A CONCEPTUAL FRAMEWORK FOR THE ASSESSMENT OF THE CRITICALITY OF KEY FAILURE MODES IN MICRO-ELECTRO MECHANICAL SYSTEMS (MEMS) ACCELEROMETERS

by

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A THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in the
Department of Mechanical Engineering
in the Graduate School of
The University of Alabama

TUSCALOOSA, ALABAMA

2011

ABSTRACT

Micro-Electro Mechanical Systems (MEMS) are a fast growing field in microelectronics. MEMS are commonly used as actuators, and sensors with a wide variety of applications in health care, automotives, and the military. The MEMS production cycle can be classified as three basic steps: 1. design process, 2. manufacturing process; and 3. operating cycle. Several studies have been developed for steps 1 and 2, however, information regarding criticality analysis of operational failure modes in MEMS is lacking, and thus, the application of reliability engineering methodologies is needed. MEMS are extremely diverse, and failure modes can be unique for each device. In this study, a conceptual framework for the assessment of the criticality of key failure modes in MEMS accelerometers is proposed.

The conceptual framework establishes seven steps to perform the criticality analysis. The first step consists in the selection of the particular MEMS device and associated technical specifications. The second considers the key environmental conditions for the device's operation. The third and fourth are the selection of the failure mechanism class, and the definition of the failure mechanisms under the given environmental conditions. The fifth step deals with determining the device's common failure modes. Steps six and seven involve the development and implementation of the Failure Mode, Effect and Criticality Analysis (FMECA).

Thirteen MEMS failure modes were analyzed under three different scenarios, and the obtained results discussed. The conceptual framework was successfully completed, the results were validated, and the effectiveness of the applicability of FMECA to automotive MEMS established.

DEDICATION

This thesis is dedicated to God for giving me the spiritual strength and guiding through the challenges of creating this document. To my wife Mariorly, for her patience and love during the many difficult moments. Also, to my mom, dad, and brothers for their support and understanding.

LIST OF ABBREVIATIONS

AFM	Atomic force microscope
AHP	Analytical Hierarquical Procedure
β	Failure mode effect probability
C_m	Failure Mode Criticality Number
$\mathbf{C_r}$	Item Criticality Number
D	Detection
DLC	Diamond like Carbon
ESD	Electro Static Discharge
FIT	Failure Rate over 10^9 hours
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode Effect and Criticality Analysis
H_2O	Water
HTOL	High Temperature Operating Life
IC	Integrated Circuit
MEMS	Micro Electro Mechanical Systems
MTTF	Mean Time to Failure
MOS	Metal Oxide Semi Conductor
NASA	National Aeronautics and Space Administration
O	Occurrence

RPN	Risk Priority Number
S	Severity
STM	Scanning Tunneling-Tip Microscope
SAM	Self Assembled Monolayer
TPMS	Tire Pressure Monitoring System
α	Failure mode ratio
λ_p	The Failure Rate

ACKNOWLEDGMENTS

I am pleased to have this opportunity to thank the many colleagues, friends, and faculty members who have helped me with this research project. I am most indebted to my advisor and friend Dr. Daniel Fonseca, the chairman of this thesis, for sharing his research expertise and motivation through this process. I would also like to thank all of my committee members, Kevin Chou and Gary Moynihan for their invaluable support of both the thesis and my academic progress. I would also like to thank to Betsy Singleton for her assistance and help during this two years at UA.

This research would not have been possible without the valuable information provided by Sandia National Laboratories.

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CHAPTER 1

INTRODUCTION

Micro-Electro Mechanical Systems (MEMS) are a relatively new and fast growing field in microelectronics. MEMS are commonly used as actuators, sensors, radio frequency and microfluidic components, as well as biocomposites, with a wide variety of applications in health care, automotive and military industries. Many industry experts believe that the market for MEMS will grow to over $30B in the next 50 years (Miller et al., 1998).

The MEMS lifecycle can be divided in three basic steps: 1.) the design process, 2. the manufacturing process; and 3. the operating cycle. Several research studies have been conducted for the design and manufacturing of MEMS, however, information regarding failure analysis for MEMS can still be considered in its infancy stage (Van Spengen, 2003).

There is a need to develop new tools and methodologies to understand the behavior of MEMS devices for distinct applications and operation conditions. MEMS are extremely diverse and their failure modes can be unique under different conditions (Walraven, 2003).

1.1. Micro Electro Mechanical Systems

MEMS represent a technology that can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of micro-fabrication. Dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters (Bhushan, 2007). Likewise, the types of MEMS devices can vary from relatively simple structures having no moving elements, to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics. The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality, whether or not these elements can move (Bhushan, 2007). MEMS are manufactured using batch fabrication techniques similar to those used for integrated circuits. Unprecedented levels of functionality, reliability, and sophistication can be placed on a small silicon chip at a relatively low cost (Miller et al., 1998)

The real potential of MEMS starts to become fulfilled when these miniaturized sensors, actuators, and structures can all be merged onto a common silicon substrate along with integrated circuits (i.e., microelectronics). While the electronics are fabricated using integrated circuit (IC) process sequences (e.g., CMOS, Bipolar, or BICMOS processes), the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer, or add new structural layers, to form the mechanical and electromechanical devices. MEMS can be merged not only with microelectronics, but with other technologies such as photonics. This is sometimes called “heterogeneous integration.” Clearly, these technologies are filled with numerous commercial opportunities (Bhushan, 2007).

1.1.1 Micro Electro Mechanical Systems (MEMS) Automotive Applications

Figure 1 shows the main applications of MEMS in the automotive industry as pressure sensors, gyroscopes, accelerometers and flow sensors. With new safety government regulations, companies are forced to innovate and create new devices on a fast pace market.

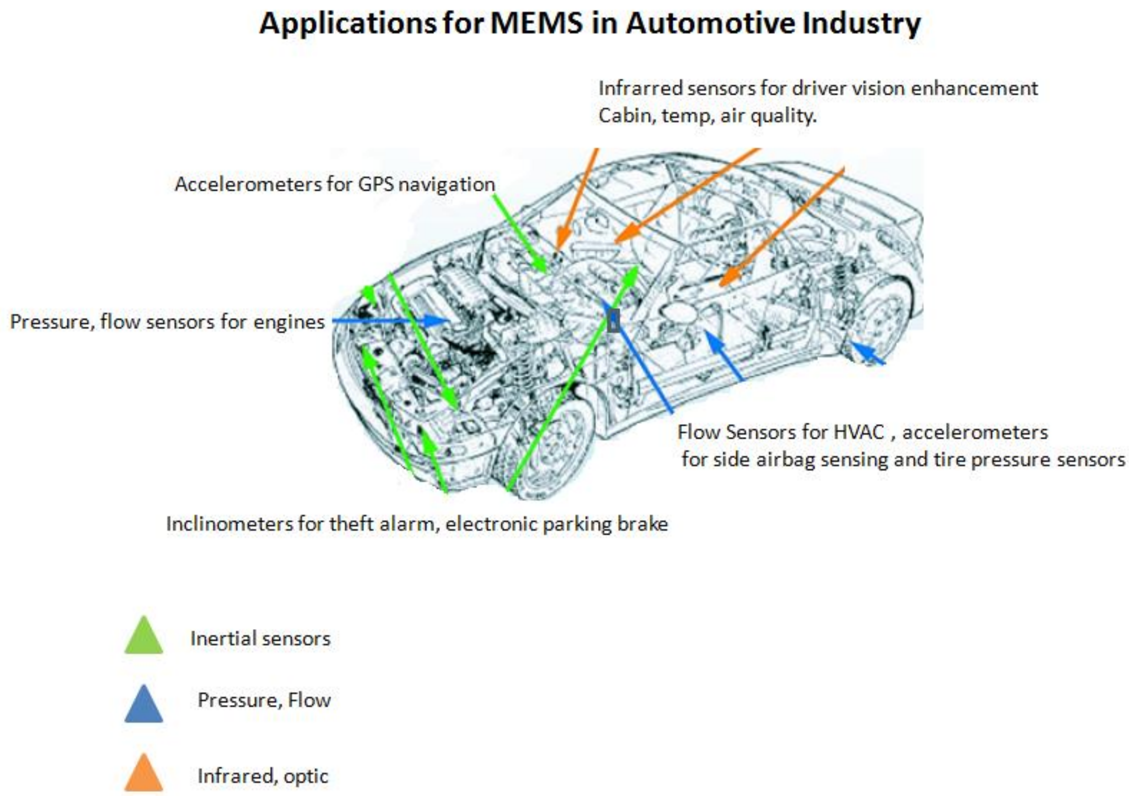

Figure 1.1: Application for MEMS in Automotive Industry

After 25 years of research, the automotive industry in the 1990's recognized the benefits of MEMS as airbag accelerometers. Early airbags required several bulky accelerometers mounted in the front of the car, with separate electronics near the airbag costing over \$50. Today, MEMS integrate all the components on a single chip at a cost of under \$10. The automotive industry was the first to introduce MEMS in high volume applications, in fact, because of their relatively low cost and good reliability, car manufacturers started using them in side impact airbags. (Eddy and Sparks, 1998)

The automotive sector currently accounts for $1.6 billion; by 2011 the market will top $2.2 billion (Dixon, 2010). It is estimated that the total number of car MEMS will grow from over 430 million units in 2006 to 780 million in 2011, an annual growth of 13 % (Dixon, 2010). Leading markets are ESP gyroscopes ($272 million), airbags ($260 million), followed by pressure with manifold air pressure (MAP) and break application pressure (BAP) (total $ 192 million), side airbags and tire pressure monitoring systems (TPMS). The market for TPMS will grow at 50% this year (Dixon, 2010). MEMS accelerometers are now used as sensors for airbag actuation in over 50 % of the new cars being built (Miller et al. 1998).

1.1.2 MEMS Device and Technical Specifications

An accelerometer is an electromechanical device that measures acceleration forces. These forces may be static, like the force of gravity pulling at our feet, or dynamic, caused by moving or vibrating the accelerometer (Andrejasic, 2008).

In 1990, MEMS revolutionized the automotive industry. Since then, MEMS have become the prime technology used for airbag deployment in vehicles. The MEMS components currently available on the market can be divided to six categories (Table 1.1):

Table 1.1
MEMS products
(Chollet et al.2008)

Product Category	**Examples**
Pressure Sensor	Manifold Pressure (MAP), tire pressure
Inertia Sensor	Accelerometers, gyroscopes
Microfluidic/Bio MEMS	Inkjet printer nozzle, DNA chips
Optical MEMS	Micro-grating array for projection
RF MEMS	High Q- Inductor, switches, antenna, filter
Others	Relays, microphone, data storage, toys

MEMS accelerometers are a highly enabling technology, they provide lower power, compact and robust sensing. Also, they can be used for several applications in the automotive industry. MEMS design and technical specifications depend on the type of application, e.*g*., (vibration monitoring, vehicle collision sensing and shock detection). Table 1.2 shows the technical specifications for a commonly used accelerometer in the automotive industry.

Table 1.2
Accelerometers Technical Specifications

ANALOG DEVICES AUTOMOTIVE ACCELEROMETER	
Supply Voltage	-0.3 V to +21V
Operating Temperature Range	-40°C to 125°C
Storage Temperature Range	-55°C to 150°C
Sensor Range	+-50 *g* to +- 500 *g*
Mechanical Shock	Unpowered: +- 4000 *g* Powered: +- 2000 *g*
Package	5 x 5 mm
Drop Test	1.2m

For this specific device, stresses above those listed in Table 1.2 may cause permanent damage or affect device reliability. This accelerometer was also considered for this investigation, and its capabilities are analyzed more in depth in Chapter 4.

1.1.3 MEMS in the Automotive Environment

A MEMS accelerometer requires interaction with the environment to perform their mission. Automotive environment and surroundings are very aggressive for MEMS, and thus, they require special attention. Standardized testing of automotive MEMS components is partially covered in the Society of Automotive Engineers and the military via SAE J1221, SAE J575G and Military Standard 750. These standards detail accelerating testing such as high and low temperature storage, temperature cycling, and thermal shock (Eddy and Sparks, 1998).

The Automotive industry requires accelerometers lifetime from five to ten years, or 100,000 to 150,000 miles on desert, tropical, or arctic locations. Also, for commercial trucks components, it is required ten years or 1 million miles of free problem use (Eddy and Sparks, 1998). In Table 1.3, the standard automotive environment conditions for MEMS are presented:

Table 1.3
Automotive MEMS Environment
(Eddy and Sparks, 1998)

Temperature:	-40 °C to 85 °C driver interior, 125 °C under the hood, 150 °C on the engine,200-600°C in the exhaust and combustion areas.
Mechanical Shock:	3000 g During assembly (Drop Test), 50-500G on the vehicle.
Vibration:	15g, 100hz to 2khz.
Electromagnetic Impulses:	100 to 200 Volts/meter.
Exposure to:	Humidity, salt spray, in some applications fuel, oil, brake fluid, transmission fluid, ethylene, glycol, freon or exhaust gases.

In this investigation, the conditions depicted in Table 1.3 were considered for analysis of the MEMS accelerometer failure mechanisms and failure modes.

1.1.4 MEMS and Nanotechnology

Nanotechnology is the ability to manipulate matter at the atomic or molecular level to make something useful at the nano-dimensional scale (Bhushan, 2007). Basically, there are two approaches in its implementation: the top-down and the bottom-up. In the top-down approach, devices and structures are made using many of the same techniques as used in MEMS, except that they are made smaller in size, usually, by employing more advanced photolithography and etching methods. The bottom-up approach typically involves deposition, growing, or self-assembly technologies. The advantages of nano-dimensional devices over MEMS involve benefits mostly derived from the scaling laws, which can also present some challenges as well (Bhushan, 2007).

Some experts believe that nanotechnology promises to: 1. place essentially every atom or molecule in the place and position desired – that is, exact positional control for assembly, 2. make almost any structure or material consistent with the laws of physics that can be specified at the atomic or molecular level; and 3. keep manufacturing costs not greatly exceeding the cost of the required raw materials and energy used in fabrication (i.e., massive parallelism) (Pan, 1999).

