Thermal and Mechanical Reliability of Five COTS MEMS Accelerometers

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ABSTRACT

Micro-electro-mechanical sensor systems (MEMS Sensors) are being considered for a variety of applications in space and launch operations. These applications include health and status monitoring, environmental monitoring, automated control, repair and service. A microaccelerometer performance was characterized in detail and their failure mechanisms were identified by subjecting them to 1,000 thermal cycles under extreme temperatures (-65 to +150°C) and to 30,000 shocks at 2,000 g. In addition, several other MEMS sensors (microaccelerometers and temperature sensors) were characterized at the extremes of their temperature ranges. It consists of a 10-day test that subjected various microaccelerometers to both continuous thermal cycling between temperatures of -40 °C and +85 °C and mechanical loading. A comparison of the data from microaccelerometers of the same type and between several types will be presented. Self-test output signals and X-ray evaluation test data after completion of 182 thermal cycles will also be presented.

INTRODUCTION

MEMS Definition and Applications

Microelectromechanical systems (MEMS), also known as microsystems technology (MST) or micromachines, are integrated micro devices or systems combining electrical, mechanical, fluidic, optical, (and all physical domains) components fabricated using integrated circuit (IC) compatible batch-processing techniques and range in size from micrometers to millimeters. Miniaturization of mechanical systems promises unique opportunities for new directions in the progress of science and technology. Micromechanical devices and systems are inherently smaller, lighter, faster, and usually more precise than their macroscopic counterparts. However, the development of micromechanical systems requires appropriate fabrication technologies that enable the features such as definition of small geometries, precise dimensional control, design flexibility, interfacing with control electronics, repeatability, reliability, and high yield and low cost per device will enable the MEMS advanced technologies for the systems in the 21st century.

The majority of today's MEMS products are components or subsystems and their main emphases are on the system levels. Current devices include accelerometers, pressure, chemical, and flow sensors, micromirrors, gyroscopes, fluid pumps, and inkjet print heads. Current MEMS devices for electronic and optical applications include RF MEMS switches, optical network, and thermal sensors. Future and emerging applications include high-resolution displays, high-density data storage devices, etc. Current technology mainly addresses millimeter (mm) to micrometer (µm) level MEMS devices. Devices are being further developed in the range of submicron to nanometer scale (nano electromechanical systems, NEMS) for various applications.

Sensors and Accelerometer

Sensors and actuators are the two main categories of MEMS. Sensing systems are used for process control and measurement instrumentation. A transducer is used for both the input and the output blocks of the sensing system. The role of the input transducer is to get information or sense from the real world about the physical or chemical quantity. This is the reason why input transducers are commonly called sensors. Often the electrical signals generated by sensors are weak and have to be amplified or processed in some way. This is done by the signal processing.

For example, accelerometers are widely used for navigational and airbag deployment safety systems in automobiles. The current generation of accelerometer devices integrates electronic circuitry with a micromechanical sensor to provide self-diagnostics and digital output. It is anticipated that the next generation of devices will also incorporate the entire airbag deployment circuitry that decides whether to inflate the airbag. As the technology matures, the airbag crash sensor may be integrated one day with micromachined sensors to form a complete microsystem responsible for driver safety and vehicle stability.

A MEMS solution with lighter weight becomes attractive, if it enables a new function, provides significant cost reduction, or both. Space operations will benefit from the comparatively low mass, volume and power required by MEMS. In addition, MEMS are often simple and cheap to produce, install and operate. However, space and launch operations require extremely high reliability and trustworthiness from their systems, especially in human space exploration. MEM devices can often be deployed redundantly to decrease their reliability risk without inflicting large claims on scarce resources. In addition, most microdevices have self-test or diagnostic features as integral capabilities. The task for the systems designer is to use these characteristics (compactness, redundancy, self-test) to extend the lifetime of MEMS, while at the same time enhancing their reliability and trustworthiness.

Purpose of This Investigation

Packaging and testing of integrated circuit (IC) is well advanced because of the maturity of the IC industry, their wide applications, and availability of industrial infrastructure.[1] This is not true for MEMS with respect to packaging and testing[2]. It is more difficult to adopt standardized MEMS device packaging for wide applications, although MEMS use many similar technologies to IC packaging. Packaging of MEMS devices is more complex since in some cases it needs to provide protection from the environment while in some cases allowing access to the environment to measure or affect the desired physical or chemical parameters. Most of the silicon circuitry is sensitive to temperature, moisture, magnetic field, light, and electromagnetic interference. Microscopic mechanical moving parts of MEMS also have their unique issues. Therefore, testing MEMS packages using the same methodologies, as those for electronics packages with standard procedures might not always be possible especially when quality and reliability need to be assessed.

