Introduction

This technical note is intended to provide general guidelines for characterizing noise performance of MEMS accelerometers. These guidelines are general in nature and based on recommended industry practices. The user must apply their actual experiences and development efforts to optimize designs and processes for their testing techniques. The goal of this experiment is to establish reliable estimates on the resolution of MEMS accelerometers.

Feature Description

Often customers are faced with a dilemma of selecting an appropriate sensor that can provide the precision needed for their application. Ultimately the noise floor of the sensor determines the resolution, which is dependent on bandwidth. Thus it is very important to identify inherent accuracy of the sensor and accuracy of the analog-to-digital converter. In order to properly characterize the noise of these sensors, the effective isolation of an accelerometer from external vibrations is critical. Characterizing accelerometer performance requires that noise due to mechanical and electrical external sources be separated from the noise intrinsic to the sensor.

Defining Inherent Accuracy of Sensor

The sources of accelerometer noise can be broken down into the electronic noise from the circuitry which is converting the motion into a voltage signal and the mechanical noise from the sensor itself. There are several sources of electronic noise – Johnson noise, shot noise, flicker noise, etc. – which are discussed in detail in many electronic and electrical engineering textbooks. The ASIC inside Kionix's accelerometer products has been designed to reduce these sources of noise as much as possible. The mechanical noise of the sensor comes from thermo-mechanical noise and environmental vibrational noise.

Thermo-mechanical noise (or Brownian noise) derives from the fact that MEMS accelerometers are comprised of small moving parts. These small parts are susceptible to mechanical noise resulting from molecular agitation. Fundamentally, the magnitude of the thermo-mechanical noise density ($ND_{thermo\text{-}mech}$) depends on the the resonant frequency ω, mass m, damping Q, and temperature T of the sensor.

$$ND_{thermo-mech} = \frac{\sqrt{\frac{4k_B T\omega}{mQ}}}{g} \quad \text{in units of } {}^{g}\!\big/\!\sqrt{Hz}$$

In the absence of large environmental vibrations, thermo-mechanical noise is often one of the limiting noise components of MEMS accelerometers. As with the electronic noise of the ASIC, good design practices of the sensor reduce the thermo-mechanical noise as low as possible.

Test Environment

Attention to the environment is important in order to obtain accurate noise measurements of an accelerometer. Mechanical vibration noise sources, like compressors or other machinery, operating nearby can cause inaccurate sensor noise readings. When characterizing the noise performance of a sensor at Kionix, the sensor under test is mounted on a large mass on an isolation table floating on compressed air. The isolation table is located in a room on the ground floor to minimize building vibrations. The room is temperature controlled and quiet with no heavy machinery operating near by. Rapid fluctuations in temperature could cause variations in the output that are perceived as noise. If noise measurements are being performed in a temperature chamber, it is extremely important that fans, compressors, and solenoid valves remain off while the data is being collected. For electrical isolation, the sensor under test is typically powered using a battery rather than a DC power supply. The battery provides a clean DC voltage without coupling any 60Hz noise into the system.

Analog Noise Measurements

For analog accelerometers, the output voltage measurements are made with an AC coupled oscilloscope or AC voltmeter. Readings are averaged to obtain the average RMS amplitude. This is the accelerometer RMS noise in volts. To determine the accelerometer RMS noise in g’s, divide the RMS volts by the sensitivity of the accelerometer.

Noise Density

To calculate accelerometer’s noise density, you need to know the equivalent noise bandwidth, *B*, of your system. For a first order simple RC low pass filter (which is the most common filter):

$$B = 1.57 f_{-3dB} \quad Hz$$

For other filters, the noise bandwidth will have other factors. For example, a Butterworth filter will give the following noise bandwidths:

$$B = 1.57 f_{-3dB} \quad Hz \qquad (1^{st}\ order)$$

$$B = 1.11 f_{-3dB} \quad Hz \qquad (2^{nd}\ order)$$

$$B = 1.05 f_{-3dB} \quad Hz \qquad (3^{rd}\ order)$$

$$B = 1.025 f_{-3dB} \quad Hz \qquad (4^{th}\ order)$$

Once the noise bandwidth is known, the following equation is used to calculate the noise density (*ND*) parameter of an accelerometer from the measured RMS acceleration noise (a_n):

$$ND = \frac{a_n}{\sqrt{B}}$$

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As an example, the noise density you might measure with a KXPS5-2050 with a 50Hz first order low pass filter would be:

$$ND = \frac{1.55mg_{rms}}{\sqrt{1.57(50Hz)}} = 0.175\, {}^{mg}\!/\!_{\sqrt{Hz}} = 175\, {}^{\mu g}\!/\!_{\sqrt{Hz}}$$

The noise density is a useful parameter because it allows you to quickly calculate the accelerometer noise (and resolution) for different filter designs.

