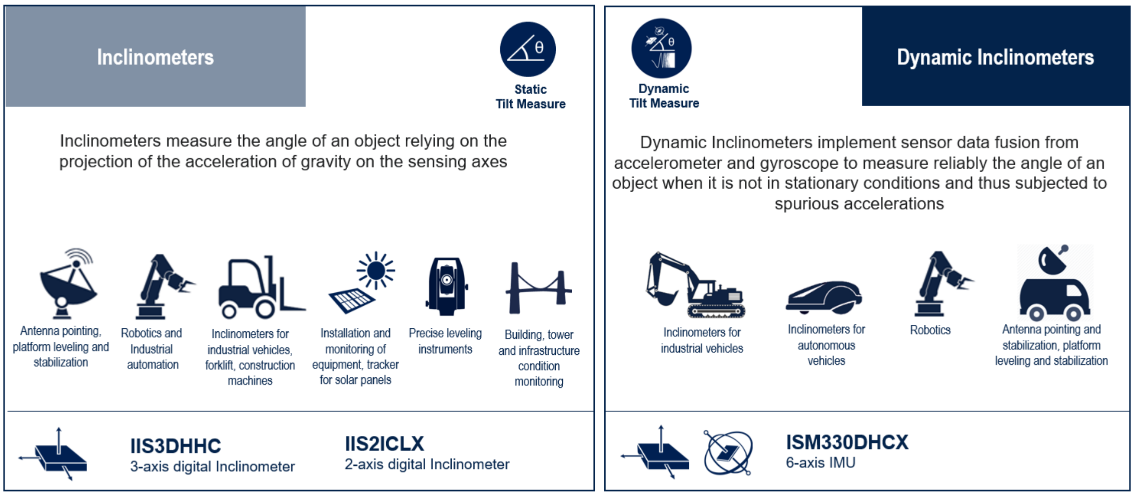
Inclinometers are used to measure tilt, slope, or inclination angle with respect to the Earth's gravity vector. Inclinometers are used in a wide variety of applications such as game controllers, land surveying, aircraft flight controllers, satellite antennas, platform leveling, solar panels, vehicles, cameras, mobile phones, and industrial and medical applications for platform leveling.

Typical technologies used in tilt estimation are liquid capacitive sensing, gas bubbles in liquid, electrolytes, MEMS accelerometers, or IMUs. MEMS inclinometers are popular because of their smaller size, low cost, and ease of integration. Recent advancements in MEMS technology further reduce noise, size, and power consumption.

Inclinometers are mainly divided into two categories based on algorithms used:

- **Static Inclinometers** are used primarily for static applications such as antennas or platform stabilization and monitoring, Structural Health Monitoring (SHM), Active Rollover Protection (ARP) in agricultural equipment, robotic position sensing and control, solar panel installations and tracker, chassis leveling for industrial machinery, and precise leveling instruments. In these applications, the average acceleration remains close to the Earth's gravity (g = 9.81 m/sec^2 or 32.2 feet/sec^2) or experience only short-term external acceleration, hence a static inclinometer is a suitable solution for inclination angle which provides reliable accuracy. External acceleration (any type of motion such as movement, vibration, and so forth) will introduce errors in tilt measurements from static inclinometers.
- **Dynamic inclinometers** are a solution for measuring the orientation of slope (tilt), elevation, or depression of an object with respect to the gravity vector while the object is not stationary and is subjected to rapid motions, vibration, or shock. Since inclinometers measure the angle of an object with respect to the gravity vector relying only on the projection of gravity acceleration, any external acceleration (any type of motion such as movement, vibration, and so forth) will introduce errors in tilt measurements. In order to overcome this issue, it is possible to use a gyroscope in addition to the accelerometer. Such a solution using an IMU and combining measurements from both sensors using advanced algorithms such as Kalman filters, which process signals from the accelerometer and gyroscope to get an error-free value from each sensor, is indicated as a Dynamic Inclinometer.

Figure 1. Inclinometers and applications

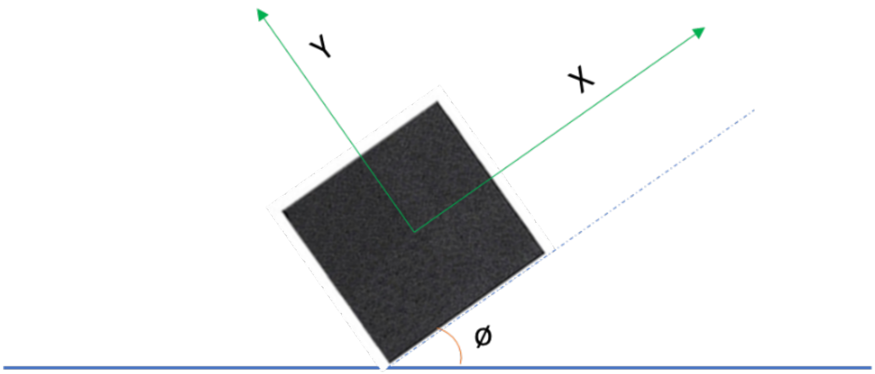


The inclination angle, which represents the angle between the gravity vector and the sensor/device axis, can be represented in 3D space using three different components. The choice of representation varies across industry and depends on the number of sensing axes of the sensor. In the next section, we describe the principles behind computing inclination angle using an accelerometer and different axes modes.

1 Single-axis or single-plane tilt calculation

In certain applications, only the measurement of a single inclination angle is required and this mode is used to measure the tilt with respect to the X-axis. The following figure shows the sensing axis of the accelerometer for measuring the gravity component.

Figure 2. **Tilt measurement using 1 or 2 axes**



The accelerometer measures the gravity vector projection on its sensing axis. In the case of a single-axis sensor, the gravity component along the X-axis only is measured and for a 2 or 3-axis sensor, the remaining component along the Y-axis is measured with the Z-axis remaining fixed. Using both X and Y axes in the computation may be referred as dual-axis tilt computation in some literature.

The X-axis measures the gravity projection as:

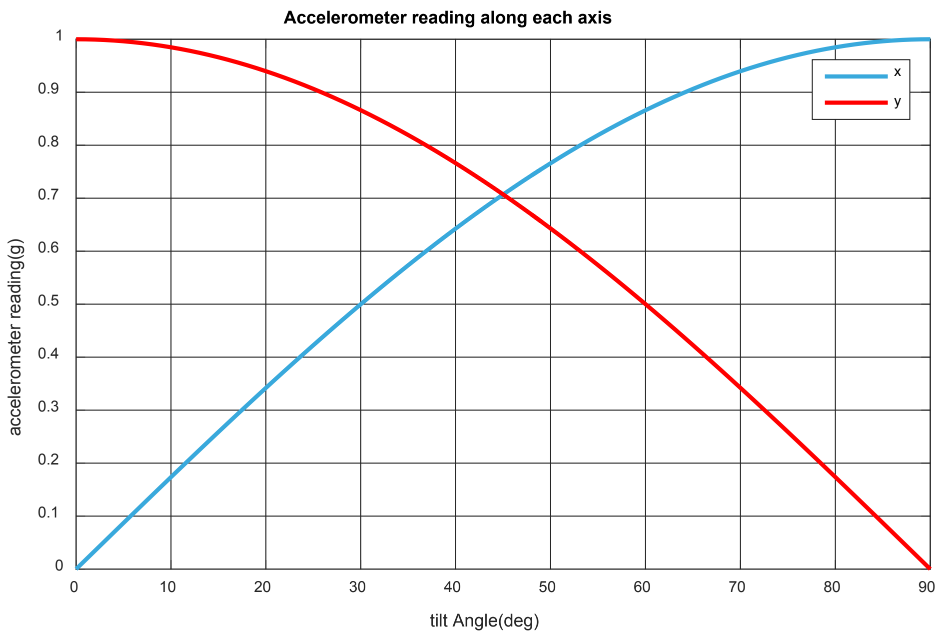
$$X = g * \sin(\Phi) \tag{1}$$

If the accelerometer has 2 or more axes, the Y measurement is:

$$Y = g * \cos(\Phi) \tag{2}$$

The X and Y measurements with respect to φ are shown in the following figure.