MEMS package reliability depends on the package type, i.e. ceramic, plastic, or metal, and the reliability of the device. The MEMS device reliability depends on its materials and wafer level processes and the sealing methods used for environmental protection. Key package reliability issues were reviewed in a previous paper and needs for understanding characterization and failure mechanisms were identified. Implementation of conventional IC reliability to determine if they could accelerate MEMS accelerometer failure was discussed in a recent paper[4]. It was found that while mechanical stresses were more effective in inducing MEMS related failures, some traditional reliability tests did accelerate MEMS-related failure.

This study utilizes conventional environmental tests in a synergistic approach to determine reliability issues associated with commercial-off-the-shelf packages. COTS accelerometers and temperature sensors were considered for evaluation in order to be able to use a large number of them, therefore generating meaningful statistical reliability data, and determining their associated risk. In addition, it is hoped that comparative performance analysis will identify aberrations or self-test signals that will serve to flag the onset of false readings or device failure. Data of this nature will be invaluable for quality assurance and risk mitigation by formulating the software to assess the veracity of signals from individual sensors and build reliable scenarios from networked systems. This paper will include a large number of test data gathered under thermal and mechanical loading for a variety of MEMS sensors.

ACCELEROMETER TYPES

Numerous packages were subjected to environmental characterization. The devices under test included accelerometers manufactured by:

- Motorola Semiconductor Products
- Analog Devices, Inc.
- Kistler Instrument Corporation

Additionally, temperature measurement devices from Analog Devices and Dallas Semiconductor were tested and used to monitor temperatures within the test chamber. The Analog Device AXDL 250 was characterized at GSFC under the NASA Electronic Parts and Packaging (NEPP)[5] program A summary of this characterization is also shown below. The other four accelerometers and temperature device characterizations were performed by the Aerospace Corporation for NASA/Johnson Space Center. They also collaborated with JPL under the NEPP program[6]. In the following, after discussion on AXDL 250, the test procedures and results of thermal and mechanical experiments for the other four accelerometers will be presented.

CHARACTERIZATION ADXL 250

Package Description

Analog Devices ADXL250 is a dual-axis, surface micromachined accelerometer rated for ± 50 g and packaged in a hermetic 14-lead surface mount Cerpack. The operating temperature range of the part is from –55 °C to +125 °C and the storage temperature range is from –65 °C to +150 °C. The part can withstand acceleration up to 2000 g.

The device is fabricated using a proprietary surface micromachining process that has been in high volume production at Analog Devices, since 1993. The two sensitive axes of the ADXL250 are orthogonal (90°) to each other and in the same plane as the silicon chip. The differential capacitor sensor consists of fixed plates (stationary polysilicon fingers) and moving plates attached to the beam (inertial mass) that shifts in response to the acceleration. Movement of the beam changes the differential capacitance, which is measured by the on-chip circuitry (the clock frequency of the capacitance meter is 1 MHz). Figures 1 provides an overview of the chip and the capacitive sensor with the close up views of the elements of the sensor including spring attachment and polysilicon finger attachment.

