AN 005

Tilt-Sensing with Kionix MEMS Accelerometers

Introduction

Tilt/Inclination sensing is a common application for low-g accelerometers. This application note describes how to use Kionix MEMS low-g accelerometers to enable tilt sensing. Applicable theory, plots and equations are provided with this note as guidelines.

Tilt Sensing Applications

Accelerometers have countless potential tilt-sense applications in today's motion-enabled world. Tilt-sensing opportunities exist in a variety of industries, such as automotive, consumer electronics and military/aerospace, and include:

Vehicle stability systems
Inclinometers
Cell phone/PDA screen navigation
Motion-enabled game play
Tilt-enabled computer mouse/pointer
Tilt-compensated electronic compass

Some of these applications currently utilize dual-axis accelerometers that, at times, are adequate for the job. A tri-axis accelerometer, however, can enable additional functionality, accuracy and precision.

Dual-Axis Tilt Sensing

Presently, low-g dual-axis (X, Y) accelerometers are often used in tilt-sensing applications where the force of gravity is used as an input to determine the orientation of an object. The sensor is most responsive to changes in tilt when the sensitive axis is perpendicular to the force of gravity, yielding a sensitivity of approximately 17.45mg/° of tilt. The sensor is least responsive to changes in tilt when the sensitive axis is oriented in its +1g or −1g position, yielding an approximate sensitivity of only 0.15mg/° of tilt.

When horizontally mounted, as shown in Fig. 1, a dual-axis accelerometer's diminishing sensitivity through increased tilt prevents accurate tilt sensing when the accelerometer is tilted beyond 45° along either axis. Also, the absence of a Z-axis sensor means the accelerometer cannot detect an inversion, causing improper functioning.

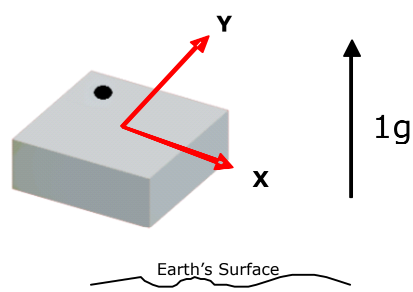

Fig. 1) Horizontally Mounted Dual-Axis Accelerometer. The g vector indicated is the apparent acceleration measured by a Z-axis sensor due to the static gravitational force.

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These problems can be addressed by mounting the accelerometer vertically, as shown in Fig. 2, creating an X, Z sensor. Unfortunately, an additional accelerometer will be required to sense both X-tilt and Y-tilt, increasing the bill of materials and potentially doubling cost.

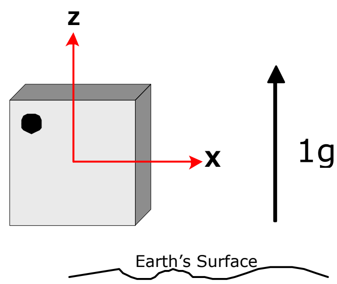

Fig. 2) Vertically Mounted Dual-Axis Accelerometer

The integration of a Kionix tri-axis (X, Y, Z) accelerometer into this application provides the all-important Z-axis that functions with the tilted axes to maintain constant sensitivity and sense the inversion of the accelerometer, thus permitting a full, unrestricted range of tilt.

Tri-Axis Tilt Sensing

Kionix technology provides for X, Y and Z-axis sensing on a single, silicon chip. When using a Kionix tri-axis accelerometer, the Z-axis can be combined with both of the tilting axes to improve tilt sense precision and accuracy. For this note, we will follow the tilt assignments described below in Fig. 3.