Although MEMS and nanotechnology are sometimes cited as separate and distinct technologies, in reality the distinction between the two is not so clear. In fact, these two technologies are highly dependent on one another. The well-known scanning tunneling-tip microscope (STM) which is used to detect individual atoms and molecules on the nanometer scale is a MEMS device. Similarly, the atomic force microscope (AFM) which is used to manipulate the placement and position of individual atoms and molecules on the surface of a substrate is also a MEMS device. In fact, a variety of MEMS technologies are needed as interfaces in the nano-scale domain (Pan, 1999).

Likewise, many MEMS technologies are becoming dependent on nanotechnologies for successful new products. For example, the crash airbag accelerometers that are manufactured using MEMS can have their long-term reliability degraded due to dynamic in-use stiction effects between the proof mass and the substrate. A nanotechnology called Self-Assembled Monolayers (SAM) coatings are now routinely used to treat the surfaces of the moving MEMS elements, so as to prevent stiction effects from occurring. (Bhushan, 2007).

Many experts have concluded that MEMS and nanotechnology are two different labels for what is essentially a technology encompassing highly miniaturized things that cannot be seen with the human eye. A similar broad definition exists in the integrated circuits domain which is frequently referred to as microelectronics technology, even though state-of-the-art IC technologies typically have devices with dimensions of tens of nanometers. Whether or not MEMS and nanotechnology are one in the same, it is unquestioned that there are overwhelming mutual dependencies between these two technologies that will only increase in time. Perhaps, what is most important are the common benefits afforded by these technologies, including: increased information capabilities; miniaturization of systems; new materials resulting from new science at miniature dimensional scales; and increased functionality and autonomy for systems (Bhushan, 2007).

1.2 MEMS Reliability

Reliability for MEMS devices is identified as the next manufacturers challenge for the forthcoming years due to a growing market and stricter government safety regulations. It is necessary to understand several variables to have an approach of their behavior and functionality. Very high levels of reliability are required in most industrial applications, such as automotive.

For example, the automotive industry is now focused on failure rates lower than 10 FIT. 1FIT is the usual unit corresponding to a proven failure over 10^9 hours (Van Spengen, 2003). In this context, several steps must be developed to understand internal variables (i.e technologies related) and external variables (i.e. environment and operation conditions).

In automotive applications, MEMS reliability analysis is extremely important to identify and understand the different failure mechanisms that can be implicit such as mechanical, thermal and chemical aspects related to the diversity of materials that can be used. Recent studies expect airbag penetration to increase from 40 to 60 million vehicles over the next five years (i.e. 80% of cars worldwide) (Eddy and Sparks, 1998).

1.3 Research Scope and Objectives

In this study, a conceptual framework for the assessment of the key failure modes in MEMS is proposed, using a specific type of automotive accelerometers devices as application domain. Thus, the objectives of this study are:

1. Develop a conceptual framework for MEMS based on the failure mode, effect and criticality analysis (FMECA).
2. Identify and select a set of MEMS accelerometer devices used in the automotive industry.
3. Identify the critical variables and associated failure mechanisms for the selected devices.
4. Construct a data base with the most relevant failure modes for the chosen MEMS accelerometers devices.

5. Apply the developed conceptual framework procedure to assess the criticality of the MEMS devices.

CHAPTER 2

LITERATURE SEARCH

This section provides an overview of relevant available literature on failure mechanisms, failure modes and reliability assessment for MEMS. Computer searches revealed a considerable number of scholarly papers on different issues regarding MEMS accelerometers and their applications. The search engines used during this literature review belong to world leading publishers such as Elsevier, IEEE and SPIE digital libraries. Also Sandia National Laboratories and JPL/NASA reports were assessed during this research.

2.1 MEMS Accelerometer Device and Applications

The Springer Handbook of Nanotechnology 2007 states that MEMS have played key roles in many important areas such as transportation, communication, automated manufacturing, environmental monitoring, health care, defense systems and a wide range of consumer products. For this reason, MEMS offers attractive characteristics such as reduced size, weight and power dissipation as well as improved speed and precision compared to their macroscopic counterparts.

Bhushan (2007) defined MEMS accelerometers as a proof of mass suspended by compliant mechanical suspensions anchored to a fixed frame. In accelerometers, an external acceleration displaces the support frame relative to the proof mass, the result is an internal stress change in the suspension, which can be detected by piezoresistive sensors as a measure of the external acceleration.

Figure 2 shows the sensor structures for vertical devices. Bhushan (2007) explained that in vertical devices, the proof mass is suspended above the substrate electrode by a small gap typically on the order of a micrometer, forming a parallel-plate sense capacitance. The proof mass moves in the direction perpendicular to the substrate (*z*-axis) upon a vertical input acceleration, changing the gap and hence the capacitance value.

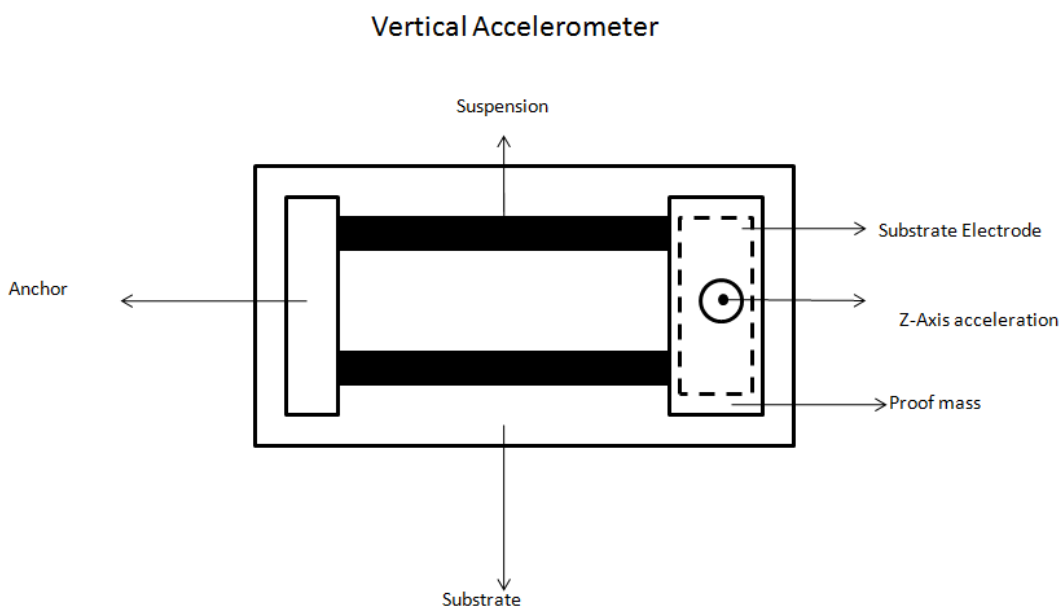

Figure 2.1: Vertical Accelerometer

Figure 3 shows the lateral accelerometer structure with a number of movable fingers attached to the proof mass that forms a sense capacitance with a group of fixed parallel fingers. The proof mass moves in a plane parallel to the substrate when subjected to a lateral input acceleration, thus changing the overlap area of these fingers and finally the capacitance value. In other words, this device detects a negative acceleration to determine when a crash has occurred and deploying airbags at the right moment. It is considered the automotive industry standard for air-bags deployment systems.

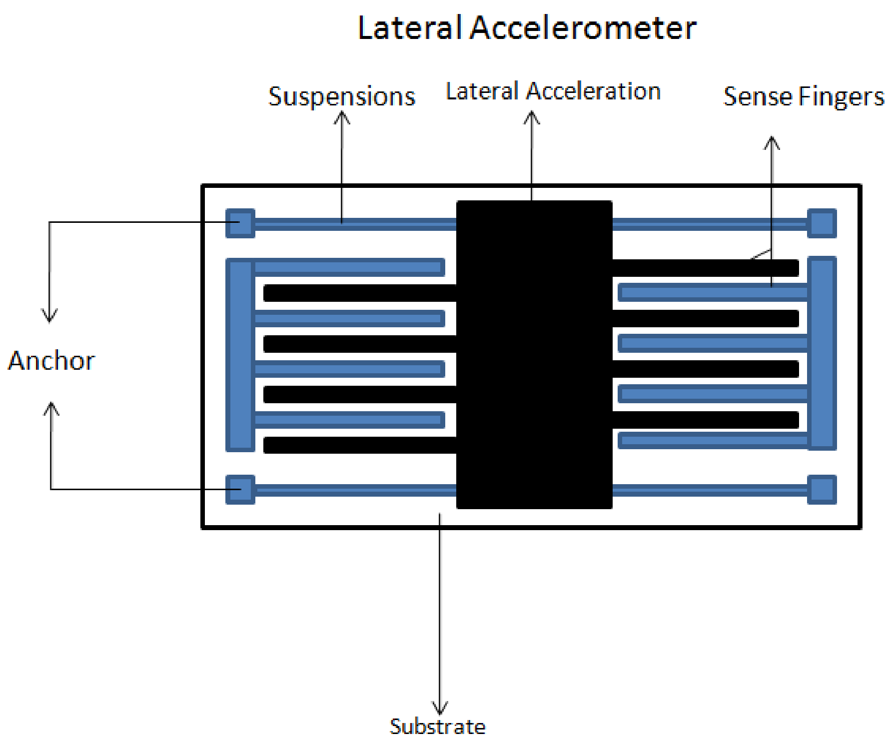

Figure 2.2: Lateral Accelerometer

MEMS accelerometers are used in automotive industry for frontal and side impact detection associated with the air-bag deployment. Also, accelerometers are being used in emerging applications such as sensors for roll-over, vehicle dynamics control, navigation, and tire pressure monitoring (Monk, 2002). MEMS accelerometers are also being incorporated in personal electronic devices such as media players and gaming devices. Specifically in smartphones for interface control and orientation in camera systems (Andrejasic, 2008).

2.2 Historical Background of MEMS Reliability

Several studies have been conducted regarding MEMS reliability due to their increasing high volume of industrial applications and growing markets. Ohring (1998) defines reliability as the sum of all characteristics of a device concerning its ability to achieve specified requirements under well defined conditions over a given period of time. A similar approach was described by Miller et al. (1998) who defined three prerequisites for a valid reliability assessment: 1. statistical significance, 2. a technique for accelerating fundamental failure mechanisms; and 3. a valid physical model to allow prediction of failure during actual use.

Considering the rapid evolution of MEMS technology, Delak et al. (1999) described a detailed analysis of testing for accelerometers using different techniques such as high temperature operating life (HTOL), high temperature storage, temperature cycle, thermal shock, mechanical drop and random drop. This kind of testing encouraged MEMS manufacturers to show extensive information on their websites regarding reliability product data and testing techniques. In this context, Lee et al. (1996) studied the critical issues of MEMS in four categories: functional interfaces, reliability, modeling, and integration. They conducted burn-ins, and accelerated tests to ensure the production of a reliable MEMS device.

Arney (2001) described a design for reliability plan to accelerate the time to time to market of emerging MEMS utilizing an interdependent relationship, and a tight feedback loop between all contributors to device, subsystem, and system design, fabrication, manufacturing and testing, reliability physics and packaging. A similar analysis was developed by Muller et al. (2001) that defined reliability as a constituent of quality and describes the changing of quality over the time. Muller (2001) also defined a methodical approach to increase reliability in early stages of MEMS development and established that the major parameter to quantify the reliability of a device and to give a numerical definition is the mean time to failure (MTTF).

Van Spengen (2003) examined the available literature regarding MEMS reliability. In his work, generic MEMS elements are clearly identified as well as their failure mechanisms with brief explanations. In a similar context, Walraven (2003) discussed the future challenges for MEMS failure analysis; he classified the MEMS into six distinct categories: 1. sensors; 2. actuators; 3. radio frequency MEMS; 4. optical MEMS; 5. microfluidic MEMS; and 6. bio MEMS. The author discussed several analysis techniques to be developed to assess the failures mechanisms.

In other empirical studies, Norman et al. (2004) evaluated the reliability of defect-tolerant architectures for nanotechnology with probabilistic model checking. Keller et al. (2005) also expressed concern in their investigation for the need of developing new measurement techniques for reliability in MEMS and the need for new reliability concepts with fully nano- mechanical approaches.

Bhaduri et al. (2006) proposed a probabilistic model checking-based methodology to automate the reliability analysis of MUX architectures. This investigation also quantified probabilistically fault models and provided a quick reliability evaluation for multiplexing architectures. Zha (2006) developed a web enabled database system for the design and manufacturing of micro-electro mechanical systems (MEMS) which can provide the networked design and manufacturing services over the internet.

Otieno et al. (2009) proposed a reliability degradation model of transistor gates to examine their feasibility at a nanoscale. A methodology of statistical reliability analysis is also discussed for high k dielectric material. This investigation emphasizes the lack of techniques to measure parameters to determine reliability under different failure mechanisms.

2.3 Failure Mechanisms and Failure Modes in MEMS

One of the most critical points in developing a reliability analysis is to understand the way in which a system can fail, or commonly known as its "root cause". For that reason, a failure mode is defined as the apparent failure on a system, and the failure mechanism as the physical cause (mechanical, chemical or thermal) of the failure modes in the system. Bhushan (2007) emphasized that we have to start with a clear distinction between failure modes and failure mechanisms in MEMS. In this approach, Beegle et al. (1999) developed a MEMS accelerometer test lab. Descriptions and usage of the equipment were presented and data of their analysis were described.

Similar investigations were developed by Tanner et al. (1999) by evaluating the effect of humidity, vibrations and shock environments in micro-electro mechanical systems. Also, failure mechanisms and failure modes for each condition were discussed as well as analytical data used in the experiments. Moreover, Vallett (2002) introduced state-of-the-art microelectronic failure analysis processes, instrumentation, and principles. The major limitations, and future prospects determined from industry roadmaps were discussed by the author.