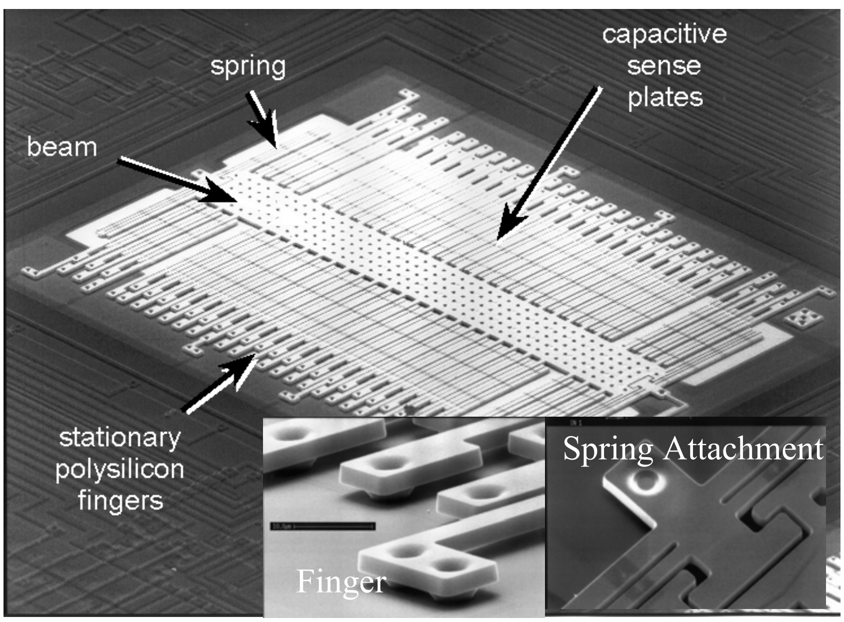


Figure 1: ADXL250 Capacitive Micromachined Accelerometer

Thermal Cycling Characterization

Temperature cycling was performed on 10 parts, in the range of –65 °C to +150 °C, with 15 minutes dwell time at each temperature. Measurements were taken after 100, 200, 400, 700, and 1000 cycles. No significant changes were observed with thermal cycling. Other electrical parameters showed a similar trend.

Mechanical Shock Behavior

Mechanical shock testing was performed on two groups of devices with ten samples in each group. The first group was subjected to 2000 g shocks in X-direction and the second group to 2000 g shocks in Z-direction. Measurements were taken after 100, 300, 1000, 3,000, 10,000, and 30,000 shocks.

Except for one sample of the first group, which failed after 10,000 shocks, all other retained their integrity to 30,000 shocks with only minor changes in their parameters.

All samples, except for the failed one, passed PIND testing. The failed part exhibited permanent noise bursts indicating presence of free particles inside the cavity.

Failure Analysis

The failed part and several good parts from different groups were decapsulated after testing and examined using optical and SEM microscopes. No microcracks or other defects, which would indicate fatigue-related damage in the sensors, were observed in any of the parts.

A site with a structural anomaly was found in the sealing glass of the failed device. This site had excessive voiding and porosity, which most likely was due to a contaminant embedded in the glass. Additionally, Electron beam induced current technique (EBIC) was used in an attempt to find any anomaly in the failed Y-channel electronic circuit as compared to the X-channel. EBIC images of the two channels were similar, suggesting that no damage to electronics had occurred.

A small particle with a size of approximately 1 μm, which most likely chipped out from the package, was found jammed between the comb fingers in the Y-channel sensor in the failed part. This particle appears to have wedged electrodes of the capacitor sensor, causing the Y output to be stuck high.

CHARACTERIZATION OF FOUR ACCELEROMETERS

Four other accelerometers were mounted on two boards as shown in Figure 2. The Motorola accelerometers on boards 1 and 2 were mounted in a 16 pin DIP sockets which were wire-wrapped to a 40-pin header socket mounted on each board. The Kistler accelerometer on each board was wired directly to the 40-pin header socket. The Analog accelerometers were packaged in 10-pin TO-100 metal Cans which were inserted into 10 pin sockets and mounted vertically on each board.

The thermal test was designed to determine the thermal stability characteristics of accelerometers at temperatures of -40 and +85°C. Accelerometers were mounted on fiberglass circuit boards and thermally cycled in a Delta Design Model 9039 environmental test chamber. This chamber has a built-in heater and is chilled using liquid nitrogen (LN2). The chamber temperature was controlled with a thermocouple and a Macintosh computer using a LabView program.

Figure 3 shows temperature data for the first two cycles that are recorded at one-minute intervals. The sawtooth pattern was programmed into the test chamber to allow ample time for temperature stabilization and equilibration at the extremes. After an initial ramp up to +85°C over a period of 10 minutes, the devices were soaked at that temperature for a period of 20 minutes.

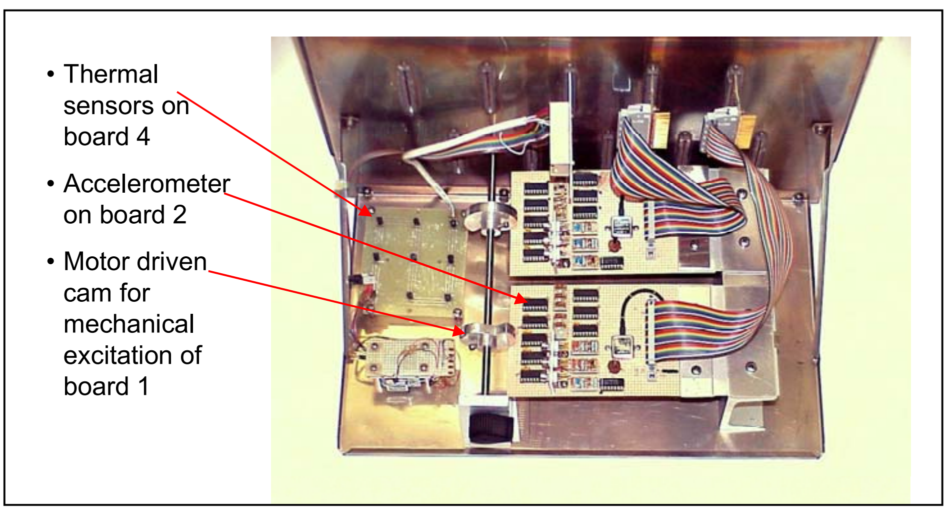


Figure 2: Thermal Cycling experimental test set up with motor driven cam for mechanical excitation