Figure 3. **Accelerometer reading**



The tilt angle φ can be computed using:

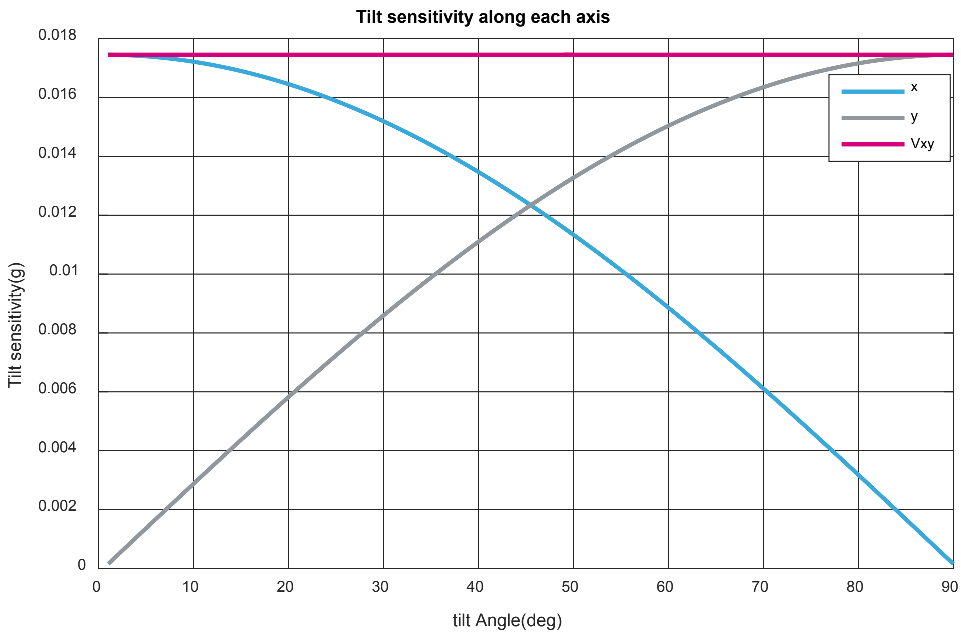
$$\Phi = g * \sin^{-1}(X) \quad (3)$$
$$\Phi = g * \cos^{-1}(Y)$$
$$\Phi = g * \tan^{-1}(X/Y)$$

All 3 formulas shown in Equation 3 compute the φ angle. From Figure 3, it can be observed that the sensor shows more sensitivity to a change in angle when the sensor axis is perpendicular to the gravity vector. The sensitivity can be measured either by computing the slope at each φ or differentiating Equation 3 with respect to φ. The sensitivity analysis can be useful to understand how any error in each axis can affect the tilt angle calculation and the impact of the error is not constant.

The sensitivity is computed and shown in Figure 4. As we can see from the figure, the sensitivity using arcsin or arccos changes with respect to the tilt angle. As we see from the plots, as the sensitivity of arcsin decreases, the sensitivity of arccos angle increases, and using arctan allows us to maintain the sensitivity constant.

The other advantage of using arctan2, and thus a 2 or 3-axis sensor, is the ability to compute the tilt angle with [0,360] range while with a single axis the range is maximum up to [-90,90] and with high resolution only for small angles.

Figure 4. Tilt sensitivity

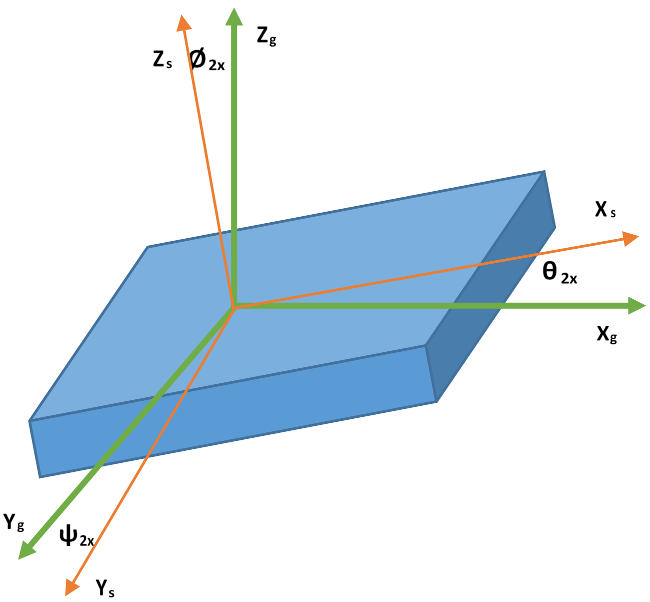


2 Dual-axis or dual-plane tilt sensing

Dual-plane mode is suitable for applications where the inclination is needed on both orthogonal horizontal axes.

Dual-plane mode computes the angle between the X-axis, Y-axis, and the horizontal plane. This mode also computes the gravity inclination (vertical axis and gravity vector) or angle between the horizontal plane and sensor XY plane.

Figure 5. **2 or 3-axis accelerometer tilt computation**



Theta$_{2x}$ measures the angle between the X-axis and the horizontal plane. The range of angle is [-90, 90] degrees.

$$\theta_{2x} = \sin^{-1}(X) \tag{4}$$

Psi$_{2x}$ measures the angle between the Y-axis and the horizontal plane. The range of angle is [-90, 90] degrees.

$$\psi_{2x} = \sin^{-1}(Y) \tag{5}$$

Phi$_{2x}$ measures the angle between the XY plane and the horizontal plane. The range of angle is [0, 90] degrees for a 2-axis and [-90, 90] for a 3-axis sensor.

$$\Phi_{2x} = \sin^{-1}(Vxy) \tag{6}$$

In a 2-axis sensor, we do not have information about the Z-axis direction and Vxy is computed by:

$$Vxy = \sqrt{\left(X^2 + Y^2\right)} \tag{7}$$

For a 3-axis sensor, Vxy is replaced by $\sqrt{(1-Z^2)}$.

The tilt angle can also be represented by the roll and pitch angle and can be computed by:

$$Pitch = \sin^{-1}(X) \tag{8}$$
$$Roll = \tan^{-1}(Y, Z)$$

3 Software libraries

Three different libraries are offered for ST sensors to support high-accuracy tilt estimation.

- **MotionTL2**: The MotionTL2 library offers real-time tilt estimation with multi-axis mode support for a 2-axis accelerometer.
- **MotionAC2**: The MotionAC2 library offers 2-axis accelerometer calibration for bias and scale factor. This library is suitable to execute calibration logic in runtime and during factory calibration.
- **MotionDI** : The MotionDI library offers a real-time dynamic inclinometer with support of calibration for a 3-axis accelerometer and gyroscope.

These libraries are available (in binary format) on st.com, refer to X-CUBE-MEMS1 along with the associated user manuals.

4 Error and calibration

Accelerometers are designed to measure acceleration using a mechanical structure that is subjected to many sources of error which affect the measurement and tilt measurement accuracy. Some of these errors are:

- White noise and vibration
- Bias/offset and temperature drift
- Sensitivity and nonlinearity
- Cross-axis sensitivity

Another factor that affects tilt accuracy (but it is not related to the accelerometer) is the misalignment of the sensor.

4.1 White noise and vibration

The source of accelerometer noise arises due to electronics noise, voltage fluctuation, ADC error, thermo-mechanical effects, flicker noise, and many similar components. Usually, inherent white noise is represented by noise density in the datasheet. For example, typical IIS2ICLX noise density is specified as 15 µg/√(Hz). You can also relate the bandwidth to noise since normally the sensor bandwidth is set to half of the sampling frequency.

Even in the absence of inherent noise, the device may experience external vibration that results in adding noise in the accelerometer signal.

The accelerometer can provide measurement at output data rate (ODR) of 1 Hz to a few kHz. From the noise density expression we can observe that as we increase the sampling rate, the noise level increases proportionally to the square root of Hz. There are two main advantages of sampling at a higher ODR:

- Faster response: At high ODR, the accelerometer is able to detect sharp changes.
- Noise reduction: At high ODR, filtering allows reducing the noise due to vibration or inherent noise. At low ODR, the RMS noise is lower but is not sufficient to lower the vibration noise.