Walraven (2003) emphasized the significant success in MEMS products from a reliability perspective and categorized the following taxonomy groups to address their reliability concerns:

- Class I- No moving parts (pressure sensors and microphones)
- Class II- Moving parts, no rubbing or impacting surfaces (gyroscopes, accelerometers and RF oscillators)
- Class III- Moving parts with impacting surfaces.
- Class IV- Moving parts with impacting and rubber surfaces

In addition, Walraven (2003) briefly stated that some failure mechanisms described earlier would affect a MEMS device regardless of its class. Failures due to stiction and particle contamination have been shown to cause failure in all 4 classes of devices. Other investigators used Walraven (2003) taxonomy groups classification such as Tanner (2009) who also concluded that these classes typically share failure mechanisms and increase complexity.

Materials can be considered critical for their behavior under extreme conditions such as high temperatures, humidity, vibration etc. Sharpe (2006) identifies three general categories for mechanical properties analysis of MEMS: 1. Elasticity from an applied force or vice versa; 2. inelastic device behavior; and 3. materials strength to set operating limits. Results of measurements of metals mechanical properties used in MEMS as well as references on materials and tests of interest were discussed. Additionally, specific data on important material such as

DLC (Diamond-Like-Carbon), nickel and nickel-iron, and polysilicon properties were analyzed in deep.

Several studies have been conducted to understand MEMS failures depending on the material composition, especially in silicon, which is commonly used for MEMS. Shea (2006) discussed MEMS failure mechanisms and failure modes for space applications. Also, he explained reliability concerns under special environmental conditions such as radiation, vacuum, and thermal-vibration shocks. Ritchie et al. (2004) examined the premature fatigue failure of silicon-based micron-scale structures for MEMS, and the fracture properties of mineralized tissue, specifically human bone. Fitzgerald et al. (2009) described and validated a general methodology to predict the reliability of Single–Crystal Silicon MEMS devices. This methodology used experimental data generated from fracture testing specimens combined with finite element modeling to predict the fracture probability for any MEMS device under any loading.

Pomeroy et al. (2008) developed a dynamic-stress analysis method, based on time resolved micro Raman spectroscopy, for reliability studies of micro electromechanical systems. Also, Jadaan et al. (2003) designed a probabilistic Weibull methodology to understand the behavior and mechanical properties of MEMS brittle materials. This investigation concluded that a Weibull probabilistic method is applicable at the MEMS scale size, and that is provides significant prediction data of their short and long term behavior.

Starman Jr et al. (2000) investigated the measurement of residual and induced stress in a MEMS micromirror flexure utilizing micro-Raman spectroscopy. This investigation showed that micro-Raman spectroscopy can be used as an effective measurement technique to determine local and induced stress values in MEMS devices. Schwalke et al. (2001) investigated the breakdown of extra thick gate oxides (50–150 nm) used in power MOS device. Weibull probability plots were used to describe the failure distribution of the thick gate oxides. Luo et al. (2003) examined some fundamental reliability aspects of high- film through ramp voltage stress testing.

By studying dielectric relaxation, and analyzing the transient conductivity, breakdown modes of the tested high- film were identified; a sensitive method of breakdown detection in ramped voltage tests was then proposed.

Accelerated testing has also been used to determine materials properties and measure reliability. Brown et al. (1997) developed a resonant fatigue accelerated testing to demonstrate a failure mode that was previously unknown. Their work indicated that moisture can decrease the lifetime of ciclicly stressed polysilicon components.

2.4 Criticality Schemes

It is a well-known fact that neglecting reliability in early conception and design of MEMS results catastrophical later on the product lifecycle. Traditional failure methodologies for macro systems cannot be transferred directly to the micro and nanoscale. However, a good understanding of failure mechanisms and environmental conditions interactions can be helpful to apply techniques such as failure mode and effect analysis (FMEA), and analytical hierarchical procedure (AHP) in order to identify root causes and to apply corrective actions through all stages. Critically levels can be identified in operation conditions as well. Numerous studies have been conducted for the mentioned methodologies in macro systems applications. Price (1995) described how an existing tool for automating electrical design failure mode and effects analysis (FMEA) can be augmented to make incremental design FMEA much less of a burden for the engineer. The tool is able to generate the effects for each failure mode and to assign significance values to the effects.

Eubanks et al. (1996) presented a method for developing a device behavior model to enhance reliability at the early stages of conceptual design. The model facilitates a semi-automated advanced failure modes and effects analysis. The model performs analyses and simulations of device behavior, reasons about conditions that depart from desired behaviors, and analyzes the results of those departures. The proposed method rigorously specifies pre- and post-conditions, yet it is flexible in the syntax of device operation. The paper shows how the method can capture failures normally missed by existing FMEA methods.

Kmenta et al. (1998) proposed a systematic method applicable at the early stages of design to enhance life-cycle quality of ownership: Advanced Failure Modes and Effect Analysis (AFMEA). The proposed method uses behavior modeling to simulate device operations and helps identify failure and customer dissatisfaction modes beyond component failures. The investigation also showed how Advanced FMEA applies readily to the early stages of design and captures failure modes normally missed by conventional FMEA.

Kimura et al. (2002) proposed a computer aided FMEA, discussing its theoretical basis. An extended product model is introduced, where possible machine failure information is added to describe used machine status. Generic behaviour simulation to extended product models to detect abnormal or mal-behaviour of machines under used conditions were developed. For validating the proposed computer-aided FMEA method, several experiments were performed for mechatronics products.

Fonseca and Knapp (2000) developed a framework for the implementation of Reliability Centered Maintenance in the initial design phase of industrial chemical using AHP and Likelihood Index. Grandzol (2005) developed an Analytic Hierarchy Process for Faculty Selection in Higher Education. Also, Frei et al (1999) presented a methodology that combines tournament ranking and AHP approaches to create a ranking scheme that deals explicitly with missing data and ties in the tournament scheme. Kumar (2003) implemented an analytic hierarchy process to analyze the risk of operating cross-country petroleum pipelines in India.

2.5 Literature Search Summary

All the previously discussed studies are focused on the need for assessment and analysis through the design, fabrication, and testing of MEMS. Accelerated testing is the method of choice to determine MEMS reliability, and to understand their behavior under different applications. However, there have been no exhaustive studies of using a quantitative/qualitative methodology such as failure mode effect and criticality analysis (FMECA) in MEMS.

The transfer of these methodologies commonly used in macro-systems into micro-systems environments represents a great challenge. However, the flexibility of these tools and availability of reliability data for MEMS represent the key for the development of a procedure to priorizate failure modes in MEMS devices. This study has as a main goal to undertake such an endeavor.

CHAPTER 3

RESEARCH SCOPE AND METHODOLOGY

In this study, a conceptual framework was developed for the assessment of the criticality of key failure modes in MEMS. To accomplish this, MEMS accelerometers used in the automotive industry were evaluated. The conceptual framework was established as a step by step methodology as follows:

1. Select MEMS device and technical specifications.
2. Set MEMS environmental conditions under operation.
3. Select the failure mechanism class as proposed by Walraven (2003).
4. Define general failure mechanisms for the given environmental conditions.
5. Determine the common failure modes in the selected class and create a database.
6. Identify the analysis to be performed: i.e., quantitative/qualitative Failure Mode, Effect and Criticality Analysis (FMECA) analysis.
7. Apply the FMECA methodologies to priorizate MEMS failure modes.

In order to develop this conceptual framework, a well-known methodology such as Failure Mode, Effect and Criticality Analysis, commonly used in macro-systems, was adapted to micro-systems environments by following the above methodology.

3.1 MEMS Failure Mechanisms and Failure Modes

A critical part of understanding the reliability of any system comes from understanding the possible ways in which the system may fail. In MEMS, there are several failure mechanisms that have been found to be the primary sources of failure within devices (Stark, 1999).

3.1.1 Mechanical Fracture

Mechanical fracture is defined as the breaking of a uniform material into two separate sections. In MEMS, it usually leads to the catastrophic failure of the device, although there are some structures that may have moderate performance degradations. No matter what the actual outcome, any fracturing is a serious reliability concern (Figure 3.1) (Stark, 1999).

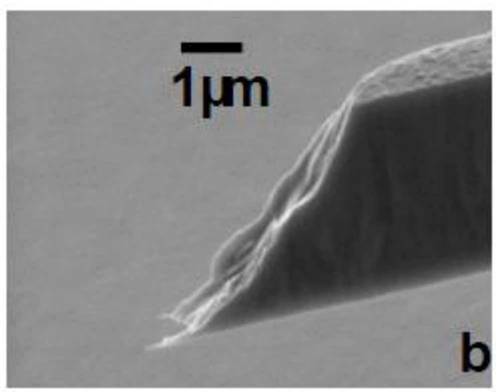

Figure 3.1
Surface Fracture
(Courtesy of Sandia National Laboratories)

There are three types of fractures: ductile, brittle, and intercrystalline fractures. Ductile fracture, as the name implies, occurs in ductile materials. It is characterized by almost uninterrupted plastic deformation of a material. It is usually signified by the necking, or extreme thinning, of a material at one specific point. Brittle fracture occurs along crystal planes and develops rapidly with little deformation. Intercrystalline fracture is a brittle fracture that occurs along grain boundaries in polycrystalline materials, often beginning at a point where impurities or precipitates accumulate. For MEMS, the latter two types of fracture are more common (Stark, 1999). The stress levels that most accelerometer devices are subjected to are far lower than the breaking strength of the material used to build the mechanical structure (Delak et al. 1999).

3.1.2 Stiction

Stiction is considered one of the most important problems in MEMS. Internal MEMS structures are so small that surface forces cause microscopic structures to stick together when their surfaces come into contact (see Figure 3.2). The most important surfaces forces are: forces due to capillary condensation, van der Waals molecular forces, and chemical and hydrogen bonds between the surfaces. Surfaces tend to stick together when they are dried after the release etch (Bhushan, 2007).

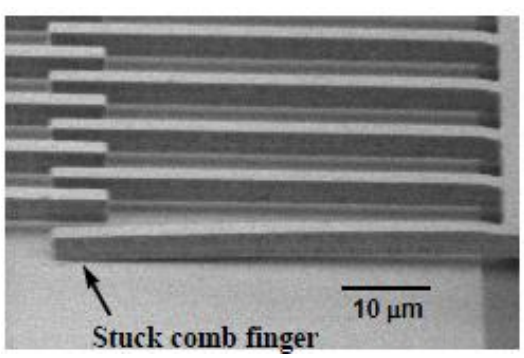

Figure 3.2
Stiction in MEMS Fingers
(Courtesy of Sandia National Laboratories)

3.1.3 Wear

Wear is caused by the motion of one surface over another. It is defined as the removal of material from a solid surface as the result of mechanical action (DiBenedetto, 1967). Wear is generally considered an undesirable effect in MEMS. There are four main processes that cause wear, those are: adhesion, abrasion, corrosion, and surface fatigue (Stark, 1999). Figure 3.3 shows the wear debris on the surface of a microengine operated to 600,000 cycles (courtesy of Sandia National Laboratories).

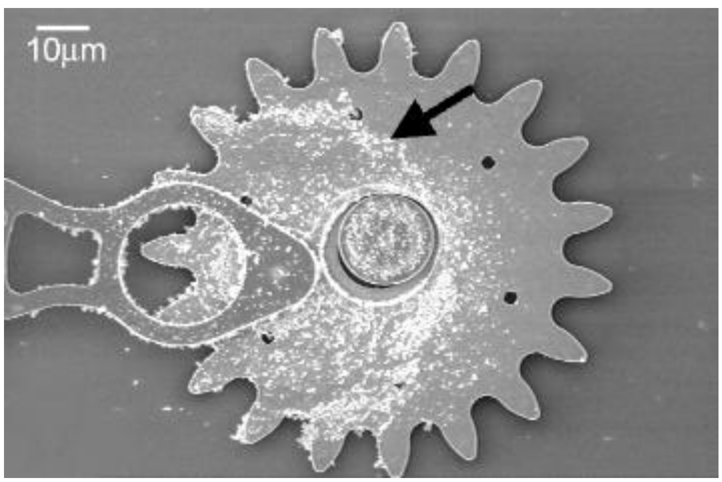

Figure 3.3
Wear Debris in Microengine
(Courtesy of Sandia National Laboratories)

Adhesive wear is caused by one surface pulling fragments off of another surface while they are sliding. This is caused by surface forces bonding two materials together. When the bonds break, they are unlikely to separate at the original interface, which fractures one of the materials. Initial studies on the long-term effects of adhesive wear have been completed, with some interesting results being discovered (Stark, 1999).

Abrasive wear occurs when a hard, rough surface slides on top of a softer surface and strips away underlying material. While less prevalent in MEMS than adhesive wear, it can occur if particulates get caught in microgears and can tear apart a surface. Corrosive wear occurs when two surfaces chemically interact with one another and the sliding process strips away one of the reaction products. This type of wear could cause failure in chemically active MEMS. Certain types of microfluidic systems and biological MEMS are susceptible to corrosive wear. Corrosive wear is dependent upon the chemical reactions involved (Stark, 1999).

Surface fatigue wear occurs mostly in rolling applications, such as bearings and gears. It affects highly polished surfaces that roll instead of sliding. Over time, the continued stressing and unstressing of the material under the roller will cause the appearance of fatigue cracks. These cracks then propagate parallel to the surface of a structure, causing material to flake off the surface. Surface fatigue wear tends to generate much larger particles than other wear mechanisms, with flakes as large as 100 nm being common in macroscopic applications (DiBenedetto, 1967). Figure 3.4 shows a surface wear in a drive gear.

