Noise and reliability measurement of a three-axis micro-accelerometer

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\textbf{A R T I C L E   I N F O}

Article history:
Received 29 September 2008
Received in revised form 3 December 2008
Accepted 16 December 2008
Available online 25 December 2008

Keywords:
Three-axis accelerometer
Low frequency noise measurement
Reliability

\textbf{A B S T R A C T}

A special measurement system is developed to measure the combined noise and reliability of a three-axis micro-accelerometer. Three parametric tests are provided: gravitational, thermal and acoustical. The measurements were performed on both the in-plane and the out-of-plane axes. The temperature-dependence and acceleration-dependence of the noise was found, in agreement and contrast to the theories. The device is found to be very reliable when subjected to individual tests, but exhibits slight deviations during the combined tests.

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\section{1. Introduction}

A three-axis surfaced micro-machined accelerometer is one of the latest MEMS products on the market. Major applications are for the video game systems, disc drive protections, cell phones, health care and toys. The mechanical sensor uses a single proof-mass for sensing the x-, y- and z-axes. The ultimate performance of this device is limited by the intrinsic noise within the device, mainly due to the combined effect of thermally dependent electrical and mechanical noise sources. Noise from any source limits the utility of the accelerometer in low g and high accuracy situations. Understanding and controlling the relative importance and interactions of electrical and mechanical noise are intellectually challenging problems. In addition, as a result of the rapidly decreasing cost of accelerometers over the past few years, manufacturers may be forced to sacrifice some design specifications, which will degrade their accelerometers' reliability.

Over the years, a number of research groups have modeled and characterized the noise of single axis micro-accelerometers, but none of them investigated the dependence of noise on acceleration. Yoshida et al. \cite{1} proposed a linear noise model, which does not include the thermal--mechanical characteristics in the circuit noise. They found that the simulated noise spectrum is generally matched to the measured noise from a capacitive-servo accelerometer. Kulah et al. \cite{2} presented the noise analysis of a second-order sigma–delta accelerometer intended for micro-g resolution. They identified several electrical and mechanical noise sources that affect the sensitivity of their device. Rocha et al. \cite{3} attempted to characterize directly the mechanical–thermal noise spectrum by repeatedly bringing the capacitive micro-sensor to pull-in, and measuring the pull-in time followed by fast Fourier transform (FFT). Although the mechanical–thermal white noise that was measured is in agreement with existing theory on damping and mechanical–thermal noise, they recognized the need to carry out more extensive analysis to fully validate the results. In all three groups, the accelerometer was custom-made.

Commercial micro-accelerometers are the most suitable test objects for noise and reliability studies because they are matured products that are used in many critical applications. Several commercial capacitive-sensing micro-accelerometers are available on the market, with similar performance specifications, but with different mechanical sensing element designs, materials, packaging and fabrication technologies and price ranges. Despite the variety of the employed detection schemes, every capacitive-sensing accelerometer can be modeled as a mass–spring–damper system, where the proof-mass deflects relative to its supporting frame due to the input acceleration, forming a second-order system, given by Eq. (1):

\begin{equation}
\frac{d^2x}{dt^2} + \frac{dx}{dt} + kx = ma_{\text{input}} \tag{1}
\end{equation}

where x is the displacement of the proof-mass m with respect to its frame, $a_{\text{input}}$ is the external input acceleration, k is the suspension stiffness (the spring constant) and c is the damping coefficient. In capacitive accelerometers, the deflection x of the seismic mass is detected by the change in capacitance of the parallel plates formed on the movable mass and stationary electrodes \cite{4}. Generally, differential capacitive-sensing schemes are employed in order to...
linearize the output, and to compensate drifts and interferences in the detection of the very small deflections.

In this work, we report on the special measurement system that is able to perform both the noise and reliability measurement, focusing on three different types of excitations. They are gravitational (tilting), thermal (high temperature) and acoustical (non-contact vibrational signal). A three-axis surface micro-machined accelerometer from ST Microelectronics (STM) has been chosen as the device under test (DUT). The chip contains the sensing elements and IC interface. The sensing elements that detect the acceleration of all three axes are manufactured using a dedicated process called Thick Epi-poly Layer for Microactuators and Accelerometers (THELMA) developed by STM to produce inertial sensors and actuators in silicon. The suspended silicon structures are attached to the substrate in a few points called anchors and free to move in a plane parallel to the substrate itself. When a linear acceleration is applied, the proof-mass displaces from its nominal position, causing an imbalance in the capacitive half-bridge. This imbalance is measured using charge integration in response to a voltage pulse applied to the sense capacitor. The nominal value of the capacitors, at steady state, is a few pF. When the acceleration is applied, the maximum variation of the capacitive load is few tenth of pF [5].