Figure 6 shows the typical error observed with the noise level constant at different angle values. We can see as we approach the orientation angle parallel to the gravity vector, due to the lower sensitivity of the sine function at 90 degrees, the error due to noise increases. Similarly Figure 7 shows the average angle error with the different white noise levels at a constant tilt angle. As we expect, the error in tilt measurement increases as the noise level increases.

Figure 6. Tilt angle error with different run

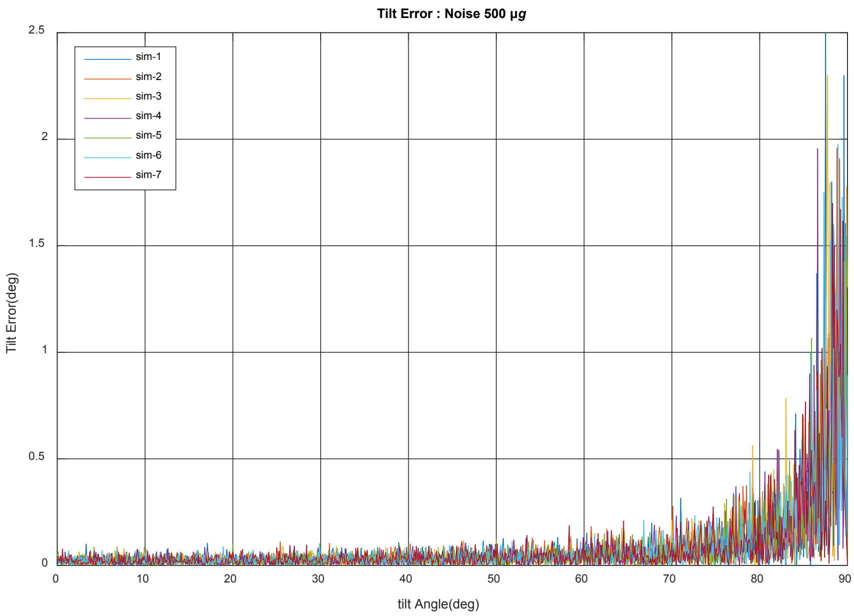
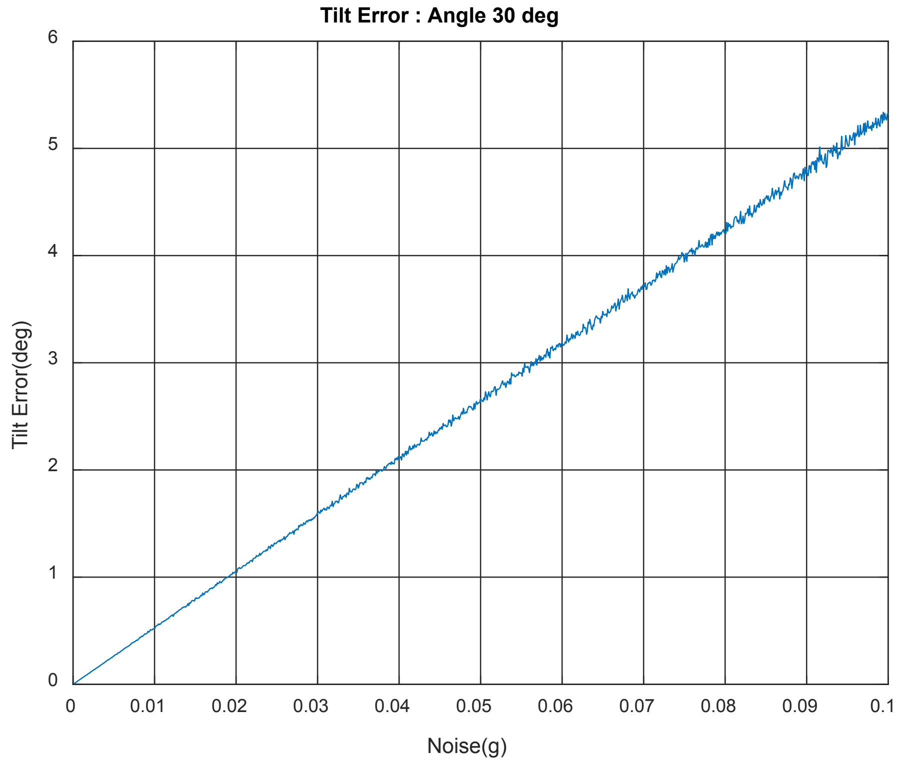


Figure 7. **Noise level and average error**



The impact of noise on the accuracy can be improved by averaging the output over n samples. The window size (n) can be selected based on the requirement of the application. A larger window size reduces the noise, but increases the latency.

Consider the signal with noise is represented by:

$$\widehat{X} = X + N\left(0, \sigma^2\right) \tag{9}$$

Where $N(0, \sigma^2)$ represents Gaussian noise with 0 mean and σ noise.

If we average the signal $\hat{X}$ with window size n, the resulting signal $\overline{X}$ is represented by:

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} \widehat{X_i} = X + N\left(0, \frac{\sigma^2}{n}\right) \tag{10}$$

Equation 10 demonstrates that the averaging of n samples reduces the noise level by a factor of n.

The MotionTL2 library offers the knob setting to control the filtering of the incoming signal, which reduces the noise and estimates the tilt angle with higher accuracy.

4.2 Offset/bias and temperature drift

Offset refers to a constant level of the accelerometer signal when no acceleration is present. The bias is often represented by the zero-*g* level. The accelerometer bias can vary because of thermo-mechanical stress during the soldering process, temperature variation, aging, and other factors.

The range of bias variation is typically defined as zero-*g* level, zero-*g* level over life, and zero-*g* level variation with respect to temperature. These three parameters allow us to estimate the typical error accumulated due to biases.

Figure 8 demonstrates the impact of constant bias on the final calculation of tilt. This figure represents the error in tilt angle if 50 m*g* offset is present in the X, or Y, or both axis. As we can see, the maximum error observed is around 2.75 degrees using the arctan formulation (Equation 3).