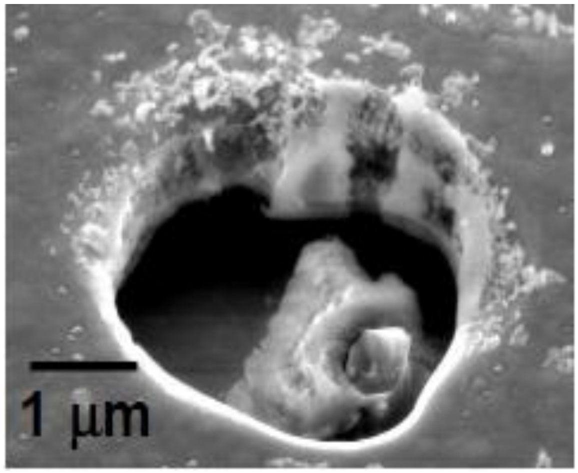

Figure 3.4
Surface Wear in a Drive Gears
(Courtesy of Sandia National Laboratories)

3.1.4 Delamination

A delamination condition occurs when a material interface loses its adhesive bond. It can be induced by a number of means, from mask misalignments to particulates on the wafer during processing. It can also arise as the result of fatigue induced by the long term cycling of structures with mismatched coefficients of thermal expansion. No matter what the actual cause, the effects of delamination can be catastrophic. If the material is still present on the device, it can cause shorting or mechanical impedance (Stark, 1999).

3.1.5 Vibration and Shocks

Vibration is a large reliability concern in MEMS. Due to the sensitivity and fragile nature of many MEMS, external vibrations can have disastrous implications.

Either through inducing surface adhesion or through fracturing device support structures, external vibration can cause failure. Long-term vibration can also contribute to fatigue (Walraven, 2003). In contrast, shocks differ from vibration in that a shock is a single mechanical impact instead of a rhythmic event. A shock creates a direct transfer of mechanical energy across the device. Shocks can lead to both adhesion and fracture. Shocks can also cause wire bond shearing, a failure mode common to all semiconductor devices (Bhushan, 2007).

3.1.6 Electrostatic Discharge and Dielectric Charging

Electrostatic discharge, or ESD, occurs when a device is improperly handled. A human body routinely develops an electric potential in excess of 1,000V. Upon contacting an electronic device, this build-up will discharge, which will create a large potential difference across the device. The effect is known to have catastrophic effects in circuits and could have similar effects in MEMS. While the effects of ESD on MEMS structures have not been published to date, it can be assumed that certain electrostatically actuated devices will be susceptible to ESD damage (Stark, 1999).

Figure 3.5 shows a typical ESD/EOS damage input protection circuitry and the catastrophic effect on the device (Walraven, 2003).

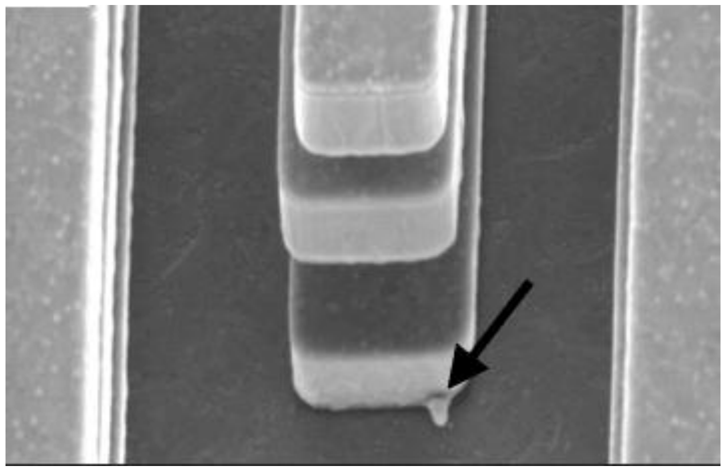

Figure 3.5
ESD Failure in Electrostatic Actuator
(Courtesy of Sandia National Laboratories)

Dielectric charging and breakdown is the charging that may occur in the dielectric layer. Sensors are known to drift over time due to charge accumulating at the surface (Stark, 1999).

3.1.7 Radiation Effects

The field of radiation effects on MEMS is becoming increasingly important. It has long been known that electrical systems are susceptible to radiation, and recent research has raised the possibility that mechanical devices may also be prone to radiation-induced damage. Especially sensitive to radiation are devices that have mechanical motion governed by electric fields across insulators, such as electrostatically positioned cantilever beams. Insulators can fail under single event dielectric rupture. A further complication is the fact that radiation can cause bulk lattice damage and make materials more susceptible to fracture (Stark, 1999).

3.1.8 Temperature

This is a serious concern for MEMS. Internal stresses in devices are extremely temperature dependent. The temperature range in which a device will operate within acceptable parameters is determined by the coefficient of linear expansion. In devices where the coefficients are poorly matched, there will be a low tolerance for thermal variations (Walraven, 2003).

Thermal effects cause problems in metal packaging, as the thermal coefficient of expansion of metals can be greater than ten times that of silicon. For these packages, special isolation techniques have to be developed to prevent the package expansion from fracturing the substrate of the device. Another area that has yet to be fully examined is the effect of thermal changes upon the mechanical properties of semiconductors. It has long been known that Young's modulus is a temperature-dependent value (Stark, 1999).

3.1.9 Humidity

Humidity is considered another serious concern for MEMS. Surface micromachined devices are extremely hydrophilic for reasons related to processing. In the presence of humidity, water will condense into small cracks and pores on the surface of these structures (Stark, 1999).

Figure 3.6 shows an experiment performed by Sandia National Laboratories to microengine gears stressed under different humidity conditions, i.e., 39%, 24%, and 1.8% of relative humidity (RH) at 25°C. The microengines were stressed for the same number of cycles, but the amount of wear debris for each humidity value was dramatically different (Sandia National Laboratories, 2000).

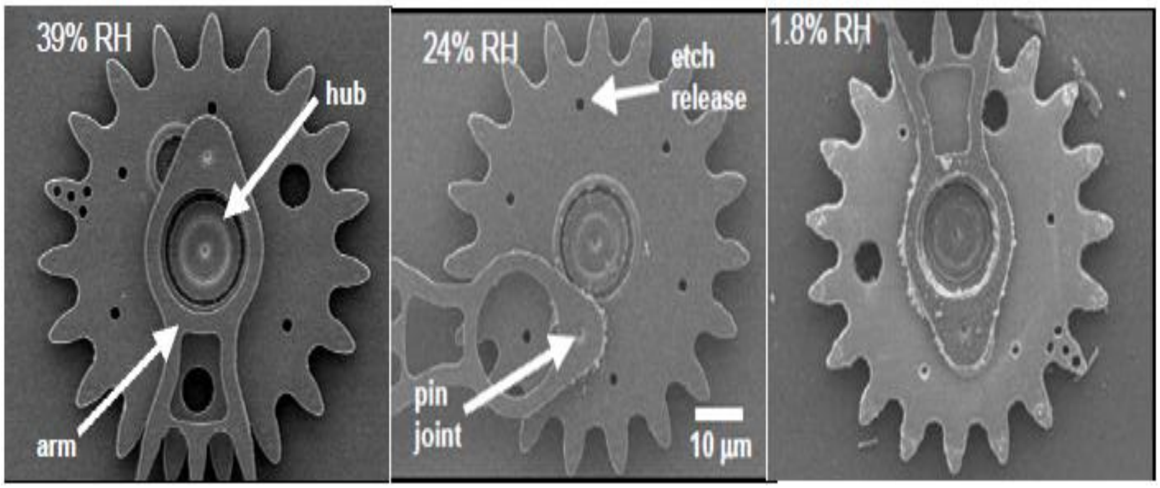

Figure 3.6
Micro Engine Gears under Humidity Stress
(Courtesy of Sandia National Laboratories)

3.1.10 Particulates

Particulates are fine particles that are prevalent in the atmosphere. These particles have been known to electrically short out MEMS and can also induce stiction. While these particles are normally filtered out of the clean room environment, many MEMS are designed to operate outside the confines of the clean room and without the safety of a hermetically sealed package. As a result, devices must be analyzed to ensure that they are particle-tolerant before they can be used as high-reliable devices in environments with high particulate densities. Another area in which contaminants cause problems is in adhesion. Proper device processing requires most materials interfaces to be clean in order to have good adhesion. If dust particles are present, the two materials are weakly bonded and are more likely to have delamination problems (Stark, 1999).

Figure 3.7 shows a wear experiment conducted by Sandia National Laboratories. Particles can be easily identified in the side wall of the device, and they are responsible to start the initial wear process.

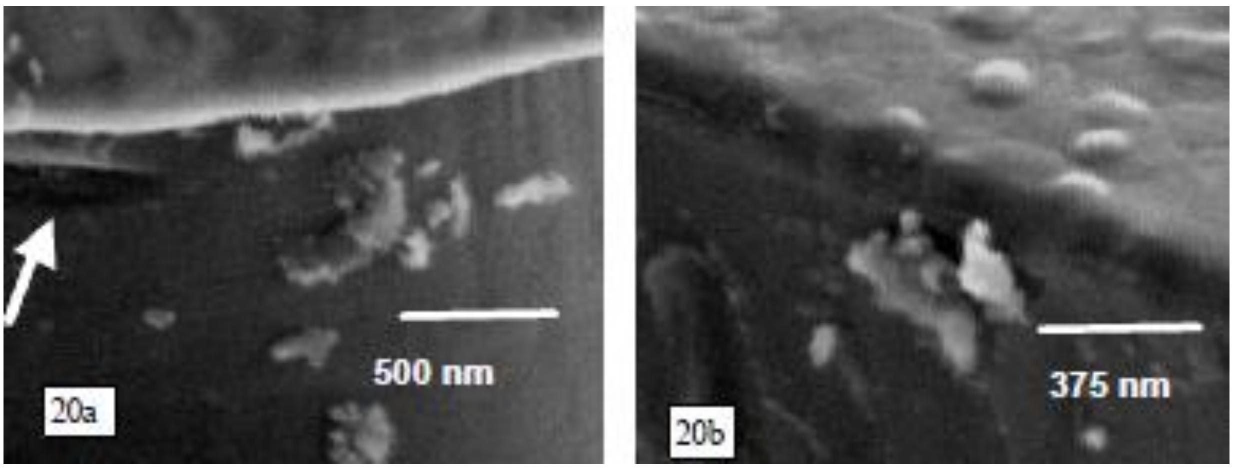

Figure 3.7
Particles on MEMS
(Courtesy of Sandia National Laboratories)

MEMS components by nature have different and unique failure mechanisms than their macroscopic counterparts. Walraven (2003) developed a general taxonomy to properly categorize each MEMS device with their related failure mechanism. Table 3.1 shows the result of this investigation:

Table 3.1
MEMS Failure Mechanisms

Class I: Accelerometers, Pressure sensors, Inkjet print heads, Strain Gauges.	**Failure Mechanism Description**: Unknown to fail due to operation. Particulate contamination can and typically will induce failure. Particles can be difficult to detect because they may not electrically interfere with the operation of a device. Particulate contamination may serve to mechanically obstruct the device while its electrical integrity is maintained.
Class II: Gyroscopes, comb drives, resonator ad filters.	**Failure Mechanism Description**: These devices have intentionally designed moveable parts that interact with the rest of the device to perform a given function, they are susceptible to fatigue, fracture or particulate contamination
Class III: Relays and Valves	**Failure Mechanism Description:** MEMS devices with impacting surfaces have the potential to create debris, fracture components, induce cracks, etc. Impact failures are very dependent upon the force exerted on the opposite MEMS structure.

Table 3.1-Continued
MEMS Failure Mechanisms

Class IV: Shutters, Scanners, Optical Switches	**Failure Mechanism Description:** These devices have moving, impacting structures with the addition of rubbing surfaces. Rubbing creates friction and often will result in the creation of wear material or debris. The formation of this material may result in several different failure mechanisms. These are: failure by particle contamination binding the device, particles causing third body wear changing the motion tolerance, particulate contamination preventing or obstructing motion, and adhesion of rubbing or contacting surfaces . The mechanism for wear may depend on the temperatures reached during rubbing. Many parameters must be examined to determine the root cause of wear, making analysis straight forward but time consuming.

For this investigation, MEMS accelerometers used in the automotive industry were classified as Class 1 from Table 3.2. Thus, failure mechanisms for the mentioned class are the main focus off the analysis leading to the identification of the failure modes for the MEMS.

3.2 Failure Mode Effect and Analysis

The Failure Mode and Effect Analysis is a logical, structured analysis of a system, subsystem, device, or process (Schubert, 1992). It is one of the most commonly used reliability and system safety analysis techniques. A FMEA consists of breaking a system down into what can fail, how it can fail, and why it fails, and then determining the effects of those failures on the system (PTC, 2010). The most commonly used FMEA standards include The Department of Defense MIL-STD-1629, The Department of the Army Technical Manual 5-698-4, the SAE-ARP5580 (Aerospace Industry), and the SAE J1739 (Automotive Industry).

The FMEA process is a bottom-up approach to system analysis. The analysis begins at the lowest level desired for study, such as a part or a step in a process, and evaluates the possible failure modes associated with that item. The next step consists in establishing, based on system knowledge and analyst experience, the resulting effects of the failure modes. Finally, the analyst may also determine the severity of that effect, the probability of occurrence of that effect, and how the effect could be detected (PTC, 2010). This process continues until the overall system effects are evaluated.

The main objective of a FMEA is to evaluate all parts of a system or process. Also, FMEA results critical to ensure that system reliability and safety objectives are met, as well as corrective actions to improve the analysis (Beauregard et al., 1996).

The SAE- J1739 (2009) establishes a step by step guidance for the application of Failure Mode and Effects Analysis. The document states the following three basic cases for which FMEA's are generated, each with a different scope:

1. **Design FMEA (D-FMEA):** Design FMEA evaluates the initial design for manufacturing, assembly, service and recycling requirements, including functional requirements and design alternatives. Design FMEA should be initiated before or at the design concept finalization and be continually updated as changes occur or additional information is obtained throughout the phases of product development. Design FMEA should be completed before the production drawings are released for tooling (SAE, 2009).
2. **Machinery FMEA (M-FMEA):** The Machinery FMEA supports the design processing reducing the risk of failures through:

- Aiding in the objective evaluation of equipment functions, design requirements and design alternatives.
- Increasing the probability that potential failure modes and their effects on the machinery have been considered in the design and development process.
- Providing additional information to aid in the planning of thorough and efficient design, validation and development programs.
- Developing a ranked list of potential failure modes prioritize according to their effect, thus establishing a priority system for design improvements, development and validation testing analysis.

Machinery FMEA should be initiated during the design concept development and should be continually updated as changes occur or additional information is obtained throughout the phases of machinery development. The analysis should be completed before engineering release for construction (SAE, 2009).