Digital Noise Measurements

While performing digital measurements, one should pay special attention to Aliasing/Nyquist Theorem. Thus, sensors to be tested should be bandwidth-limited accordingly. The required sampling frequency in accordance with the Nyquist Theorem is the Nyquist frequency (f_N):

$$f_N = 2 * f_{-3dB}$$

where f_{-3dB} is the low pass filter cutoff frequency. In order to reconstruct the signal accurately, we recommend that the sampling rate be between five to ten times the low pass filter cutoff frequency. Please also note that no dynamic tests were done in this experiment in order to characterize the ADC performance. The intentions of this experiment were purely in defining input referred noise or otherwise known as code transition noise. In an ideal ADC, the input analog voltage is increased and the ADC maintains a constant output code until a transition region is reached at which point the ADC instantly jumps to the next code value and remains there until next transition region is reached. A practical ADC has a certain amount of code transition noise, and therefore a finite transition region width [1]. Input referred noise is generally characterized by examining a histogram of a number of output samples while the input to the ADC is held at a constant DC value.

To measure the input referred noise, the input to the ADC needs to be heavily decoupled (setting the low pass filter frequency 50 Hz or lower) and a large number of samples collected and plotted as a histogram (around one million conversions are more than adequate for low noise ADC). Since the noise is approximately Gaussian, the standard deviation of histogram is the RMS noise (Figure 1).

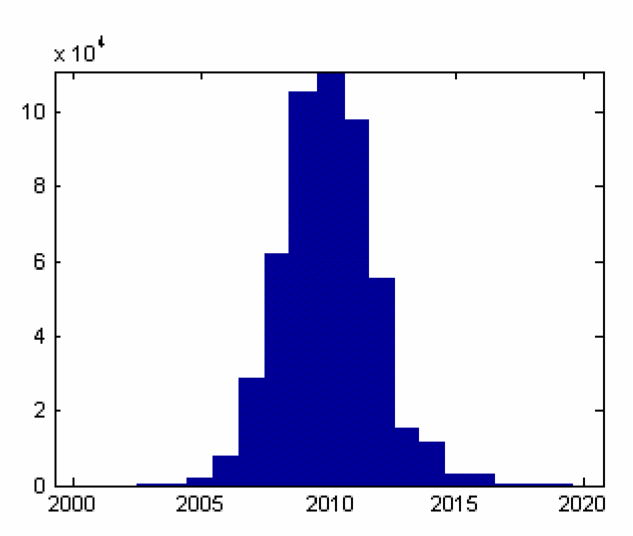

Fig 1. ADC output code

As seen in Fig. 1, there are also some inherent differential nonlinearity (DNL) associated with this ADC but for most part it is approximately Gaussian. If there is significant DNL, but the results still follow a somewhat Gaussian distribution then the standard deviation should be computed for several DC input voltage values and the results averaged. If the code distribution is significantly non-Gaussian, this could indicate a bad PC board layout, poor grounding techniques, or improper power supply decoupling.

Reducing Noise

This noise could be reduced by placing a higher order filter on the outputs or by reducing the bandwidth of the filter. Of course, one of the penalties for placing a higher order filter on the outputs is the number of external components required on the printed circuit board. One of the penalties for reducing the bandwidth is the increase in startup/response time of the outputs. Depending on the application, this may result in a sluggish response of the application to motion, resulting in a poor experience for the user.

Another technique that can be used to reduce noise is over-sampling and averaging. In most applications, digital data from the accelerometer is used in computations or in control functions. This digital data is either obtained directly from the accelerometer or after the analog data from the accelerometer is passed through an analog to digital converter (ADC). In either case, the system is acquiring accelerometer information at a particular sampling frequency. For a cell phone screen rotation application, the sampling rate may be 10 Hz while a hard drive protection application may require 1000 Hz.

Oversampling is the process of sampling a signal with a sampling frequency significantly higher than the Nyquist frequency. For example, the cell phone screen rotation may be acquiring data at a 100 Hz sampling frequency. Every 10 samples are averaged together, and that average value is reported at a 10 Hz frequency and used in the application to determine if the screen has rotated. In this way, the noise in the acceleration signal is reduced. If multiple samples (*N*) are taken of the same quantity with a random noise signal, then averaging those samples reduces the noise by a factor of $1/\sqrt{N}$.

References:
1. IEEE Std. 1241-2000. IEEE Standard for Terminology and Test Methods for Analog to Digital Converters

The Kionix Advantage

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:

Hard Disk Drive protection
Vibration analysis
Tilt screen navigation
Sports modeling
Theft, man-down, accident alarm
Image stability, screen orientation & scrolling
Computer pointer
Navigation, mapping
Game playing
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.