Based on the above description, one can conclude that there are three primary noise sources in the three-axis surface micro-machined accelerometer measurement. The first source is from the mechanical vibration of the sensing elements, the second source is from the IC interface, and the third source is from the special measurement system itself.

In addition to noise measurement, the STM accelerometer was subjected to reliability measurement in the form of accelerated testing. The concept of accelerated testing is to compress time and accelerate the failure mechanism in a reasonable test period so that the accelerometer’s reliability can be assessed. The only way to accelerate time is to stress potential failure modes. Failure occurs when the stress exceeds the device’s strength. The device’s unreliability increases with the increasing stresses and improves the chances for failure occurring in a shorter period of time. We used the most common acceleration method in accelerated testing known as overstressing. It consists of running the device at higher-than-use level of stresses. Bazu et al. [6] performed the testing by exposing the same device to the combination of mechanical stress (tilting) and thermal stress (high temperature). We have developed a more accurate and elaborate reliability setup, leveraging on the noise measurement equipment. The description of the measurement system and testing mechanisms are given in the next section.

2. Measurement and testing system

The objective of this project is to provide a combined setup to perform the noise and reliability measurement of a commercial micro-accelerometer. The main equipment is shown in Fig. 1, consists of copper enclosure and holder. The RF-shielded copper enclosure is attached to the holder to enable tilting. The PCB-mounted DUTs are placed inside the copper enclosure, with their axis of sensitivity parallel to the holder, while the holder firmly grips the copper enclosure. Tilting could generate 0g, +1g and –1g output level for any of the three axes, as shown. The steel heater plate is positioned at the bottom of the copper enclosure to provide thermal stress up to 120°C through conduction to the DUT. The piezoelectric disc placed inside the enclosure provides sinusoidal acoustic signal from 20 Hz to 20 kHz with variable amplitudes. With the above setup, the system is capable of providing three types of excitations: gravitational, thermal and acoustical, for noise and reliability measurement.

A low frequency noise measurement (LFNM) technique is employed from DC up to 100 kHz. Fig. 2 shows the noise measurement system. The system consists of: the DUT, a coupling capacitor, a shielded copper enclosure, a low noise amplifier, the spectral analyzer and a personal computer for data plotting and analysis. A battery power supply of +4.5 V in the separate RF shield was employed. The analog voltage output from the DUT was fed through the coupling capacitor to the Stanford Research SR560 low noise amplifier (LNA), capable of amplifying with the voltage gain of 10–50,000. This LNA has bandwidth from DC to 1 MHz. After that, the amplified noise voltage was fed into an analyzer. That analyzer computes the power spectrum of the noise signal and displays the results in dBm. A Hewlett Packard 35665A dynamic signal analyzer was used for the low frequency measurements from DC to 100 kHz with a noise floor of –110 dBm. The data from the analyzer were fed to the personal computer via a GPIB link for processing and analysis. MATLAB was used to plot the noise power (in dBm) versus the frequency (Hz), and for further analyses.