3. **Process FMEA (P-FMEA):** Process FMEA is utilized to accomplish the following:

- Identify the process functions and requirements.
- Identify potential product- and process-related failure modes.
- Assess the potential customer effects of the failures.
- Identify the potential manufacturing/assembly process causes of failures, and identify process variables on which to focus controls for occurrence reduction or detection of the failure conditions.
- Identify process variables on which to focus process controls.
- Develop a ranked list of potential failure modes, thus establishing a priority system for preventive/corrective action considerations.
- Document the results of the manufacturing/assembly process.

Process FMEA should be initiated before or at the feasibility stage and prior to tooling for production. It should take into account all manufacturing operations from individual components to assemblies (SAE, 2009).

FMEA can be measured by calculating a risk priority number (RPN). The RPN reveals the overall risk of a particular failure mode occurring in the system. The RPN is usually calculated as:

$$RPN = (S)x\ (O)x\ (D) \tag{3.1}$$

Severity x Occurrence x Detection

In order to get the RPN number in a FMEA, established rankings to determine values for severity *(S)*, occurrence *(O)* and detection *(D)* must be considered. For the scope of this investigation, process FMEA rankings were considered.

Several guidelines such as the MIL-STD-1629, the SAE J1739 and the Department of the Army define rankings for these variables as follows:

• **Severity *(S)*:** Indicates the severity of the effect of a particular failure mode. The severity ranking is important to determine relative concerns amongst failure modes. In Table 3.2, a severity ranking is assigned to each system level effect. A lower ranking indicates a less severe failure effect. A higher ranking indicates a more severe failure effect.

Table 3.2
Severity Rankings
(MIL-STD-1629, 1998)

SEVERITY RANKINGS		
Ranking	**Effect**	**Description**
1	Minor	No noticeable effect. Unable to realize that a failure has occurred.
2	Marginal	Annoying. No system degradation.
3	Moderate	Causing dissatisfaction. Some system degradation.
4	Critical	Causing a high degree of dissatisfaction. Loss of system function.
5	Catastrophic	A failure which may cause death or injury. Extended repair outages.

In contrast, Table 3.3 shows the Severity (*S*) rankings used by the Department of the Army. The severity ranking criteria selected to perform FMEA analysis must be consistent throughout the analysis.

Table 3.3
Severity Rankings
(Department of the Army, 2006)

SEVERITY RANKINGS		
Ranking	**Effect**	**Description**
1	None	No reason to expect failure to have any effect on safety, health, environment or mission.
2	Very Low	Minor disruption t facility function. Repair to failure can be accomplished during trouble call.
3	Low	Minor disruption t facility function. Repair to failure may be longer than trouble call but does not delay mission.
4	Low to Moderate	Moderate disruption to facility function. Some portion of mission may need to be reworked or process delayed.
5	Moderate	Moderate disruption to facility function. 100% of mission may need to be reworked or process delayed.
6	Moderate to High	High disruption to facility function. Some portion of mission is lost. Significant delay in restoring function.
7	High	High disruption to facility function. Some portion of mission is lost. Significant delay in restoring function.
8	Very High	High disruption to facility function. All of mission is lost. Significant delay in restoring function.
9	Hazard	Potential safety, health or environmental issue. Failure will occur with warning.
10	Hazard	Potential safety, health or environmental issue. Failure will occur without warning.

Severity classifications provide a qualitative measure of the worst potential consequences resulting from an item failure (Department of the Army, 2006).

• **Occurrence *(O)*:** This variable designates how frequently a particular failure mode occurs. Table 3.4 shows the occurrence ranking that can be used to subjectively assign a failure rate to a piece of equipment or component. The ranking corresponds to an estimated failure rate based on the analyst's experience or available reliability data. These values establish the qualitative failure probability level for entry into a Criticality Analysis (CA) worksheet format (Department of Defense, 1998).

Table 3.4
Occurrence Rankings
(Department of Defense, 1998)

OCURRENCE RANKINGS		
Ranking	**Failure Rate (Hours)**	**Description**
1	-	Unlikely. Unreasonable to expect this failure mode to occur.
2	1/10,000	Isolated. Based on similar designs having a low number of failures.
3	1/1,000	Sporadic. Based on similar designs that have experienced occasional failures.
4	1/100	Conceivable. Based on similar designs that have caused problems.
5	1/10	Recurrent. Certain that failures will ensue.

The failure rates values can be adjusted for a particular application. Rates can be in hours, days, or cycles (Department of the Army, 2006). On the other hand, Table 3.5 shows the

Occurrence rankings used by the Department of the Army. The occurrence criteria selected to perform FMEA analysis must be consistent throughout the analysis as well.

Table 3.5
Occurrence Rankings
(Department of the Army, 2006)

OCCURRENCE RANKINGS		
Ranking	**Failure Rate (Hours)**	**Description**
1	1/10,000	Remote probability of occurrence; unreasonable to expect failure to occur.
2	1/5,000	Very low failure rate. Similar to past design that has, had low failure rates for given volume/loads.
3	1/2,000	Low failure rate based on similar design for given volume/loads.
4	1/1,000	Occasional failure rate. Similar to past design that has had similar failure rates for given volume/loads.
5	1/500	Moderate failure rate. Similar to past design having moderate failure rates for given volume/loads.
6	1/200	Moderate to high failure rate. Similar to past design having moderate failure rates for given volume/loads.
7	1/100	High failure rate. Similar to past design having frequent failures that caused problems.
8	1/50	High failure rate. Similar to past design having frequent failures that caused problems.
9	1/20	Very high failure rate. Almost certain to cause problems.
10	1/10	Very high failure rate. Almost certain to cause problems.

• **Detection (D):** This variable indicates how often a particular failure mode can be detected. Table 3.6 shows qualitative values that can be used to determine this variable.

Table 3.6
Detection Rankings
(Department of Defense, 1998)

DETECTION RANKINGS		
Ranking	**Detection Criteria**	**Description**
1	80%–100%	Very high probability of detecting the failure before it occurs. Almost always preceded by a warning.
2	60%–80%	High probability of detecting the failure before it occurs. Preceded by a warning most of the time.
3	40%–60%	Moderate probability of detecting the failure before it occurs. About a 50% chance of getting a warning.
4	20%–40%	Low probability of detecting the failure before it occurs. Always comes with little or no warning.
5	0%–20%	Remote probability of detecting the failure before it occurs. Always without a warning.

In comparison, Table 3.7 shows the detection rankings used by the Department of the Army.

Table 3.7
Detection Rankings
(Department of the Army, 2006)

DETECTION RANKINGS		
Ranking	**Detection**	**Description**
1	Almost Certain	Current control(s) almost certain to detect failure mode. Reliable controls are known with similar processes.
2	Very High	Very high likelihood current control(s) will detect failure mode.
3	High	High likelihood current control(s) will detect failure mode
4	Moderately High	Moderately high likelihood current control(s) will detect failure mode.
5	Moderate	Moderate likelihood current control(s) will detect failure mode.
6	Low	Low likelihood current control(s) will detect failure mode.
7	Very low	Very low likelihood current control(s) will detect failure mode.
8	Remote	Remote likelihood current control(s) will detect failure mode.
9	Very Remote	Very remote likelihood current control(s) will detect failure mode.
10	Almost Impossible	No known control(s) available to detect failure mode.

RPN values for every failure modes are obtained after entering the severity, occurrence, and detection values, and are used to determine how critical the failures are, and how they can be eliminated, or the risks mitigated.

Figure 3.8 shows an illustrative example of an FMEA worksheet. Relevant data regarding the system and his mission is presented. Also, a potential failure mode (a water temperature greater than 75°F), and a failure mechanism (a cooling tower malfunction) are clearly specified.

Severity, occurrence, and detection values are entered in order to obtain the preliminary RPN of 96 (Equation 3.1). After this, recommended actions are proposed with a responsible for this action i.e., (M.Sequera), in order to eliminate or mitigate the existing failure mode. Finally, after corrective actions are applied, a new analysis for the severity, occurrence, and detection results in a final RPN of 16 (Equation 3.1). In conclusion, the variation between the preliminary results (a RPN of 96) and the final (RPN of 16) represents the measurable improvement in the analysis.

FAILURE MODES AND EFFECT ANALYSIS (FMEA)

SYSTEM: Mechanical System — DATE: 2/8/2010

PART NAME: Industrial Water Supply — SHEET: 1 of: 1

REFERENCE DRAWING : N/A — COMPILED BY: M.Sequera

MISSION : Provide Temperature to Control Room — APPROVED BY: D. Fonseca

PROCESS FUNCTION	POTENTIAL FAILURE MODE	POTENTIAL EFFECTS OF FAILURE MODE	SEVERITY *(S)*	FAILURE MECHANISM (CAUSE)	OCURRENCE *(O)*	CURRENT PROCESS CONTROL	DETECTION (D)	RPN	RECOMMENDED ACTION	RESPONSIBILITY	ACTIONS TAKEN	SEVERITY *(S)*	OCURRENCE *(O)*	DETECTION (D)	RPN
Ind water/ supply water to condenser at 75°F & 1000 GPM	Water Temperature greater than 75°F	Air Temp may rise	6	Cooling tower Malfunction	4	Temp sensor/ water analysis	4	96	Check sensors regularly	M.Sequera	5/11/2010	4	2	2	16

Figure 3.8
Failure Mode and Effect Analysis Example

FMEAs are typically performed based on published standards or guidelines, or they can be developed by organizations following their own standards (PTC, 2010).

Another important aspect is the fact that these variables can be adapted to the system that is being analyzed. FMEAs that are used to perform analysis of criticality as well are commonly known as Failure Mode, Effects, and Criticality Analysis (FMECA).

3.3 Failure Mode Effect and Criticality Analysis

The FMECA was originally developed by the National Aeronautics and Space Administration (NASA) to improve and verify the reliability of space program hardware. In 1980, The Department of Defense MIL-STD-1629A (Reliability Program for System and Equipment Development and Production, Failure Mode, Effects and Criticality Analysis) was introduced as the standard for the U.S. military until 1998. On August 4, 1998, the military standard MIL-STD-1629A was rescinded, with instructions for users to “consult various national and international documents for information regarding failure mode, effects, and criticality analysis” (O’Conner, 1996).

Later on in 2006, The Department of the Army used the cancelled MIL-STD-1629A to develop an updated version of the military standard that establishes requirements and procedures for performing a FMECA. This new technical manual was called the TM 5-698-4. Other military standards, such as the MIL-STD-785B, were used to establish procedures for performing a FMECA on equipment or systems as well.

The Department of the Army (2006) established that the TM 5-698-4 evaluates and documents, by failure mode analysis, the potential impact of each functional or hardware failure on mission success, personnel and system safety, maintainability, and system performance. Each potential failure is ranked by the severity of its effect so that corrective actions may be taken to eliminate or control risk.

Although the MIL-STD-1629A was discontinued, its basic concepts are applied during the development phases and operation conditions of all critical systems and equipment whether it is military, commercial, or industrial systems. The techniques presented in this standard may be applied to any electrical or mechanical equipment or system (Department of the Army, 2006).

The TM 5-698-4 explains on a step by step basis how to develop an FMECA. First, a FMEA is recommended to be completed prior to performing the Criticality Analysis (CA). The Criticality Analysis adds the benefit of showing the analysts a quantitative ranking of the system failure modes. On the other hand, the Criticality Analysis allows the analysts to identify reliability and severity related concerns with particular components or systems.

3.3.1 Criticality Analysis

Dodson and Nolan (1999) define Criticality Analysis (CA) as a procedure by which each potential failure mode is ranked according to the combined influence of severity and probability of occurrence. On the other hand, the TM 5-698-4 defines The Criticality Analysis (CA) as the measure of the frequency of occurrence of the effects of a failure mode, as well as the significance of an entire piece of equipment or system, on safe, successful operation, and operation requirements (Department of the Army, 2006).

The Criticality Analysis can be accomplished using either a quantitative or a qualitative approach. There are differences on each approach. If reliability information is available, a quantitative analysis must be performed. In contrast, if reliability information is not available, a qualitative analysis is recommended, and the analyst must perform the criticality analysis based on his/her experience and expectations on the system. This methodological tool allows analysts to rank the significance of each potential failure mode for each component in the system based on the available reliability information (failure rate) as well data transferred from the FMEA such as the severity ranking. This tool can be used to prioritize and minimize the effects of critical failures early in the design as well as in operation conditions (Department of Defense, 1998).

3.3.2 Quantitative Failure Mode, Effects and Criticality Analysis

Once it is determined that sufficient failure rate data and failure mode distributions are available, a Quantitative Failure Mode, Effects and Criticality Analysis can be assessed. Some of the categories can be derived from the FMEA such as failure modes, failure mechanisms, and severity (*S*).

The MIL-STD-1629A establishes an approach to calculate the criticality number (C_m). A description of each category and variables used in the quantitative Criticality Analysis are listed below (Department of the Army, 2006):

- **Beta (β):** Is defined as the failure effect probability and is used to quantify the described failure effect for each failure mode indicated in the FMECA. The beta (β) values represent the conditional probability or likelihood that the described failure effect will result in the identified criticality classification, given that the failure mode occurs. The β values represent the analyst's best judgment as to the likelihood that the loss or end effect occurs. Table 3.8 shows recommended values for (β).

Table 3.8
Failure Effect Probability
(Department of Defense, 1998)

Failure Effect	**B Value**
Actual Loss	1
Probable Loss	0.10 to 1
Possible Loss	0 to 0.10
No effect	0

- **Alpha (α)**: The probability, expressed as a decimal fraction, that the given part or item will fail in the identified mode. If all of the potential failure modes for a device are considered, the sum of the alphas should equal one. Determining Alpha is done as a two part process for each component being analyzed. Table 3.9 shows an example of a hypothetical failure mode ratio (α) used for existing failure modes in a blower.