Figure 8. Tilt error due to bias

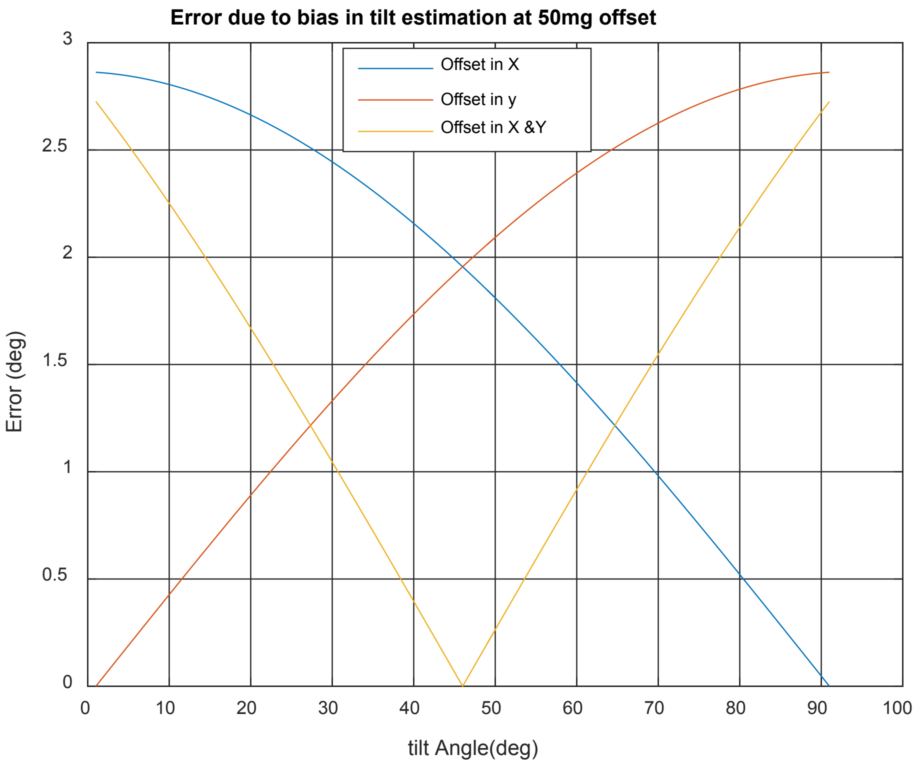
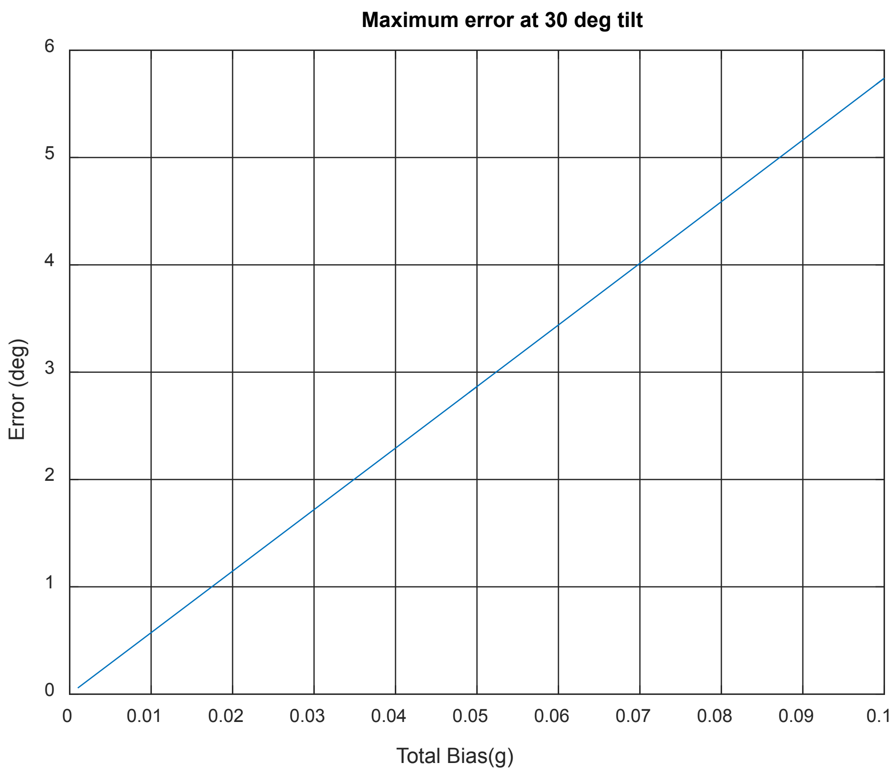


Figure 9 shows the maximum error when the total bias (||Xoff+YOff||) error varies from 1 m*g* to 100 m*g* at a selected angle (30 degrees). As we can see in this figure, the error grows linearly as the total bias increases.

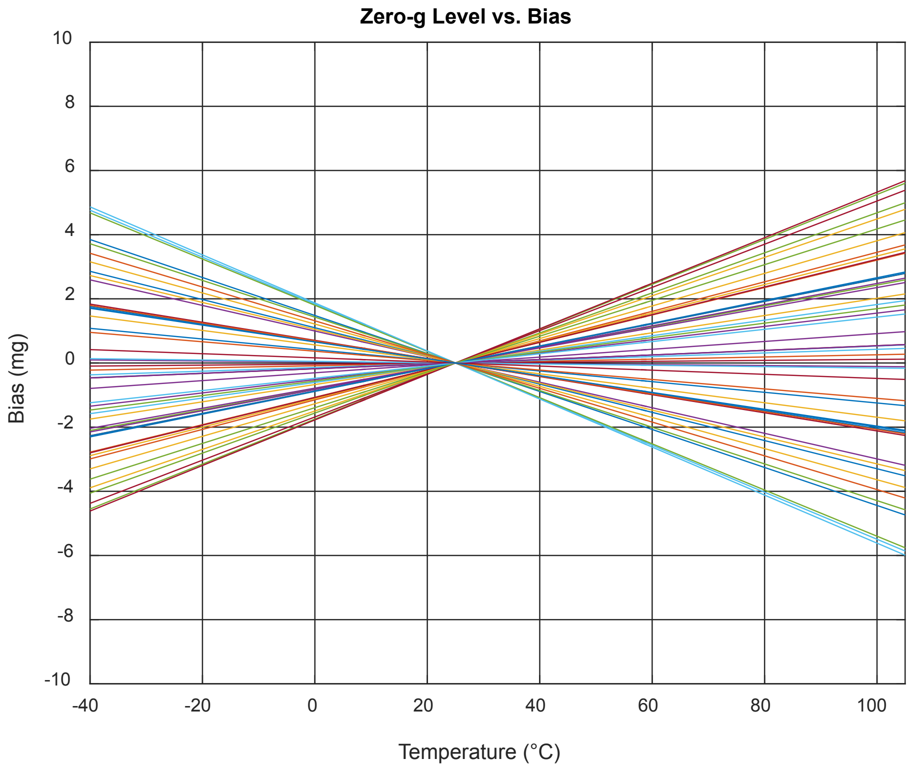
Both Figure 8 and Figure 9 demonstrate the impact of accelerometer bias. Hence, it is recommended to perform accelerometer calibration in order to reduce the error.

Figure 9. **Maximum error in tilt estimation using arctan**



The bias varies with temperature. Zero-*g* level vs. temperature is defined by how the bias of the accelerometer changes with temperature. The accelerometer is a mechanical system and temperature affects the properties of the device and its structure. The IIS2ICLX sensor is well calibrated and shows very small bias drift due to temperature (~ 0.020 m*g*/°C). Figure 10 shows the typical bias variation with a temperature between -40 to +105 °C for the IIS2ICLX sensor with maximum 0.075 m*g*/°C variation. As we can see the total variation in bias is around ±6 m*g* which corresponds to ± 0.34 degrees.

Figure 10. Bias level change vs. temperature



Most ST MEMS sensors have stable performance against temperature variation and normally do not require temperature compensation and are well-calibrated at room temperature (25 °C). In the case of a specific application requirement, an offset temperature compensation procedure can be applied. The 2-point procedure is as follows:

1. Measure the accelerometer reading at temperature T1, at fixed position and zero external acceleration.
2. Increase/decrease the temperature by at least 10 degrees and record the accelerometer reading and temperature T2.
3. Compute the slope for each axis with respect to the temperature difference (T1-T2) using:

$$Slope\,T_{T1} = \frac{AccX_{T2} - AccX_{T1}}{(T2 - T1)} \tag{11}$$

4. Store $SlopeT_{T1}$ and correct the next reading at T using the expression:

$$AccX_{compensate} = AccX_T - (T - T1) * SlopeT_{T1} \tag{12}$$

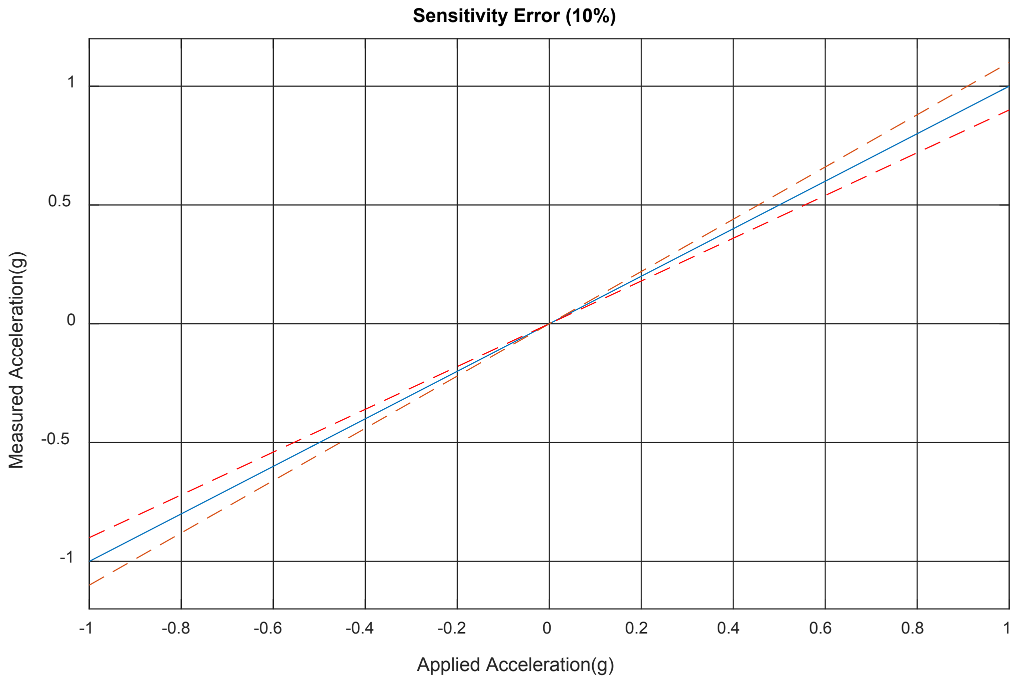
As an alternative for reducing the bias error, we recommend performing at least post-solder factory calibration of the sensor using the MotionAC2 library. We also recommend using the MotionAC2 library during runtime to correct any drift due to temperature or aging. The MotionAC2 library offers runtime calibration with offset and scale factor correction.

4.3 Sensitivity and nonlinearity

Sensitivity is defined as the ratio of change in the accelerometer reading to actual acceleration. Ideally, the relationship is linear and defined by m*g*/LSB. In sensors, the sensitivity will change over time and with temperature. These parameters are specified in the datasheet as sensitivity deviation (%).

The following figure shows the sensitivity in the ideal case and with maximum and minimum sensitivity.

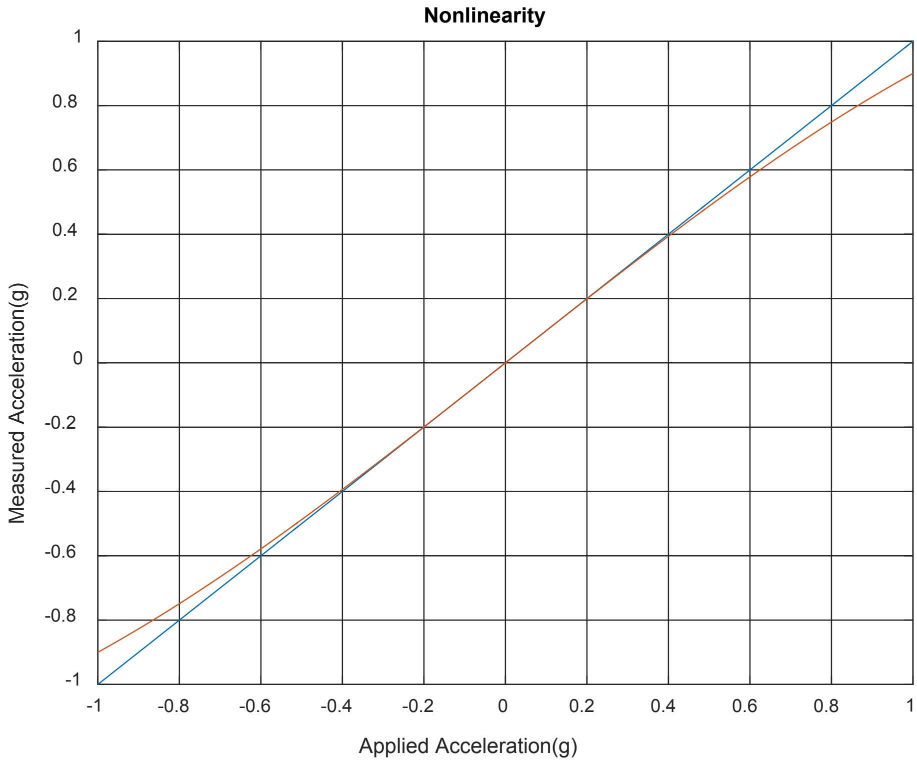
Figure 11. Accelerometer sensitivity



Temperature also affects the sensitivity of the accelerometer. Typically it is defined as a percentage per degree Celsius (%/°C). For the IIS2ICLX sensor, the value is under 0.012%/°C and can be ignored for most applications.

Nonlinearity: The sensitivity of the device is always not linear over the full operating range because the physical response of the sensing element is inherently nonlinear. The correction terms determined in factory calibration allow representing sensitivity as a linear function. However, deviation is observed from constant sensitivity that cannot be approximated using a linear function. Nonlinearity is defined as maximum deviation from ideal constant sensitivity in the form of percentage with respect to full scale. IIS2ICLX sensitivity nonlinearity is around 0.1% FS.

Figure 12. Nonlinearity

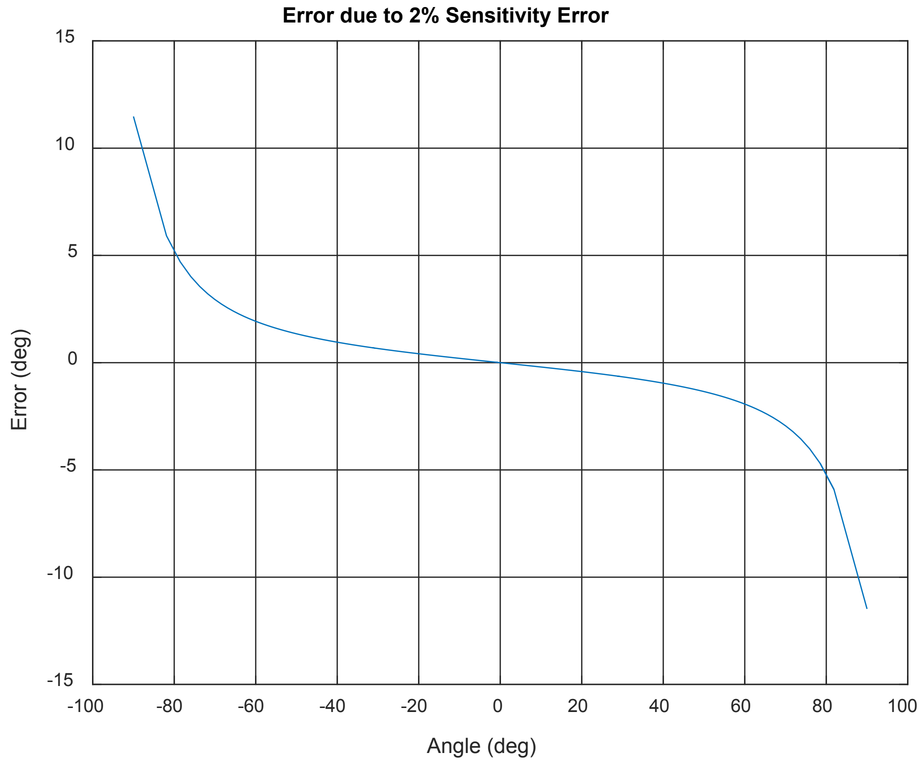


Sensitivity change and nonlinearity have a similar impact on the final accuracy of tilt. We should also note that the impact of sensitivity error on single-axis versus dual-axis tilt computation is significant.

The impact of sensitivity on the single-axis is easy to visualize and easy to represent but 2-axis tilt computation varies with relative sensitivity error between the X and Y-axis. If the sensitivity error on each axis is similar, there is no impact on tilt computation because of division operation. The impact is significant if each axis has opposite (positive and negative side) errors in sensitivity.