Two electrical parameters are used to quantify the reliability of the devices in accelerated testing, namely sensitivity (S_o) and zero-g level (V_o). Sensitivity (S_o) is the output voltage change per g unit of acceleration applied, and zero-g level (V_o) is described as the
actual output signal in steady state when there is no acceleration and also the factory-calibrated parameter. The sensitivity and zero-g level are critical to detecting small changes in the analog output signal and very significant for tilt angle applications. These analog parameters are ratiometric to the voltage supply. The sensitivity and zero-g level will increase or decrease linearly with the voltage supply. The feature provides the cancellation of the error related to the voltage supply along an analog to digital conversion chain. They are measured from the analog DC outputs of the DUT’s three axes when the DUT is subjected to the mechanical and thermal stresses similar to the work performed in [6], but with improved setup. The improvement is primarily on the precision measurement. The first is in term of the gravitational measurement (by tilting). Bazu et al. [6] use rotator to change the orientation, which is manually controlled by hand. This is imprecise, in comparison to our more elaborated setup as detailed out in Fig. 1. The second improvement is on high temperature measurement. Bazu et al. use resistive heater, which is placed on the back of the circuit board containing the accelerometer. The flow of heat from the heater to the board will not be uniform and will dissipate quickly into the air, since the circuit is not concealed. This work employs a steel plate heater located on the bottom of the copper enclosure. The heat is transferred slowly and uniformly to the inside of the sealed copper enclosure. Furthermore the temperature inside the enclosure is monitored regularly by a thermo-couple. The mechanical test stresses the micro-sensor’s capacitive beams from −1 g to +1 g for some period of times. The thermal test is capable to heat the DUT up to 120 °C. In addition, our setup also introduces the acoustical test to send an ultra-sound vibration to excite the micro-sensor’s structure. This is accomplished by using a piezoelectric disc that emits an acoustic sine signal from 20 Hz to 20 kHz with varying amplitudes, supplied by external function generator.

3. Measurement results and analysis

Figs. 3 and 4 show the noise characteristics of x-axis (in-plane) and z-axis (out-of-plane) of the STM three-axis accelerometer, respectively. All the measurements were done from DC to 100 kHz. In Fig. 3, the total noise power spectral density (referred to as PSD in this paper) at three different accelerations from the x-axis is plotted together with the noise PSD of the measurement system (referred to as setup NF in Fig. 3). One can extract four important types of information from these figures. The first is that at low frequencies the noise power spectral densities of the accelerometers at 0 g, +1 g and −1 g are much higher than the noise power spectral density of the measurement system. This clearly allows one to extract the noise characteristics of DUT from the amplifier noise in the measurement system. The second type of information comes from the observation that the noise characteristics of all three accelerations have 1/f-like noise at frequency lower than 60 kHz, and white noise at higher frequencies. The third observation is the fact that the noise PSD’s at +1 g and −1 g have similar shapes compared to the noise PSD at 0 g but with slightly lower magnitude (about 2–3 dBm in this study). The fourth observation is the spectral peak that can be seen at 66 kHz. The peak is the sampling frequency of the sample and hold circuit (S&H), that is, the oscillator inside the IC interface circuitry. It must be noted that this peak is essentially accidental, that is, it is not due to the inescapable electronic or mechanical noise mechanisms. It has no practical impact since it occurs at higher frequencies than the range where the accelerometer can be used.

The noise PSD of the z-axis at 0 g, +1 g and −1 g, are illustrated in Fig. 4. We observed that the noise PSD’s at +1 g and −1 g have similar shapes compared to the noise PSD at 0 g but with slightly higher magnitude, that is the similar shapes are in agreement, but the relative magnitudes is in contrast to the noise characteristics of the x-axis. It must also be noted that the amplitude of the z-axis’s noise PSD and the spectral peak at 66 kHz are stronger compared to the x-axis.

Most importantly, we found an acceleration-dependence of the noise in both x- and z-axes of the STM device, in contrast to the prevailing theory [7]. In general, there are five types of electrical noise sources that could be found in the IC interface circuitry. These are the thermal noise, the shot noise, the flicker noise, kT/C noise and the quantization noise. None of these electrical noise sources are acceleration dependent. In addition, the prevailing theory states that the mechanical noise is given by Eq. (2):

\[ F_{\text{mechanical noise}} = 4\sqrt{ckT} \]  

(2)

where c is the damping factor, k is the Boltzmann constant and T is the temperature. Eq. (2) states that the mechanical noise source is acceleration independent. The results obtained from this work and previous works on Analog Devices and Freescale micro-accelerometers prove otherwise [4].

The temperature dependant of noise in micro-accelerometer is also studied using the thermal test. Eq. (3) shows the well-known Johnson noise, denoted by \( V_{n} \).
\[ V_{in} = \sqrt{4kTBR} \]

where \( k \) is the Boltzmann constant, \( B \) is the measurement bandwidth, \( T \) is temperature, and \( R \) is the resistance.

Looking from Eqs. (2) and (3), the theory governing the behavior of mechanical and electrical noise in MEMS accelerometers predicts that both electrical and mechanical noise should vary as the square root of the temperature. The noise PSD of both \( x \)- and \( z \)-axes were also measured at 25 °C (room temperature) and 75 °C. Using Eq. (3), the noise PSD should increase by +0.7 dBm. The measured data shows an increment of approximately 1 dBm, which matched the calculated data for both axes.