Table 3.9
Failure Mode Ratio
(Department of the Army, 2006)

Part Failure Modes	Failure Mode Ratio (α)	Failure Mode Ratio (α) in %
Blows too little air	0.55	55
Blows too much air	0.05	5
Blows no air	0.40	40
The sum of α must be =1	**1**	**100**

- **The Failure Rate (λ_p):** Is the ratio between the numbers of failures per unit of time, and it is typically expressed in failures per million hours or 10^6 hours. The source of the failure rate should be clearly specified. Failure rate data from field tests are strongly recommended; however, information available from manufacturers and previous investigations can be used as well.
- **The Modal Failure Rate (λ_m)**: Is the fraction of an item's total failure rate based on the probability of occurrence of that failure mode. The sum of the modal failure rates for an item is equal to the total item failure rate for all part failure modes accounted. The modal failure rate is given by the equation:

$$\lambda_m = \alpha\, \lambda_p \qquad (3.2)$$

Where:

λ_m = the modal failure rate.

α= the probability of occurrence of the failure mode (failure mode ratio).

λ_p = the item failure rate.

- **Failure Mode (modal) Criticality Number** (**C_m**): The failure mode criticality number is a relative measure of the frequency of a failure mode. In essence, it is a mathematical means to rank importance of a failure mode effect, based on its failure rate. The equation used to calculate this number is as follows:

$$C_m = (\beta \times \alpha \times \lambda_p \times t) \qquad (3.3)$$

Where:

C_m = Failure mode criticality number

β = Conditional probability of the current failure mode

α = Failure mode ratio

λ_p = Item failure rate

t = Duration of applicable mission phase (expressed in hours or operating cycles)

- **Item criticality number (C_r)**: The item criticality number is a relative measure of the consequences and frequency of an item failure. This number is determined by totaling all of the failure mode criticality numbers of an item with the same severity level. Equation 3.4 is used to calculate such a number:

$$C_r = \Sigma (C_m) \tag{3.4}$$

Where:

C_r = Item criticality number

C_m = Failure mode criticality number

Figure 3.9 shows an illustrative criticality worksheet example of quantitative Failure Modes, Effect and Criticality Analysis with all the variables previously explained. In this example, the potential failure mode, the failure mechanism, and severity (*s*) of a group of failure modes are transferred from a previously developed FMEA. Also, potential failure modes and failure mechanism are clearly specified. Other variables, such as the failure rate (λ_p), the failure effect probability (β), the failure mode ratio (α), and the operating time (t) are entered in order to obtain the failure mode criticality number (C_m) (Equation 3.3), and the item criticality number (C_r) (Equation 3.4).

QUANTITATIVE FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

SYSTEM: Mechanical System — DATE: xxxx
PART NAME: Industrial Water Supply — SHEET: 1 of: 1
REFERENCE DRAWING : N/A — COMPILED BY:
MISSION : Provide Temperature to control room — APPROVED BY:

ITEM NUMBER	ITEM FUNCTIONAL ID	POTENTIAL FAILURE MODE	FAILURE MECHANISM (CAUSE)	SEVERITY (S)	FAILURE RATE (λp)	FAILURE EFFECT PROBABILITY (β)	FAILURE MODE RATIO (α)	OPERATING TIME	FAILURE MODE CRITICALITY NUMBER (Cm)	ITEM CRITICALITY NUMBER Σ (Cm)	REMARKS
110.1	Reservoir contain 6000 gallons of water	Leak	Crack in wall, Ruptured drain in pipe	4	1.5 x 10-6	1	1	61,320	6.38 X10 -4	6.38 X10 -4	
120.1	Pump 1 transport industrial water at 1000 GPM	Transport water at a rate below 1000 GPM	impeller degraded, leak, motor degraded	3	12.058 x 10-6	1	0.35	61,320	3 x 10-13	8.58 x10-13	
120.2		Produce no water flow	Broken coupling, suction line leak, motor inoperable	3		1	0.65	61,320	5.58 x 10-13		

Figure 3.9
Quantitative Failure Modes, Effects and Criticality Analysis (FMECA)
(Department of the Army, 2006)

Methodologies such as the Criticality Matrix are strongly recommended to document and analyze the results obtained from a FMECA. In this investigation, the Criticality Matrix was considered as the means to compare the failure modes criticality of automotive MEMS devices.

3.3.3 The Criticality Matrix

This methodology is a graphical tool used to identify and compare failure modes for all components and their probability of occurring with respect to the severity (*S*). It is used in quantitative and qualitative analyses. The matrix can be used along with the Critical Item List, or by itself, in order to prioritize components. The matrix has the distinctive ability to differentiate criticality of components with similar RPN and criticality values (Department of Defense, 1998).

Table 3.10 represents an example of the criticality matrix used in this investigation. The matrix is constructed by inserting the assigned Item Number (110.0, 120.0 and 120.1) with their corresponding failure modes, severity (*S*) indexes and the criticality number (C_m) transferred from Figure 3.9.

Table 3.10
Criticality Matrix Data
(Department of the Army, 2006)

ITEM	Failure Mode	Severity (S)	Criticality Number (C_m)
110.0	Leak	4	6.38×10^{-4}
120.0	Transport water below 1000 GPM	3	3.00×10^{-13}
120.1	Produce no water flow	3	5.58×10^{-13}

The criticality matrix displays the distribution of all the failure mode criticality numbers according to the severity category through the criticality scale. Figure 3.10 shows the visual way to understand the criticality data from Table 3.10.

For the example of Table 3.10, the Item 110.0 (Leak) represents the failure mode that requires more attention for having the higher severity number (S), and criticality number (C_m). In contrast, items 120.0 (Transport water below 1000GPM) and 120.1 (Produce no water flow) have a lower probability of occurrence by their severity numbers (S), and criticality numbers (C_m).

In conclusion, items displayed closer to the right hand corner require most attention and items closer to the left corner have a lower probability of occurrence.

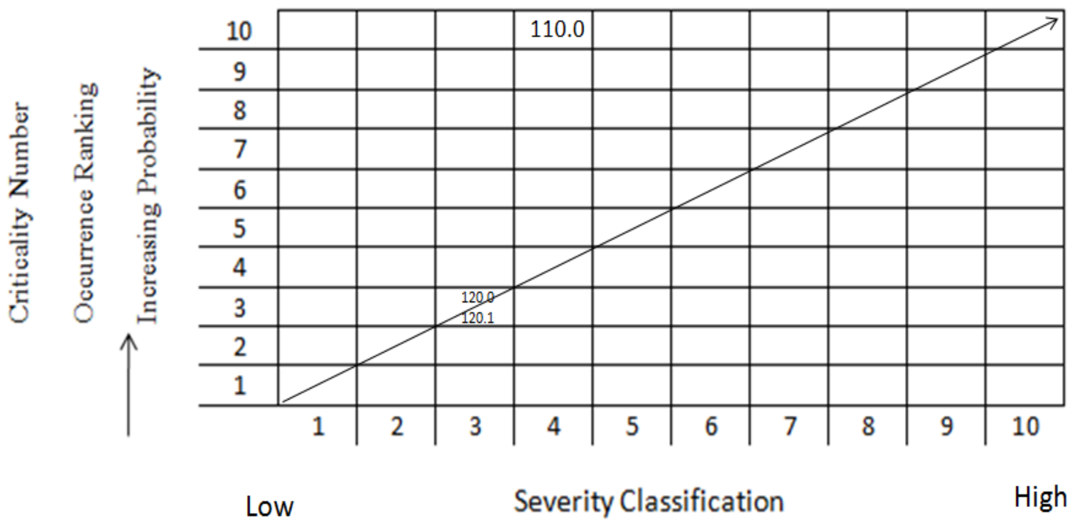

Figure 3.10
Criticality Matrix

3.4 Summary

This chapter defined the scope of the project, as well as its general methodology. The conceptual framework for the assessment of the criticality of key failure modes in MEMS was accomplished by following the discussed methodology on a step by step basis. Furthermore, several widely used MEMS devices were discussed, in particular those used in the automotive industry.

The creation of a conceptual framework for automotive MEMS accelerometers involves careful analysis of existing methodologies such as FMECA, that is commonly used in macro-systems. As it was mentioned before, it is challenging to transfer analytical tools for macro-system to the micro-system realm. Hence, several key factors such as failure mechanisms, associated failure modes, and pertinent reliability information were considered while establishing the conceptual framework of this study.

CHAPTER 4

CONCEPTUAL FRAMEWORK IMPLEMENTATION

As it was previously stated, the main objective of this project was to design a conceptual framework for the assessment of the criticality of key failure modes in MEMS accelerometers. The conceptual framework establishes seven steps to perform the criticality analysis. Also, it includes operational parameters for MEMS technology such as environmental conditions and surrounding stresses. Failure mechanisms and failure modes were analyzed in order to perform the criticality analysis (FMECA). Figure 4.1 shows an illustration of the project's methodology.

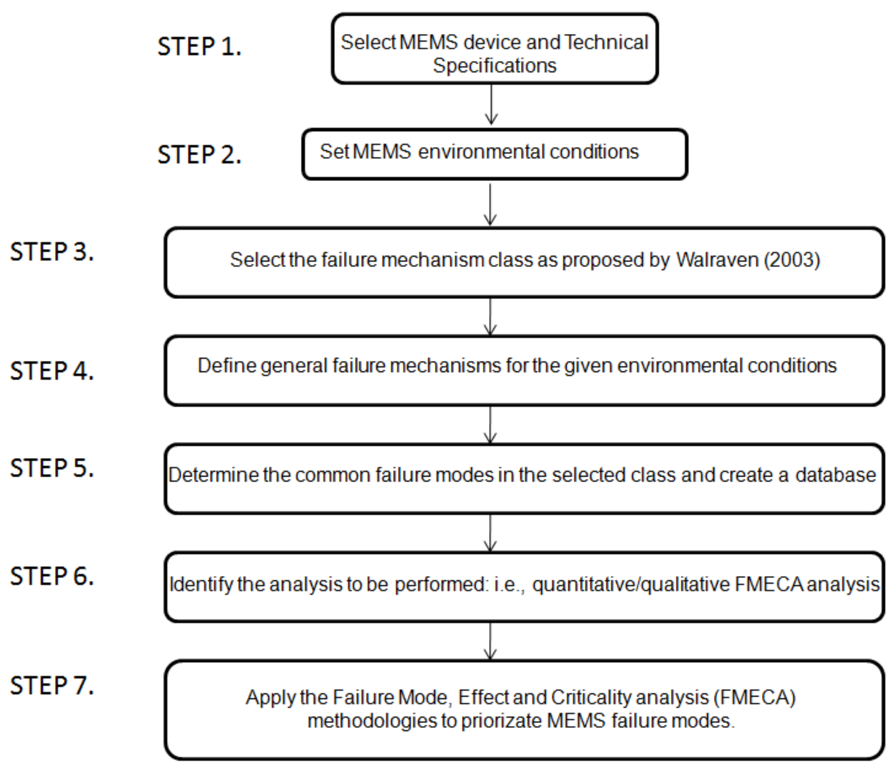

Figure 4.1
Conceptual Framework

4.1 Selection of MEMS and Technical Specifications

The first step to develop the conceptual framework was to establish the selection of the MEMS device for the analysis and its related technical specifications. The World Wide Web was used to identify and research potential automotive MEMS manufacturers with reliability data available for this study. The potential manufacturers were consolidated to two companies with a solid reputation in the automotive industry: 1) *Analog Devices*; and 2) *Robert Bosch*.

After careful examination, *Analog Devices* was selected as the manufacturer of the MEMS device used in this analysis. This company has more than 20 years of experience in automotive MEMS. In addition, useful reliability data was readily available at www.analogdevices.com for all their devices. In contrast, although *Robert Bosch* has a broad variety of MEMS accelerometers for automobiles, no reliability data was available at the time of this research.

4.1.1 ADXL 180 MEMS Accelerometer Description

The ADXL180 accelerometer is a configurable, single axis, integrated satellite sensor that enables low cost solutions for front and side impact airbag applications.

Acceleration data is sent to the control module via a digital 2-wire current loop interface bus. The communication protocol is programmable for compatibility with various automotive interface bus standards. The sensor *g* range is configurable to provide full-scale ranges from ±50 *g* to ±500 *g*. The sensor signal third-order, low-pass Bessel filter bandwidth is configurable at 100 Hz, 200 Hz, 400 Hz, and 800 Hz. The 10-bit analog-to-digital converter (ADC) allows either

8-bit or 10-bit acceleration data to be transmitted to the control module. Each part has a unique electronic serial number. The device is rated for operation from −40°C to +125°C, and it is available in a 5 mm × 5 mm LFCSP package (Analog Devices, 2011).

Table 4.1 shows the technical specifications for the chosen MEMS accelerometer used in this analysis (Analog Devices, 2011).

Table 4.1
ADXL180 Technical Specifications
(Analog Devices, 2011)

ANALOG DEVICES ADXL180	
Supply Voltage	-0.3 V to +21V
Operating Temperature Range	-40°C to 125°C
Storage Temperature Range	-55°C to 150°C
Sensor Range	+-50 G to +- 500 G
Mechanical Shock	Unpowered: +- 4,000 G Powered: +- 2,000 G
Package	5 x 5 mm
Drop Test	1.2m

4.2 Environmental Conditions for MEMS in the Automotive Industry

The second step in the conceptual framework was to set the environmental conditions to assess the criticality of key failure modes in MEMS accelerometers. As it was presented in Table 3.3, MEMS are exposed to an aggressive environment in automotive applications. For this investigation, three scenarios were considered for analysis. Table 4.2 depicts the 1st scenario for the analysis:

Table 4.2
Analysis Scenario 1

Scenario 1 for ADXL180	
Variables	
Temperature	50°C
Mechanical Shock	3000 G
Vibration	15G
Electromagnetic Impulses	100 to 200 Volts/meter

In this first scenario, a temperature of 50°C was considered for the assessment of criticality key failure modes. Table 4.3 depicts the second scenario:

Table 4.3
Analysis Scenario 2

Scenario 2 for ADXL180	
Variables	
Temperature	100°C
Mechanical Shock	3000 G
Vibration	15G
Electromagnetic Impulses	100 to 200 Volts/meter

In the second scenario, a temperature of 100°C was considered for the assessment of criticality key failure modes. Finally, Table 4.4 depicts the third scenario with a temperature of 150°C:

Table 4.4
Analysis Scenario 3

Scenario 3 for ADXL180	
Variables	
Temperature	150°C
Mechanical Shock	3000 G
Vibration	15G
Electromagnetic Impulses	100 to 200 Volts/meter

4.3 Class 1 Accelerometers

The third step in the development of the conceptual framework consists in understanding the device class, and failure mechanisms. Walraven (2003) establishes that MEMS accelerometers used in the automotive industry are classified as Class 1 (Table 3.4). Class 1 accelerometers are devices with no internal moving parts. These devices are unknown to fail due to regular operation (Walraven, 2003).