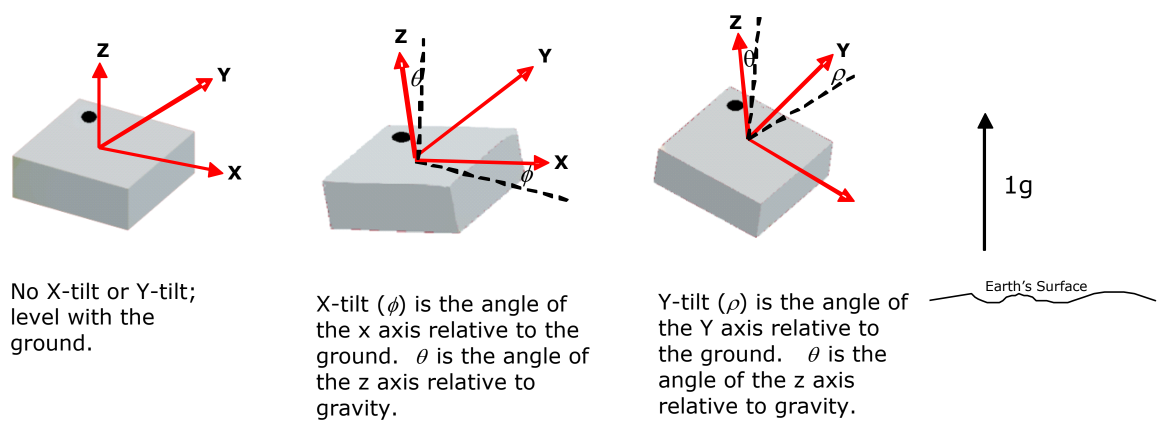

Fig. 3) X-tilt and Y-tilt Assignments Relative to Ground

Basic tilt angles can be generated from the accelerometer outputs using Eq. 1 since the X- and Y-axes follow the sine function and the Z-axis follows the cosine function. It should be noted that these angles are not the pitch and roll angles typically used in aeronautics, nor are they the direction cosine angles for describing which direction a vector is pointing. The angles ϕ and ρ are the angles that the X and Y accelerometer axes make with the fixed reference XY plane.

$$\phi = \arcsin(a_x)$$
$$\rho = \arcsin(a_y)$$
$$\theta = \arccos(a_z)$$

Eq. 1) Calculating angle from acceleration (g) where a_x, a_y, and a_z are the accelerations in the respective axis.

For example, as a Kionix tri-axis accelerometer is rotated 360° around the Y-axis, as shown in Fig. 4, acceleration due to tilt on the X- and Z-axes will change according to the table in Fig. 5. You can see that the Z-axis output is at its minimum sensitivity when the X-axis output is at its maximum sensitivity. Therefore, maximum sensitivity can be maintained if both the X and Z outputs are combined. Note that this method is valid when rotating 360° around any axis.

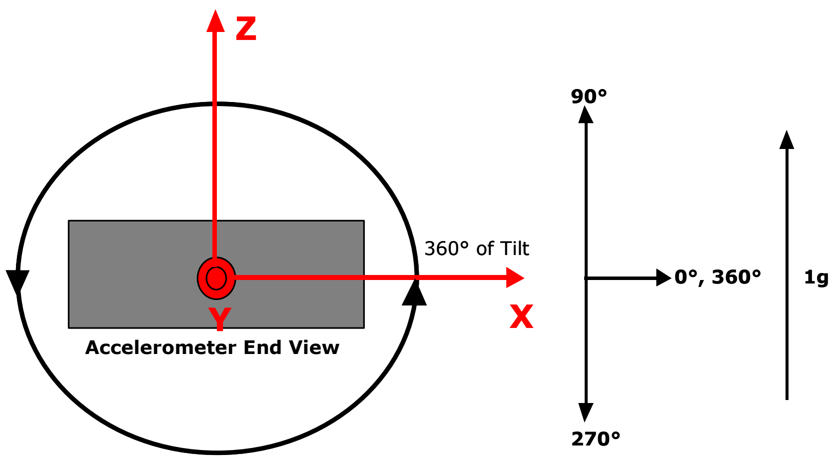

Fig. 4) Kionix Tri-Axis Accelerometer, 360˚of Tilt

	X-axis		Z-axis	
X-tilt (ϕ) in (°)	Acceleration (g)	Change per ° of Tilt (mg)	Acceleration (g)	Change per ° of Tilt (mg)
0	0	17.452	1	-0.152
15	0.259	16.818	0.966	-4.664
30	0.5	15.038	0.866	-8.858
45	0.707	12.233	0.707	-12.448
60	0.866	8.594	0.5	-15.19
75	0.966	4.37	0.259	-16.897
90	1	-0.152	0	-17.452
105	0.966	-4.664	-0.259	-16.897
120	0.866	-8.858	-0.5	-15.19
135	0.707	-12.448	-0.707	-12.448
150	0.5	-15.19	-0.866	-8.858
165	0.259	-16.897	-0.966	-4.664
180	0	-17.452	-1	0.152
195	-0.259	-16.897	-0.966	4.37
210	-0.5	-15.19	-0.866	8.594
225	-0.707	-12.448	-0.707	12.233
240	-0.866	-8.858	-0.5	15.038
255	-0.966	-4.664	-0.259	16.818
270	-1	0.152	0	17.452
285	-0.966	4.37	0.259	16.818
300	-0.866	8.594	0.5	15.038
315	-0.707	12.233	0.707	12.233
330	-0.5	15.038	0.866	8.594
345	-0.259	16.818	0.966	4.37
360	0	17.452	1	-0.152