The temperature was then ramped down to -40 °C over a 20-minute period and the devices were then held at that temperature for 20-minutes. At the end of that time, the temperature was ramped up for 20-minutes to +85 °C to repeat the cycle. Each full cycle took approximately 80-minutes, divided into four 20-minute segments. This sequence continued for 10 days, 182 cycles.

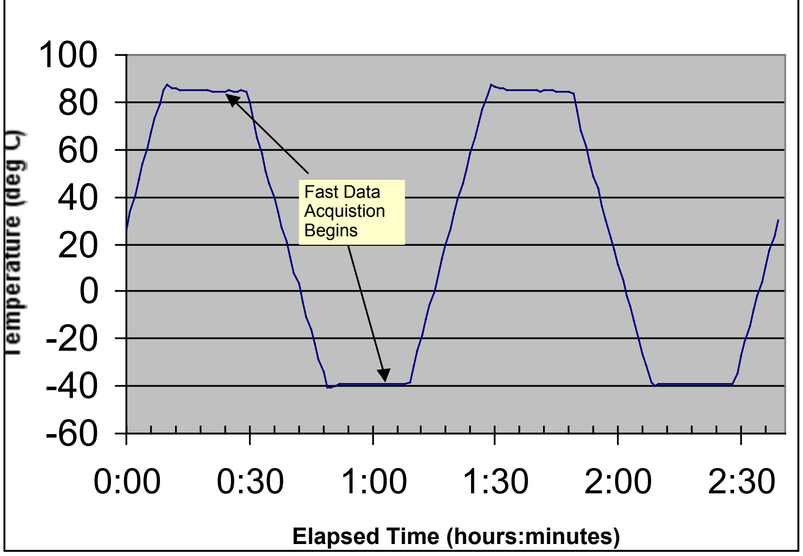


Figure 3: Thermal profile for accelerometers attached on board

Mechanical excitation was applied through the free end of fiberglass circuit boards. Boards 1 and 2 were bolted at one end to a short metal extension held in an aluminum block, which was bolted to the shelf attached to the door of the test chamber. A motor driven cam mechanism was used to periodically displace the opposite, free ends of these two boards approximately 3/4 inches in the vertical direction and then released them to freely vibrate. Upon release, the resulting board motion was that of a damped vibration of a cantilevered beam which yields alternating accelerations in the vertical direction.

The devices mounted on each of the two boards recorded these accelerations. Boards 1 and 2 were excited to motion once approximately 15 minutes into each temperature soak on every thermal cycle. The two other boards were attached directly to a shelf on the oven door and were not mechanically manipulated.

The outputs of the devices were recorded using a National Instruments AT-MIO-64F-5 data acquisition board and LabView software under Windows NT operating on a personal computer (PC) using a Pentium microprocessor. The data were stored in files on the hard drive of the computer.

Test Results

Figure 4 shows data from three different microaccelerometers recorded during the same oscillation event triggered on cycle 1 at +85°C. Due to differences in the individual sensors, the three curves appear to be different, but they have faithfully recorded similar accelerations. The Motorola XMMAS40 sensor is eight times less sensitive than the Analog Devices ADXL05J, so on this scale, the response is proportionately less. In addition, the ADXL05J appears to be out of phase with the other two sensors. The signal from the ADXL05J is inverted relative to the other two devices due to its opposite orientation on the board.