For the reliability measurement, the gravitational, thermal and acoustical tests were first conducted separately. It is found that the \( V_{\text{off}} \) and \( S_n \) values are well within the specifications. Then, the tests are combined to check for the correlation between the three
stresses imposed on the DUT. This is done by plotting the $V_{\text{off}}$ and $S_0$ against the temperature (thermal test) and the frequency of piezo-disc (acoustical test), respectively. The former is performed at 0 g, while the latter at ±1 g (gravitational test). The plots are shown in Fig. 5. Two interesting observations were noted. First, the $V_{\text{off}}$ of both axes are somewhat unstable when subjected to different temperatures, which is due to the increasing thermal electrical and mechanical noise in the DUTs. Second, the $S_0$ is slightly unstable when subjected to different acoustic frequencies, which is due to the vibration of the silicon micro-sensors, having externally excited by the piezo-disc. The results obtained from this work show that when the DUTs are subjected to the combined tests of mechanical, thermal and acoustic stresses, the sensitivity and zero-g level show deviations from the datasheets.

Table 1 shows the summary of the data that was collected from the measurement. The noise data was collected at 2 kHz, which is within the operating bandwidth of both axes.

<table>
<thead>
<tr>
<th></th>
<th>$x$-Axis</th>
<th>$z$-Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUT peak noise PSD $^a$ at 0 g, 25 °C (dBm)</td>
<td>-77.56</td>
<td>-74.79</td>
</tr>
<tr>
<td>DUT peak noise PSD $^a$ at 0 g, 75 °C (dBm)</td>
<td>-76.51</td>
<td>-73.65</td>
</tr>
<tr>
<td>DUT peak noise PSD $^a$ at ±1 g, 25 °C (dBm)</td>
<td>-79.30</td>
<td>-72.86</td>
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<tr>
<td>DUT peak noise PSD $^a$ at ±1 g, 75 °C (dBm)</td>
<td>-78.44</td>
<td>-71.70</td>
</tr>
<tr>
<td>DUT peak noise PSD $^a$ at ±1 g, 0 °C (dBm)</td>
<td>-80.27</td>
<td>-72.45</td>
</tr>
<tr>
<td>Measurement system noise PSD (dBm)</td>
<td>-100</td>
<td>-100</td>
</tr>
<tr>
<td>Sample and sampling frequency (kHz)</td>
<td>66</td>
<td>66</td>
</tr>
<tr>
<td>Sensitivity ($S_0$) at ±2g range (V/g)</td>
<td>$V_{\text{dd}}/5 \pm 10%$</td>
<td>$V_{\text{dd}}/5 \pm 10%$</td>
</tr>
<tr>
<td>Sensitivity ($S_0$) at ±8g range (V/g)</td>
<td>$V_{\text{dd}}/15 \pm 10%$</td>
<td>$V_{\text{dd}}/15 \pm 10%$</td>
</tr>
<tr>
<td>Zero-g level ($V_{\text{dd}}$) at ±2g and ±6g (V)</td>
<td>$V_{\text{dd}}/2 \pm 18%$</td>
<td>$V_{\text{dd}}/2 \pm 18%$</td>
</tr>
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$^a$ Noise measurement at $f = 2$ kHz. The operating bandwidth for $x$-axes and $y$-axes is 4 kHz, and 2.5 kHz for the $z$-axes.

### 4. Conclusion

This work aimed to provide empirical noise and reliability data on commercially important three-axis micro-accelerometer. We designed, built and improved a combined measurement system for both purposes. The setup could provide three excitations, namely the gravitational, thermal and acoustical. The noise characteristics of STM accelerometer’s $x$-axis (in-plane) and $z$-axis (out-of-plane) are measured at three different accelerations and two different temperatures. The result supported our findings from previous works. Temperature dependent and acceleration dependent noise was found in the three-axis accelerometer, in agreement and contrast of the theories, respectively. In addition, the device is found to be very reliable when subjected to individual excitations, but exhibits slight deviations during the combined tests.

### Acknowledgement

Special thanks to ST Microelectronics Italy for providing the sample accelerometers.

### References