Fig. 5) Tilt Table

Tri-Axis Tilt Calculations

The Z-axis of a Kionix tri-axis accelerometer can be combined with the X- and/or Y-axes to maintain constant sensitivity through all 360° of tilt. Figure 6 shows the expected tilt sensitivity through the first 90° of tilt when using just the tilt axis, the Z-axis and the combination of the two.

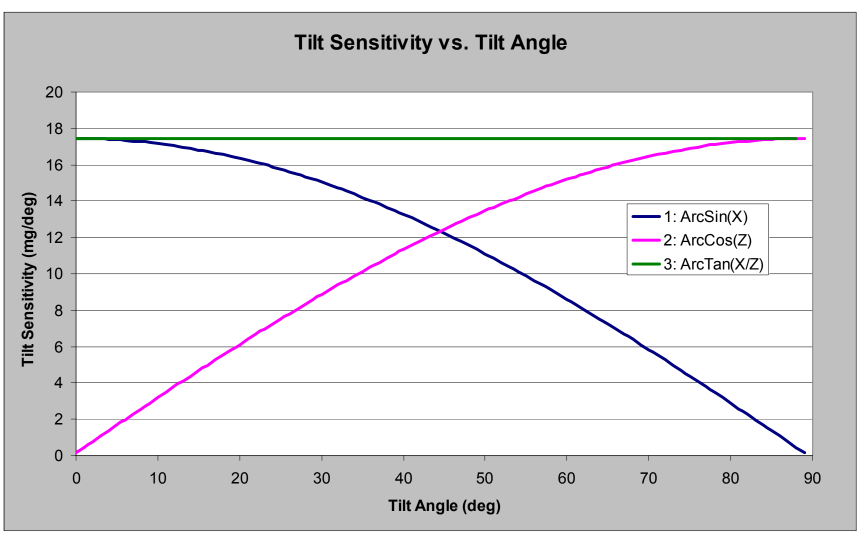

Fig. 6) Tilt Sensitivity vs. Tilt Angle

As you can see, approximately 17.45 mg/° of sensitivity can be maintained at any tilt orientation when combining an X or Y tilt axis with the Z-axis. This method allows tilt angles greater that 45° to be sensed accurately and precisely. Both X-tilt (ϕ) and Y-tilt (ρ) can be sensed simultaneously using the outputs of all three axes, as shown in Eq. 2.

$$\phi = \arctan\left(\frac{a_x}{\sqrt{a_y^2 + a_z^2}}\right) \qquad \rho = \arctan\left(\frac{a_y}{\sqrt{a_x^2 + a_z^2}}\right)$$

Eq. 2) Combined X-tilt (ϕ) and Y-tilt (ρ) Calculations

Sign Recognition

There is still an additional way to improve tilt sense precision. As shown in Fig. 7, when the X-axis tilt is approximately 90°, the same X-axis sensor output voltage can represent two different angles. To better illustrate this situation, Fig. 7 presents 360° of accelerometer tilt divided into four quadrants, Q1, Q2, Q3, and Q4.