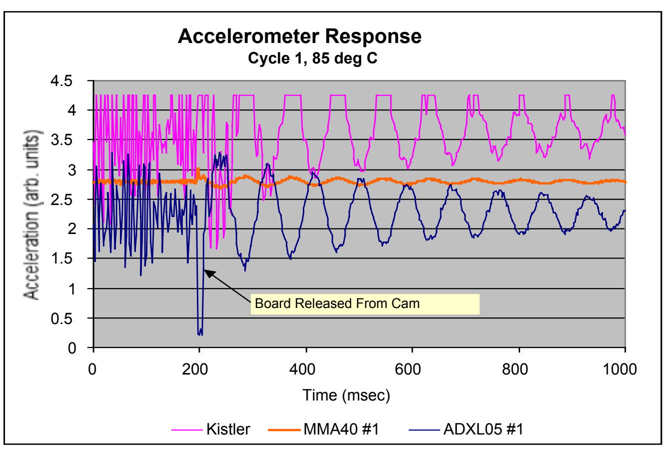


Figure 4: Range of responses for three accelerometers at hot temperature

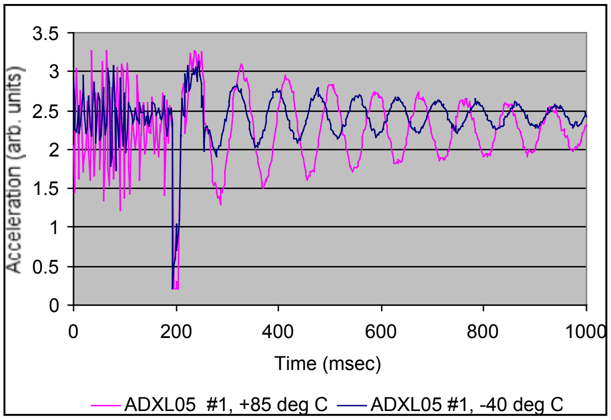


Figure 5: Responses at temperature extremes for ADXL05 Accelerometer at cycle 1

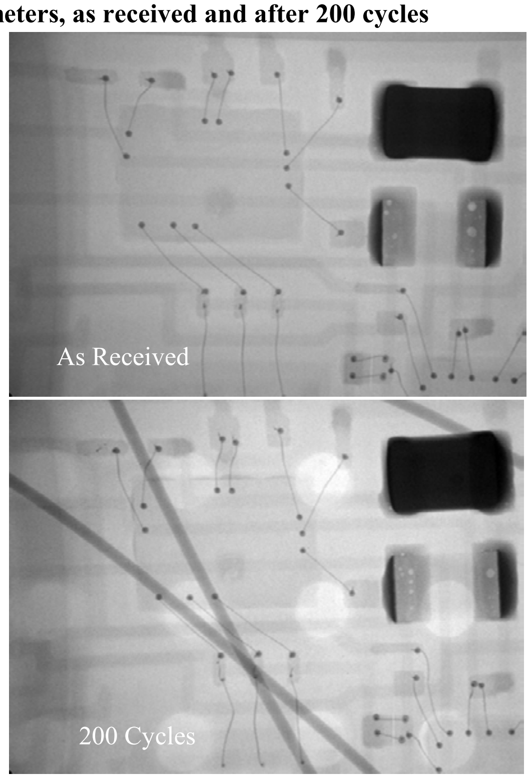
Figure 5 shows the response of the Analog Devices ADXL05J microaccelerometer to two successive events; namely the +85°C and the -40°C extremes of cycle 1. There is a delay between these two events of 40 minutes, while the temperature drops. The data at +85°C is the same as that shown for ADXL05J #1 in Figure 4.

A comparison of the two curves in Figure 5 shows behavior that can be explained by the effects of temperature variations on the aluminum hinge used to mount the board. The peak amplitudes in the acceleration are smaller and the frequency is slightly higher in the event at -40°C as compared to the one at +85°C. The frequency of an oscillating cantilevered beam is expected to increase as the square root of the bending modulus. Thus, if the modulus increases as the temperature is reduced, we would expect an increase in the frequency. This is the case for aluminum. The mechanics of our test boards are more complicated, because they are effectively compound beams of thin aluminum joined to a thick fiberglass test board. However, we expect the temperature trend to be the same and indeed observe a higher frequency at the lower temperature for every case examined.

NON DESTRUCTIVE CHARACTERIZATION BY X-RAY

Non-destructive evaluation using a real time X-ray was performed prior to and after about 182 thermal cycles to assure the quality of the packages. A representative of X-ray photos for accelerometers are shown in Figures 6. No failures or particulates that may represent gross failures were observed. After establishing such baseline, these accelerometers will be further subjected to thermomechanical exposure till failure.

Figure 6: Kistler Accelerometers, as received and after 200 cycles



CONCLUSIONS

- Analog devices ADXL250 successfully passed 1,000 thermal cycles in the range of –65°C to +150°C, as well as 30,000 mechanical shocks of 2000 g in the Z-direction and 10,000 shock in the X-direction with minor parametric changes.

- Four accelerometers: Motorola XMMAS40G, MMA1201P, Analog devices ADXL05J, Kistler 8303A1, and a temperature sensor performed within their nominal specification. They showed no degradation verified by electrical and non-destructive evaluation when subjected to 182 cycles in the range of –40°C to +85°C. This temperature regime was higher than operating temperatures of ADXL05J and 8303A1 accelerometers.

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