The ADXL180 accelerometer provides a fully differential sensor structure and circuit path. Each sensor includes several differential capacitor unit cells. Each cell is composed of fixed plates attached to the substrate and movable plates attached to the frame. Displacement of the frame changes the differential capacitance, measuring the change in acceleration (Analog Devices, 2011). The ADXL180 acceleration sensor uses two electrically isolated, mechanically coupled sensors to measure acceleration as shown in Figure 4.2:

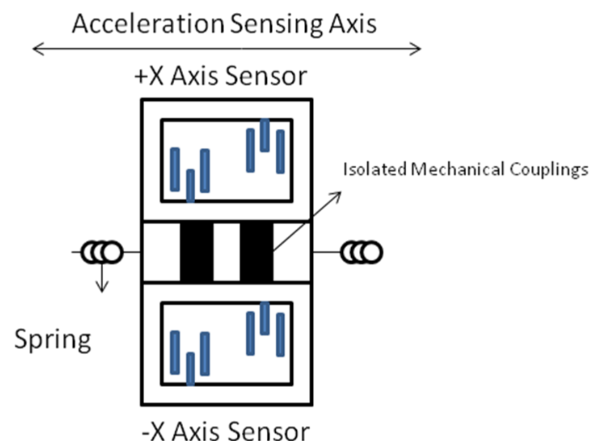

Figure 4.2
ADXL180 Accelerometer

4.4 Failure Mechanisms and Failure Modes in Class 1 Accelerometers

A clear distinction between failure mechanisms and failure modes is necessary to perform a criticality analysis. A failure mechanism is the physical, chemical, or thermal changes that lead to a failure. In contrast, the failure mode is the way in which a failure is observed and its impact on the device operation. Steps 4 and 5 in the conceptual framework are closely related and they are the key to perform the criticality analysis.

4.4.1 Failure Mechanisms in Class 1 Accelerometers

As it was stated previously, Class 1 accelerometers are unknown to fail due to operation. For this specific class, particulate contamination and stiction can typically induce to a failure. Particles can be difficult to detect because they may not electrically interfere with the operation of the device. Other general failure mechanisms, such as degradation, ESD, mechanical shock, vibration, stress and corrosion, can affect Class 1 accelerometers as well.

Several studies have been conducted to confirm these premises. Hartzell et al. (1999) proposed a methodology for the prediction of stiction behavior in micromachined accelerometers. The model was based on an empirical work to determine the probability of survival after stress shocks that cause stiction.

Figure 4.3 shows the survival probability of an accelerometer subjected to a single shock event.

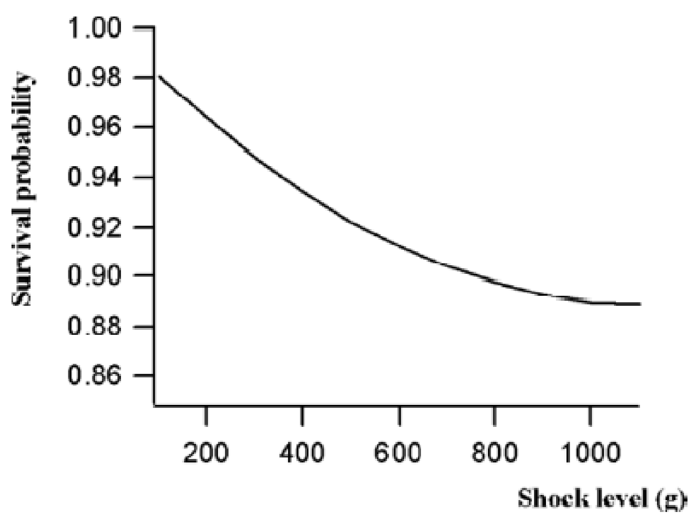

Figure 4.3
Single Shock Survival Probability (Stiction)
(Courtesy of Analog Devices)

In this approach, Hartzell et al. (1999) performed a stress testing analysis in accelerometers. The stresses were applied to 4,590 devices by using techniques such as high temperature operating life (HTOL), thermal shocks, thermal cycles and high temperature storage.

Off all the reliability tests conducted, only one failure occurred, and it was caused by stiction at high temperatures (150°C x 1000 hours).

Tanner et al. (2005) performed accelerated testing to MEMS devices at temperatures from 200°C to 300°C which were higher than the standard MEMS operating range of -50 to 125°C. Humidity was also considered for this study by using humidity levels of 500 ppmv and 2,000 ppmv, which are lower than the military standard of 5,000 ppmv (15, 8 % RH).

The results were conclusive; the failures are dependent on both temperature and humidity. Failures occur at higher temperatures (300°C) and low humidity. The predominant failure mechanisms were degradation and wear, and they can vary depending of the complexity of internal structure of the MEMS.

Tanner et al. (2000) also developed an analysis of vibration in MEMS. The vibration stress test was performed at four times the level of the typical system requirements in the automotive industry (from 20 to 30 G). Higher vibrations can produce stiction and adhesion on surfaces. Also, presence of wear debris occurs at higher vibration levels.

Brown and Davis (1998) presented another interesting investigation using ANALOG DEVICES accelerometers model ADXL05, ADXL50, ADXL150, ADXL181, commonly used for airbag usage for tests into ground and flight testing with high-g loading. The accelerometers were tested at shock levels of 13,500G and 26,000G. All the accelerometers survive the shock test. In addition, accelerometers were also tested in an air gun test that simulates extreme artillery level and tank level launch accelerations. The accelerometers survived to levels of shock up to 80,000G which are higher than the standard MEMS automotive operating range of 50-500G.

This investigation demonstrates how reliable MEMS accelerometers can be under shocks in automotive environment.

Sandia National Laboratories (2000) suggest that particulate contamination can be expected to have a serious effect on devices under shock and vibration environments. These environments cause the particles to move and can short out working devices. Also, other failure mechanisms such handling and oven curing during the packaging process of the MEMS are considered critical for their probability to induce a failure in the device.

Table 4.5 shows the failure mechanisms that were considered for the failure modes database performed later in this chapter:

Table 4.5
Failure Mechanisms

Stiction
Wear
Humidity
Fatigue
Shock and Vibration
Contamination
Temperature
Dielectric Charging and ESD

4.4.2 Failure Modes Database in Class 1 Accelerometers

For this investigation, a failure mode database was created to perform a criticality analysis. This database is based on the results of the previously mentioned literature research. Table 4.6 shows the failure modes, and their respective failure mechanisms, that were used for the criticality analysis in this study. A total of 13 failure modes were identified and were used to assess their criticality under the three established scenarios as explained in Section 4.2.

Table 4.6
Failure Modes and Failure Mechanisms

Failure Mode	**Failure Mechanism**
Wear debris between rubbing surfaces	Humidity, Wear
Sticking of finger structures due to surface forces	Stiction
Internal fracture on structure	Fatigue Stress
Finger and Substrate Adhesion	Stiction
Surface Adhesion	Shock
Cracks and Pores on the surface	Humidity , Temperature
Internal structural stress	Humidity, Wear
Collapse of electrodes due to excessive deformation	Stiction
Welding of the polysilicon finger to the ground plane	Fatigue Stress
Noise in sensor output	Stiction
Sensor output variation with temperature	Shock
Mechanical obstruction of the fingers	Contamination
Internal aging of Polysilicon	Humidity , Temperature

4.5 Failure Mode, Effect and Criticality Analysis

The last step in the development of the conceptual framework was the implementation of the Failure Mode, Effect, and Criticality Analysis . The FMECA provides a way to measure the frequency of occurrence and the effect of selected failure modes.

4.5.1 System Requirements

Based on the structure of the conceptual framework, several system technical conditions are required. Among them, high quality of graphical representations, statistical data interpretation, and user friendliness were considered essential. Therefore, Microsoft Excel 2007 was selected for this investigation for the following reasons:

- Microsoft Office 2007 is a reliable tool to introduce data, formulas and keep relation between entered values.
- The Excel spreadsheet lets the user to perform a sequential input of FMECA variables that must be introduced to complete the Criticality Analysis.

4.5.2 FMECA Preliminary Data

Preliminary data was submitted before starting the FMECA analysis. This preliminary data provides information about the system, the responsible party of the analysis, and the mission of the device. The preliminary data are listed as follows:

- System: Information on the system to be analyzed.
- Part Name: Part number by the manufacturer.
- Reference Drawing: Additional graphical info that can be useful for the analysis.
- Mission: Defines the device mission.
- Date: Date when the analysis was performed.
- Sheet: Referential number of pages from the analysis.
- Compiled by: Responsible of performing the analysis.
- Approved by: Responsible of validating the analysis.

For this investigation, these variables were classified as depicted in Table 4.7:

Table 4.7
FMECA Preliminary Data

FMECA Preliminary Data	
System	MEMS Airbag Deployment System
Part Name	ADXL180 (Analog Devices)
Reference Drawing	Not available
Mission	Deployment of airbag system
Date	2/10/2011
Sheet	1 of 1
Compiled By	M.Sequera
Approved By	D.Fonseca

.

Figure 4.4 illustrates the preliminary data submitted in the Microsoft Excel sheet of the FMECA used in this investigation.

SYSTEM:	MEMS Airbag Deployment System	DATE:	2/10/2011
PART NAME:	ADXL180 (Analog Device)	SHEET:	1 of: 1
REFERENCE DRAWING :	N/A	COMPILED BY:	M.Sequera
MISSION :	Deployment of airbag system	APPROVED BY:	D.Fonseca

Figure 4.4
FMECA Preliminary Data

4.5.3 FMECA Variables

As it was explained in Chapter 3, a group of relevant FMECA variables were defined in order to get a criticality number for every failure mode. In this study, these variables were considered as follows:

- Item Number: ADXL180 (Accelerometer described in Section 4.1.1).

- Item functional ID for Failure Modes, and Failure Mechanisms: Successive numbers that identifies failure mode and failure mechanisms. Table 4.8 shows the functional items identification for this study.

Table 4.8
Item Functional ID

Item Number	Item Functional ID	Potential Failure Mode	Failure Mechanism
ADXL180	1	Wear debris between rubbing surfaces	Humidity-Wear
ADXL180	2	Sticking of finger structures due to surface forces	Stiction
ADXL180	3	Internal fracture on structure	Fatigue Stress
ADXL180	4	Finger and substrate adhesion	Stiction
ADXL180	5	Surface adhesion	Shock
ADXL180	6	Cracks and pores on the surface	Humidity , Temperature
ADXL180	7	Internal structural stress	Humidity-Wear
ADXL180	8	Collapse of electrodes due to excessive deformation	Stiction
ADXL180	9	Welding of the polysilicon finger to the ground plane	Fatigue Stress
ADXL180	10	Noise in sensor output	Stiction
ADXL180	11	Sensor output variation with temperature	Shock
ADXL180	12	Mechanical obstruction of the fingers	Contamination
ADXL180	13	Internal aging of polysilicon	Humidity - Temperature

- Severity (S): Assigned Severity values from Table 3.6.

The highest severity value possible was assumed in this investigation for every failure mode (i.e., 10 out of 10). This is because the failure modes effects are considered catastrophic when they occur in a MEMS device. Table 4.9 shows the assigned severity values for the failure modes in this study.

Table 4.9
Failure Modes Severity

Item Functional ID	Potential Failure Mode	Failure Mechanism	Severity
1	Wear debris between rubbing surfaces	Humidity-Wear	10
2	Sticking of finger structures due to surface forces	Stiction	10
3	Internal fracture on structure	Fatigue Stress	10
4	Finger and substrate adhesion	Stiction	10
5	Surface adhesion	Shock	10
6	Cracks and pores on the surface	Humidity , Temperature	10
7	Internal structural stress	Humidity-Wear	10
8	Collapse of electrodes due to excessive deformation	Stiction	10
9	Welding of the polysilicon finger to the ground plane	Fatigue Stress	10
10	Noise in sensor output	Stiction	10
11	Sensor output variation with temperature	Shock	10
12	Mechanical obstruction of the fingers	Contamination	10
13	Internal aging of polysilicon	Humidity - Temperature	10

- Failure Rate (λ_p): Assigned failure rate from the manufacturer reliability data.

  Failure rates for ADXL180 accelerometers were available at www.analogdevices.com. Table 4.10 depicts the failure rates in hours^{-1} from ADXL180 MEMS at different temperatures, and a 90 % confidence level.

Table 4.10
Failure Rate from ADXL180 at 90% C.L

Failure Rate (λ_p) from ADXL180 at 90% C.L	
Temperature C	**Failure Rate (1/hr)**
-10	0
0	0
10	0.00001E-6
20	0.00002E-6
30	0.00005E-6
40	0.00013E-6
50	0.00028E-6
60	0.0006E-6
70	0.001E-6
80	0.002E-6
90	0.004E-6
100	0.0082E-6
110	0.014E-6
120	0.024E-6
130	0.041E-6
140	0.06745E-6
150	0.107E-6

In addition, Table 4.11 shows the failure rate values used for the three scenarios of this investigation.

Table 4.11
Failure Rate for Scenarios

Failure Rate (λ_p) for Scenarios	
50	0.00028E-6
100	0.0082E-6
150	0.107E-6

- Failure Effect Probability (β): The beta (β) values were assumed by the author of this research, based on the findings from the conducted literature research that suggest an approach based on the probabilities of different failure mechanisms. Table 4.12 shows the assigned values of beta (β) assumed in this investigation.
- Failure Mode Ratio (α): Qualitative ratio of probability of failure. Table 4.12 shows the assigned values of alpha (α) assumed in this investigation.