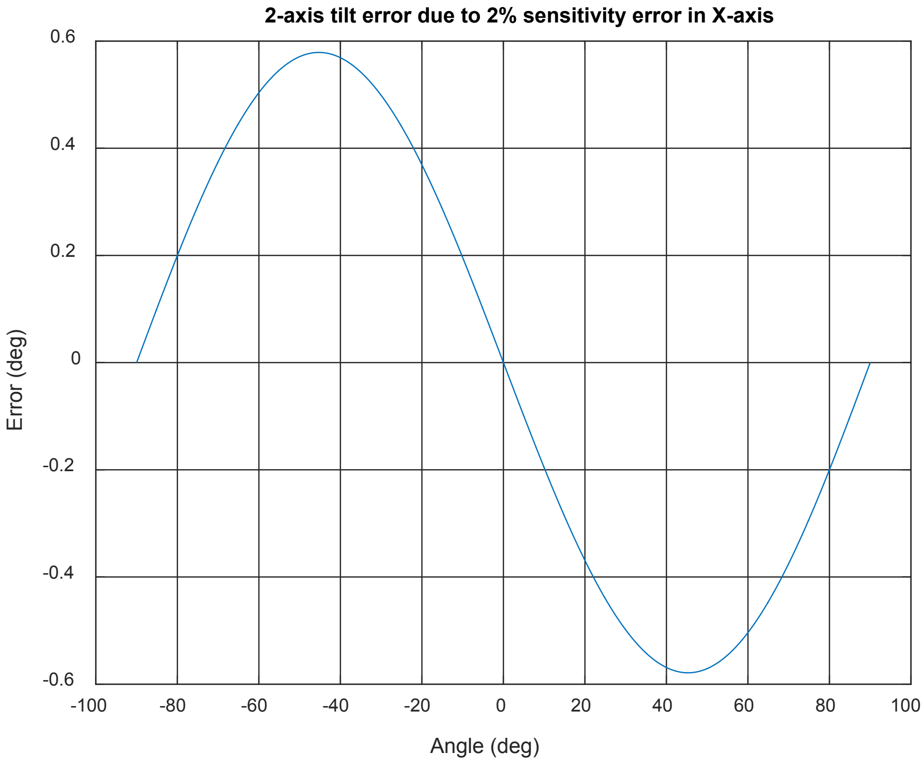
The following figure shows the error in tilt measurement due to 2% sensitivity error and we observe that the error is significant when the axis is parallel to the gravity vector (90 degrees).

Figure 13. **Single-axis - tilt angle error due to error in sensitivity**



To visualize the error in 2-axis computation, we used ideal sensitivity on the Y-axis and 2% sensitivity error on the X-axis. The following figure shows the error when we use two axes to compute a single tilt angle using the arctan formula (Equation 3) and we see the error is within 0.6 degrees compared to 12 degrees in single-axis computation. This is one reason to utilize a 2-axis sensor to measure a single tilt angle.

Figure 14. **2-axis tilt error due to 2% sensitivity error**



MotionAC2 allows the calibration of sensitivity error using the 4-point tumble calibration method.

4.4 Cross-axis sensitivity

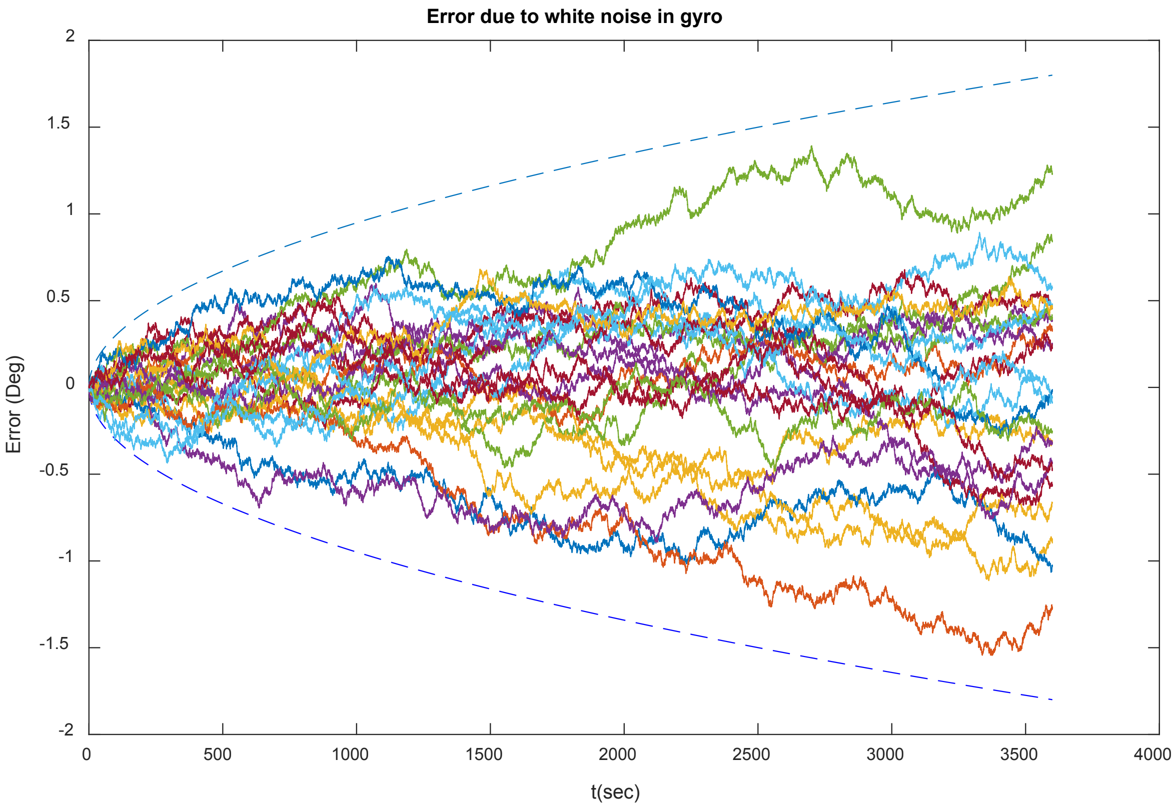
Coupling or crosstalk between two or more axes results in cross-axis error. In the presence of cross-axis error, if acceleration is imposed on one axis, the sensor measures some portion of acceleration on the other axis as well. Cross-axis sensitivity can arise due to the non-orthogonal axes.

The error due to the cross-axis remains almost constant for all the tilt angles for 2-axis tilt measurement and it is proportional to cross-axis error.

5 Dynamic inclinometer and MotionDI

An accelerometer is very suitable for a static inclinometer where the external acceleration is negligible. However, there are many applications where the external acceleration is very high or the measurement error is relatively high and susceptible to interference. For such applications, it is possible to utilize the gyroscope measurement to stabilize the tilt output, but the gyroscope also suffers from noise and drift. Hence, the integration of angular velocity would accumulate error over time and results in a significant error in tilt angle estimation. The following figure shows the impact of white noise on the integration of gyroscope measurements.

Figure 15. Error due to white noise integration



Therefore, sensor fusion between gyroscope and accelerometer measurements is essential in order to provide a solution suitable for dynamic conditions. MotionDI is a software library designed for dynamic inclinometer applications and optimized for ISM330DHCX, ASM330LHH, and ISM330DLC.

The MotionDI filtering and predictive software use advanced algorithms to intelligently integrate outputs from multiple MEMS sensors for optimum performance, in typical environmental conditions. MotionDI implements an Extended Kalman filter to estimate gyroscope bias and compute accurate tilt angle through the fusion of accelerometer and gyroscope data. The MotionDI library also supports accelerometer calibration and gyroscope temperature compensation calibration as illustrated in the following figure.