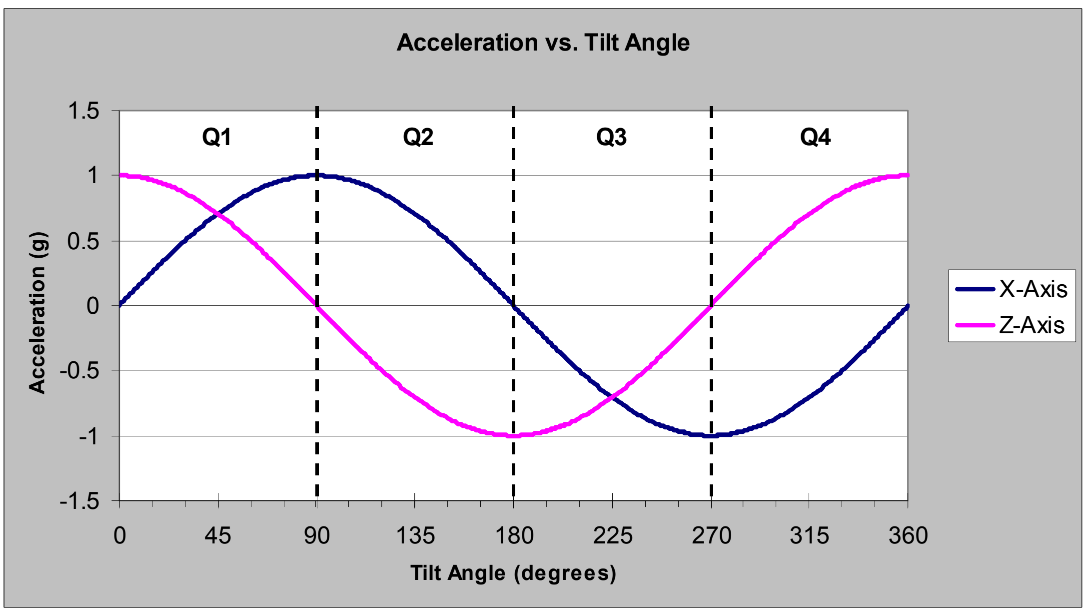

Fig. 7) Tilt Quadrants Through 360° of Pitch

Sign recognition is imperative because, for example, tilts of 45° and 135° are represented by the same sensor output, .707g. The methods presented up to now do not explain how to tell the difference between two tilt angles that result in the same sensor output. This ambiguity can be resolved by monitoring the sign of the Z-axis output. In this case, when the accelerometer is tilted at 45°, the Z-axis output is a positive value. When the accelerometer is tilted to 135°, the Z-axis output is a negative value. The sign of the X-axis and the Z-axis will indicate in which quadrant the accelerometer is being tilted, consequently indicating inversion. The table in Fig. 8 shows the expected signs for each output in each quadrant.

Acceleration Signs		
Quadrant	Xaccel	Zaccel
1	+	+
2	+	-
3	-	-
4	-	+

Fig. 8) Acceleration Signs Through Each Quadrant

Accelerometer errors

One detail so far unmentioned is the accelerometer's ability to create accurate tilt angles. Calibrating accelerometers is mostly a factory test problem. End-users can re-zero (level) X-tilt and Y-tilt in their production line. The indivisual tilt offsets can be found by placing the phone or circuit board assembly on a known flat surface and measuring the values with a near zero expectation for the ϕ and ρ values. The offset error can be zeroed out after installation and will include any platform leveling error. Sensitivity or scale factors could be done for accelerometer X and Y tilt outputs by robotically tiping the assembly and matching the resulting output with the desired output. Obviously test costs must be assessed with the desired compass accuracy and the quality of accelerometers. Additional information on the sources of error and how to minimize them can be found in Application Note:AN012 Accelerometer Errors.

The Kionix Advantage

The Kionix tri-axis accelerometers can measure 360° of tilt around any axis with great precision. Kionix technology provides for X, Y and Z-axis sensing on a single, silicon chip. One accelerometer can be used to enable a variety of simultaneous features including, but not limited to:

Tilt-screen navigation
Game playing
Image stability, screen orientation
Drop force modeling for warranty protection
HDD shock protection
Theft, man-down, accident alarm
Computer pointer
Navigation, mapping
Automatic sleep mode

Theory of Operation

Kionix MEMS linear tri-axis accelerometers function on the principle of differential capacitance. Acceleration causes displacement of a silicon structure resulting in a change in capacitance. A signal-conditioning CMOS technology ASIC detects and transforms changes in capacitance into an analog output voltage, which is proportional to acceleration. These outputs can then be sent to a micro-controller for integration into various applications. For product summaries, specifications, and schematics, please refer to the Kionix MEMS accelerometer product sheets at http://www.kionix.com/sensors/accelerometer-products.html.