Figure 16. MotionDI

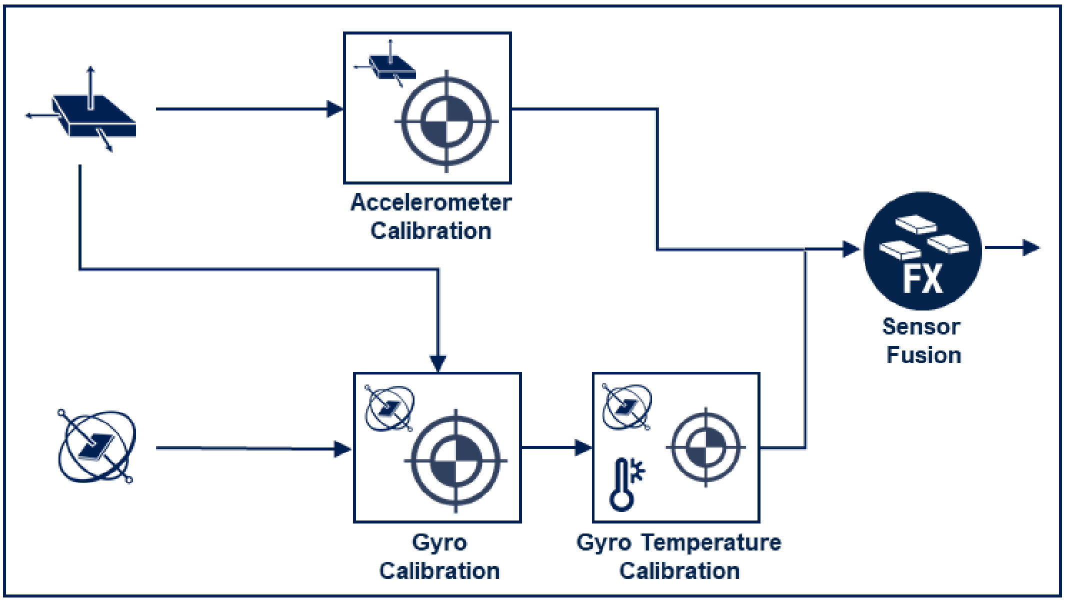
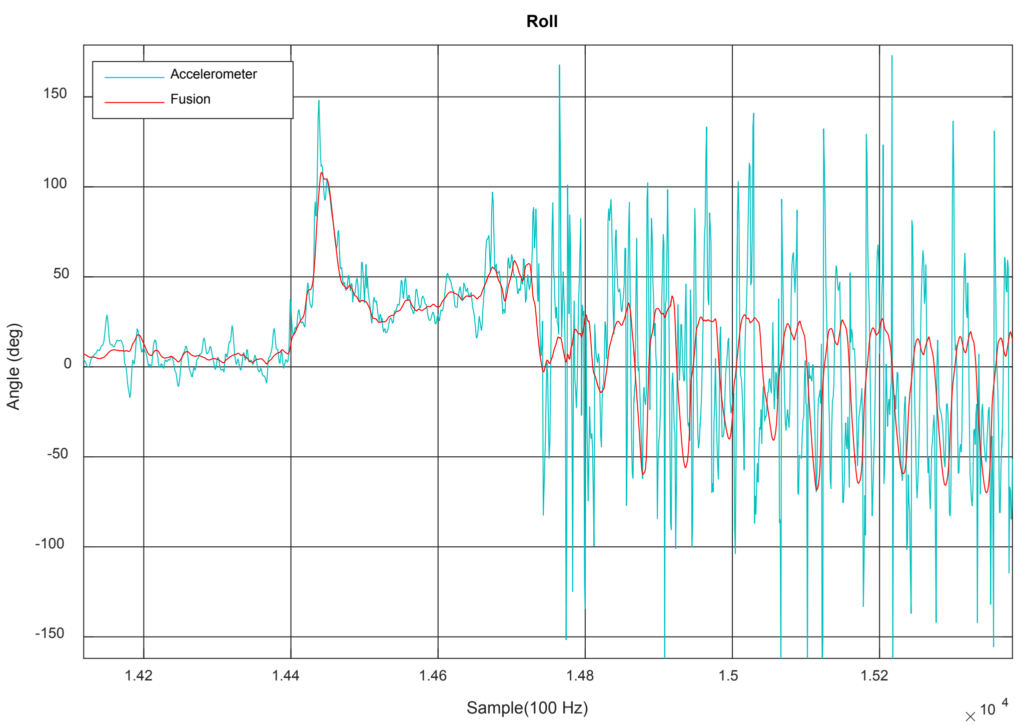


Figure 17 shows the angle estimation from the accelerometer in the presence of external acceleration and the angle estimate computed by the MotionDI library. The angle estimated from the accelerometer is erroneous due to large external acceleration, but the MotionDI library can estimate accurate tilt information using an Extended Kalman filter.

Figure 17. Sensor fusion



6 Sensor selection

The following parameters should be considered in selecting the appropriate accelerometer part to match the application requirements.

Number of axes

The sensor with a minimum number of axes required is an important criterion for any application. If the application just requires measurement of single-axis tilt, a 1-axis accelerometer is sufficient. Even if 1-axis is sufficient, we recommend selecting an accelerometer with two or more axes to improve the accuracy of tilt measurement in case the application requires measuring a tilt angle greater than 30 degrees. As we have seen in Section 1 Single-axis or single-plane tilt calculation, different error sources affect the tilt angle accuracy and a 2-axis sensor provides better stability and performance.

Measurement range (full scale)

Based on the application requirements, it is important to select a sensor that does not saturate during normal operation. As we have seen in Section 1 Single-axis or single-plane tilt calculation, the accelerometer reading is based on the current tilt angle. We should first check the typical maximum and minimum operating range of movement for the application and see if the maximum full scale of the sensor is sufficient to capture the acceleration due to the gravity vector without any saturation. If any application requires measuring [-90, 90] tilt range, it is recommended to select a sensor with a minimum 2 *g* full scale.

It is also important to examine the minimum full scale supported by the sensor because at minimum full-scale setting, the sensor resolution is maximum and it allows measuring the angle with high resolution.

The IIS2ICLX sensor supports a wide range of full scales (±0.5 *g*, ±1.0 *g*, ±2.0 *g*, ±3.0 *g*).

Operating temperature range

The sensor should operate within a specified operating temperature range. The IIS2ICLX sensor supports a wide operating temperature range of -40 °C to +105 °C.

Resolution

Sensor resolution determines the minimum or smallest change that can be detected by the sensor. The resolution should be considered to examine if the sensor meets the desired resolution for the inclinometer for the selected full range of the tilt angle. As we saw from Figure 4. Tilt sensitivity, the sensor's resolution requirement to measure tilt angle with a certain granuality is not constant for a single axis. For example, 1 m*g* resolution allows measuring tilt angle with 0.05 degree resolution near zero degree tilt angle.

The resolution of the sensor depends on various factors such as noise, bandwidth, ADC, and low-pass filter.

Noise level is one of the major limiting factors in determining the resolution. A sensor can only discern change if the external motion amplitude is higher than the sensor's noise level. Any signal that has amplitude less than the sensor's noise level is not visible, which limits what the minimum resolution can achieve. The relationship between the sensor noise level, bandwidth, and ODR (sampling rate) can be represented by:

$$Noise\ or\ resolution \sim Noise\ density * \sqrt{BW * 1.6} \sim Noise\ density * \sqrt{ODR} \tag{13}$$

Generally, sensor bandwidth is half of ODR. For IIS2ICLX the noise density is 15 μ*g*/√(Hz) and at ODR 50 Hz the sensor bandwidth is ODR/2 or 25 Hz and the expected noise is around 95 μ*g*.

The ADC, which converts the analog measurement to digital, can limit the resolution of the sensor if the ADC has lower resolution than the accelerometer noise resolution. Generally, ADC has a very high resolution but even with high resolution, ADC conversion introduces inherent noise in the signal due to rounding.

Accuracy

- **Zero-*g* level (Offset/Bias) and sensitivity error**

  Even if the zero-*g* level and sensitivity error can be addressed with factory or runtime calibration, it is important to investigate the maximum range of zero-*g* level and sensitivity error. The maximum range for both errors allows us to assess if runtime calibration is required for the application.

  Zero-*g* level and sensitivity errors are typically represented by two different terms:

  – Typical accuracy or range: the typical value represents the range of zero-*g* level or sensitivity in a sensor without performing any calibration and before any mechanical stress such as soldering. Any mechanical stress affects the typical range of the zero-*g* level or sensitivity error.

  – Change over life: the specification represents the variation of the sensor over lifetime once we perform one-time calibration.

- **Stability over temperature**

  In Section 4.2 Offset/bias and temperature drift and Section 4.3 Sensitivity and nonlinearity we see the impact of temperature on offset and sensitivity and how it causes drift in angle over temperature. It is crucial to analyze these parameters in the typical operating temperature range for the application. If the application's operating temperature range is around room temperature (25 °C), these parameters can be ignored in selecting the sensor, but in the case of a wide operating temperature range, these drifts will impact the accuracy. The process of calibrating bias and sensitivity over temperature is more complex and cannot easily be done during the runtime. Due to the limitation of calibrating these drifts, we should be careful in selecting a sensor that has lower drift with respect to temperature variation.

  The IIS2ICLX has 0.02 m*g*/°C zero-*g* level change versus temperature and the maximum zero-*g* level variation at 105 °C is ±1.6 m*g* which results in ± 0.092 degree error.

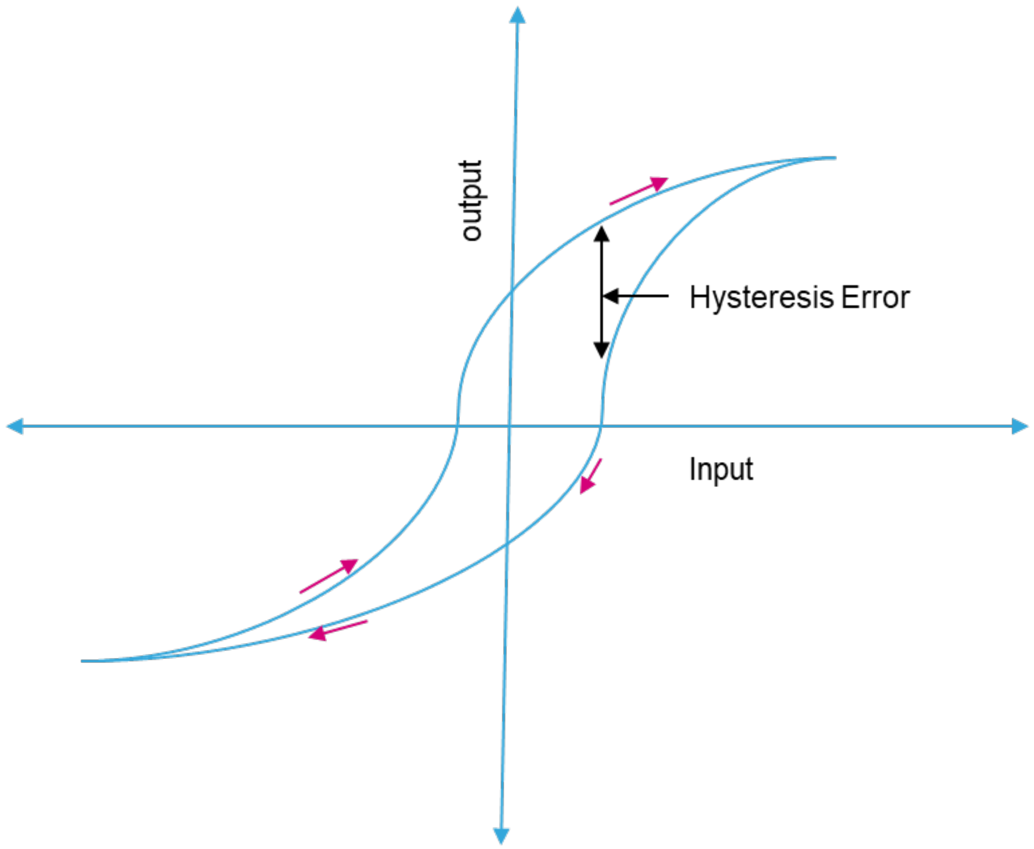
  Similarly, the sensitivity change versus temperature for IIS2ICLX is ±0.01%/°C and maximum error accumulated at 105 °C is 0.008 and maximum tilt error is around 7.26 deg at 90 degrees and the average error is around 0.95 degree for [0, 90] tilt angle range.

- **Repeatability/Hysteresis**

  It is desired to measure the same reading for a given input (force, rotation, and so forth) and external properties (temperature, humidity), regardless of which direction the changes are made.

  Due to various stress such as temperature or mechanical, a change in the characteristic of the sensing element and the difference in output for the same input is characterized as hysteresis as shown in the following figure.

Figure 18. **Hysteresis error**



  Offset and sensitivity exhibit the hysteresis error due to temperature sweep.

  The hysteresis error in offset or sensitivity can help in deciding the appropriate sensor for the application because a higher hysteresis error requires the sensor to calibrate during runtime frequently.

- **Vibration rectification (VRE)**

  The rectification to the DC component of broadband AC vibrations can shift the offset of inclinometers, leading to significant errors. The anomalous shift in the DC component can be hard to compensate in a static inclinometer where the calculation considers the DC/static component and misclassifies it as change in angle. Vibration rectification is highly dependent on the accelerometer structure, vibration frequency, and intensity.

  For any application it is really important to choose an appropriate bandwidth such that any high-frequency vibration can be rejected by the accelerometer.

- **Bandwidth**

  The bandwidth of the sensor limits the motion observed by the sensor. The sensor should be selected based on a bandwidth that is essential to capture the motion in normal operation. We should also keep in mind that the larger bandwidth leads to the integration of the noise from the higher frequency in the signal and possibly causes higher vibration rectification error as described in the last section.

Selecting a high-accuracy accelerometer is crucial in meeting the application requirements. It is important to select a sensor after comparing all the parameters previously listed. The factory calibration and runtime calibration definitely reduce the impact of major sources such as bias and sensitivity and it is recommended to calibrate the sensor using factory or runtime calibration software.

Table 1 and Table 2 compare the high-accuracy 2-axis IIS2ICLX against the IIS3DHHC accelerometer. The tables compare the various sources of error in the accelerometer reading and error contribution in tilt angle estimation. All the estimations of error are done independently of other sources of error.

Table 1. IIS3DHHC error budget

IIS3DHHC	Typ(1)	Tilt angle error
Sensitivity error	7%	1.95 deg (using 2 axes)
Sensitivity change over life	NA	NA
Sensitivity change over temperature	0.01%/°C	0.1714 deg at max error at 85 °C
Zero-*g* level offset	20 m*g*	1.2 deg at 30 degrees
Zero-*g* level offset over life	NA	NA
Zero-*g* level offset over temperature	0.4 m*g*/°C	1.21 deg at 30 degrees at 85 °C
Noise density	65 µ*g*/√50	0.02 deg at 0.4 m*g* RMS
VRE at 50 Hz, 2.5 *g* RMS	NA	NA
Operating temperature range	-40 to +85 °C	-

1. *Typical values are 1-sigma values and measured at room temperature.*

If we compare the IIS3DHHC and IIS2ICLX, most of the large error sources such as sensitivity error, zero-*g* level offset, and temperature drift have been reduced dramatically.

Table 2. IIS2ICLX error budget

IIS2ICLX	Typ(1)	Tilt angle error
Sensitivity error	2%	0.6 deg (using 2 axes)
Sensitivity change over life	0.07%	0.023 deg
Sensitivity change over temperature	0.01%/°C	0.2 deg at max error at 105 °C
Zero-*g* level offset	8 m*g*	0.75 deg at 30 degrees
Zero-*g* level offset over life	2.5 m*g*	0.25 deg at 30 degrees
Zero-*g* level offset over temperature	0.02 m*g*/°C	0.16 deg at 30 degrees at 105 °C
Noise density	15 µ*g*/√50	0.005 deg at 95 µ*g* RMS
VRE at 50 Hz, 2.5 *g* RMS	1 m*g*	0.1 deg
Operating temperature range	-40 to +105 °C	-

1. *Typical values are 1-sigma values and measured at room temperature.*

With the latest advancements in IIS2ICLX, the largest error source is still sensitivity error and zero-*g* level offset and calibrating these errors allows achieving ideal performance.

Revision history

Table 3. **Document revision history**

Date	Version	Changes
20-Aug-2020	1	Initial release
01-Jun-2022	2	Updated Table 1. IIS3DHHC error budget and Table 2. IIS2ICLX error budget

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