Table 4.12
Failure Effect Probability (β) and Failure Mode Ratio (α)

Item Functional ID	**Failure Mode**	**Failure Effect (β)**	**Failure Mode Ratio (α)**
1	Wear debris between rubbing surfaces	0.25	0.025
2	Sticking of finger structures due to surface forces	0.50	0.175
3	Internal fracture on structure	0.25	0.015
4	Finger and substrate adhesion	0.50	0.15
5	Surface adhesion	0.25	0.05
6	Cracks and pores on the surface	0.25	0.025
7	Internal structural stress	0.25	0.018
8	Collapse of electrodes due to excessive deformation	0.25	0.125
9	Welding of the polysilicon finger to the ground plane	0.50	0.02
10	Noise in sensor output	0.25	0.15
11	Sensor output variation with temperature	0.50	0.07
12	Mechanical obstruction of the fingers	0.25	0.1
13	Internal aging of polysilicon	0.50	0.017

- Operating Time (t): This value represents the expected operating time of the device in analysis. For this study, 90,000 hours (equivalent to 10 years of operational life were assumed for the selected MEMS device).
- Failure Mode Criticality Number (C_m): This number measures the frequency of occurrence of a failure mode and it is obtained by applying Equation 3.3.
- Item Criticality Number Σ (C_m): This number is determined by totaling all of the failure mode criticality numbers of an item with the same severity level.

Figure 4.5 shows an example of the completed FMECA model which is discussed in Chapter 5.

QUANTITATIVE FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

SYSTEM: MEMS Airbag Deployment System — DATE: 2/10/2011
PART NAME: ADXL180 (Analog Device) — SHEET: 1 of: 1
REFERENCE DRAWING : N/A — COMPILED BY: M.Sequera
MISSION : Deployment of airbag system — APPROVED BY: D.Fonseca

ITEM NUMBER	ITEM FUNCTIONAL ID	POTENTIAL FAILURE MODE	FAILURE MECHANISM (CAUSE)	SEVERITY (S)	FAILURE RATE (λp)	FAILURE EFFECT PROBABILITY (β)	FAILURE MODE RATIO (α)	OPERATING TIME (t)	FAILURE MODE CRITICALITY NUMBER (Cm)	ITEM CRITICALITY NUMBER Σ (Cm)	REMARKS
ADXL180	1	Wear debris between rubbing surfaces	Humidity, Wear	10	0.00028E-6	0.25	0.025	90000.00	1.575E-06	1.575E-06	
ADXL180	2	Sticking of finger structures due to surface forces	Stiction	10	0.00028E-6	0.5	0.175	90000.00	2.205E-05	2.363E-05	
ADXL180	3	Internal fracture on structure	Fatigue Stress	10	0.00028E-6	0.25	0.015	90000.00	9.450E-07	2.457E-05	

Figure 4.5
FMECA Final Sheet

4.6 Summary

This chapter described the implementation of the conceptual FMECA framework to assess the criticality of key failure modes in MEMS accelerometers used in the automotive industry. The conceptual implementation was accomplished by following the methodology discussed in Chapter 3. In addition, three scenarios for the criticality analysis were defined as well as the failure modes, failure mechanisms, severity and the variables to perform the FMECA for class 1 MEMS accelerometers. Chapter 5 focuses on the results obtained from the implementation of this conceptual framework.

CHAPTER 5

FMECA RESULTS AND VALIDATION

Once the conceptual framework was completed and reviewed, the criticality values for key failure modes in MEMS accelerometers were obtained. This chapter discusses the results obtained through the FMECA analysis. Also, the face validation of the results by an expert in MEMS is briefly discussed as well.

5.1 MEMS FMECA Results

Following the previously explained FMECA methodology in chapters 3 and 4, the Criticality Number (C_m) for every failure mode was obtained for the three described scenarios. Equation 3.3 was used to obtain criticality values:

$$C_m = (\beta \times \alpha \times \lambda_p \times t) \qquad (3.3)$$

Where:

C_m = Failure mode criticality number

β = Conditional probability of the current failure mode

α = Failure mode ratio

λ_p = Item failure rate

t = Duration of applicable mission phase (expressed in hours)

As it was previously stated, the failure mode Criticality Number (C_m) is a relative measure of the frequency of a failure mode. In essence, it is a mathematical means to rank the importance of a failure mode effect, based on its failure rate. Table 5.1 shows the results from the first scenario, i.e., operational temperature of 50°C. See Appendix A for complete computations of the FMECA analysis involving all the variables in each scenario.

Table 5.1
Failure Mode Criticality Number (Cm) for the First Scenario (T=50°C)

First Scenario (T=50°C)		
Item Functional ID	**Failure Mode**	**Criticality Number (C_m)**
1	Wear debris between rubbing surfaces	6.300E-07
2	Sticking of finger structures due to surface forces	1.449E-06
3	Internal fracture on structure	7.245E-07
4	Finger and substrate adhesion	1.512E-06
5	Surface adhesion	6.930E-07
6	Cracks and pores on the surface	1.071E-06
7	Internal structural stress	5.670E-07
8	Collapse of electrodes due to excessive deformation	1.040E-06
9	Welding of the polysilicon finger to the ground plane	7.560E-07
10	Noise in sensor output	1.071E-06
11	Sensor output variation with temperature	1.134E-06
12	Mechanical obstruction of the fingers	7.875E-07
13	Internal aging of polysilicon	9.450E-07
		ΣC_m= 1.238E-05

Table 5.2 shows the results from the Second Scenario, where the operation temperature was 100°C.

Table 5.2
Failure Mode Criticality Number (Cm) for the Second Scenario (T=100°C)

Second Scenario (T=100°C)		
Item Functional ID	**Failure Mode**	**Criticality Number (C_m)**
1	Wear debris between rubbing surfaces	3.32E-05
2	Sticking of finger structures due to surface forces	6.27E-05
3	Internal fracture on structure	1.85E-05
4	Finger and substrate adhesion	5.90E-05
5	Surface adhesion	1.66E-05
6	Cracks and pores on the surface	5.17E-05
7	Internal structural stress	5.90E-05
8	Collapse of electrodes due to excessive deformation	6.64E-05
9	Welding of the polysilicon finger to the ground plane	2.77E-05
10	Noise in sensor output	5.35E-05
11	Sensor output variation with temperature	5.54E-05
12	Mechanical obstruction of the fingers	2.21E-05
13	Internal aging of polysilicon	3.69E-05
		ΣC_m= 5.627E-04

Table 5.3 shows the results from the Third Scenario, i.e., operational temperature of 150°C.

Table 5.3
Failure Mode Criticality Number (Cm) for the Third Scenario (T=150°C)

Third Scenario (T=150°C)		
Item Functional ID	**Failure Mode**	**Criticality Number (C_m)**
1	Wear debris between rubbing surfaces	3.611E-04
2	Sticking of finger structures due to surface forces	1.445E-03
3	Internal fracture on structure	2.408E-04
4	Finger and substrate adhesion	9.630E-04
5	Surface adhesion	1.204E-04
6	Cracks and pores on the surface	4.334E-04
7	Internal structural stress	1.083E-03
8	Collapse of electrodes due to excessive deformation	1.445E-03
9	Welding of the polysilicon finger to the ground plane	4.815E-04
10	Noise in sensor output	1.445E-03
11	Sensor output variation with temperature	1.083E-03
12	Mechanical obstruction of the fingers	4.815E-04
13	Internal aging of polysilicon	7.223E-04
		ΣC_m= 1.171E-02

5.2 Analysis of the FMECA Results

Past studies of accelerated life testing mentioned in Chapter 4 demonstrated that failure mechanisms in MEMS accelerometers are as unique as their internal structures. MEMS accelerometers are robust to failure mechanisms such as fatigue, and wear, for having no moving components internally. In addition, other experiments showed that the failure modes in MEMS are dependant to temperature and humidity. Stiction and adhesion were also mentioned as the predominant failure mechanisms in MEMS accelerometers. The results of this study show nearly perfect agreement with the previous premises.

5.2.1 Analysis of the Item Criticality Number (C_r)

As it was defined in Chapter 4, the Item Criticality Number (C_r) is determined by totaling all of the failure modes Criticality Numbers (C_m) with the same severity level. Table 5.4 shows the Item Criticality Numbers(C_r) results obtained for the three scenarios.

Table 5.4
Item Criticality Numbers (C_r)

Scenarios	**Item Criticality Number** (C_r)
Scenario 1 at 50 °C	1.238E-05
Scenario 2 100 °C	5.627E-04
Scenario 3 150 °C	1.171E-02

In order to analyze the variation of the Item Criticality Number (C_r) and the way that temperature affects each scenario, a Theoretical Maximum Criticality Number (C_{Mmax}) was determined. This number was calculated by using Equation 5.1:

$$C_{Mmax} = (\beta_{max} \text{ x } \alpha_{max} \text{ x } \lambda_{pmax} \text{ x } t) \tag{5.1}$$

Where:

C_{Mmax} = Theoretical Maximum Criticality Number

β_{max} = Maximum conditional probability of the current failure mode

α_{max} = Maximum failure mode ratio

λ_{pmax} = Item failure rate

t = Duration of applicable mission phase (expressed in hours)

This calculation is considered the *worst* scenario and the maximum possible value of the criticality for the device. The β_{max} equals 1 by considering the highest probability of the effect. Similarly, the failure mode ratio α_{max} equals 1. Finally, λ_{pmax} corresponds to the failure rate value given by the manufacturer at the highest operational temperature condition (i.e., 0.176E-06 hr^{-1}). Hence, the Theoretical Maximum Criticality Number (C_{Mmax}) was calculated as follows:

$$C_{Mmax} = (1 \text{ x } 1 \text{ x } 0.107\text{E-6 } hr^{-1} \text{ x } 90{,}000\text{hrs}) \tag{5.2}$$

$$C_{Mmax} = 9.63\text{E-02}$$

The Item Criticality Number (C_r) obtained from the three different scenarios were divided by the C_{Mmax} to obtain the percentage of the Theoretical Maximum Criticality Number ($\%C_{Mmax}$) for each scenario (Equation 5.3).

$$\% C_{Mmax} = C_r / C_{Mmax} \quad (5.3)$$

Table 5.5 shows the % maximum values under different temperatures of operation in MEMS accelerometers.

Table 5.5
Percentage of the Theoretical Maximum Criticality Number ($\%C_{Mmax}$)

Scenarios	**Item Criticality Number** (C_r)	**% of the Theoretical Maximum Criticality Number (%C_{Mmax})**
Scenario 1 at 50 °C	1.238E-05	0.0128
Scenario 2 100 °C	5.627E-04	0.58
Scenario 3 150 °C	1.171E-02	12.16

In the First Scenario, the Item Criticality Number (C_r) represents a 0.0128% of the Theoretical Maximum Criticality Number (C_{Mmax}). The Failure Rate (λ_p), the Failure Mode Effect probability (β), and the Failure Mode Ratio (α) have lower values for the assumed temperature of 50°C (See Appendix A). In conclusion, the obtained values means that the failure modes presented in the First Scenario at 50° C are not critically affected by the temperature, and do not represent a high risk of failure to the ADXL180 MEMS accelerometer.

In the Second Scenario, the Item Criticality Number (C_r) increases considerably to 0.58% of the Theoretical Maximum Criticality Number **(**C_{Mmax}). In this case, the Failure Rate (λ_p), the Failure Mode Effect probability (β), and the Failure Mode Ratio (α) are increased for the assumed temperature of 100°C (See Appendix B). At this point the failure modes suffer an initial degradation process that activates failure mechanisms such as stiction, wear, and contamination.

In the Third Scenario, the Item Criticality Number (C_r) increases dramatically from 0.58% to 12.16% of the Theoretical Maximum Criticality Number (C_{Mmax}). For this scenario, the Failure Rate (λ_p), the Failure Mode Effect probability (β), and the Failure Mode Ratio (α) are increased to the maximum value for operational conditions of a temperature of 150°C (See Appendix C). This result clearly indicates that higher temperatures accelerated failure modes in MEMS. Also, failure mechanisms such as stiction, adhesion, and wear can affect the device.

5.2.2 Individual Failure Modes Analysis

Individual failure mode analysis was performed by comparing the obtained data from tables 5.1, 5.2 and 5.3. To measure the change in the respective criticality numbers, an Increment Index (I_I) was created to compare the result for each scenario. Equation 5.4 was used to obtain the Increment Index (I_I) results in the Table 5.6:

$$I_I = \text{Final } C_m \text{ Value} - \text{Initial } C_m \text{ Value} / \text{Initial } C_m \text{ Value} \qquad (5.4)$$

Table 5.6 shows the failure mode's Increment Index (I_I) values from the First Scenario (50 °C) to the Second Scenario (100°C). In addition, Table 5.7 shows the rankings for the failure modes with the highest Increment Index (I_I). The highest I_I was that of Item 7 with an I_I of

103.13 times the criticality number at 50°C. Other failure modes such as items 8, 1, 10, 11, 6, and 2 have considerably high Increment Index (I_I).

These results confirm the premise that MEMS accelerometers are highly dependent on the temperature changes.

Table 5.6
Failure Modes Increment Index (I_I) from 50°C to 100°C

Item Id	**Failure Mode**	**Scenario 1**	**Scenario 2**	**I_I**
1	Wear debris between rubbing surfaces	6.300E-07	3.321E-05	51.71
2	Sticking of finger structures due to surface forces	1.449E-06	6.273E-05	42.29
3	Internal fracture on structure	7.245E-07	1.845E-05	24.47
4	Finger and substrate adhesion	1.512E-06	5.904E-05	38.05
5	Surface adhesion	6.930E-07	1.661E-05	22.96
6	Cracks and pores on the surface	1.071E-06	5.166E-05	47.24
7	Internal structural stress	5.670E-07	5.904E-05	103.13
8	Collapse of electrodes due to excessive deformation	1.040E-06	6.642E-05	62.90
9	Welding of the polysilicon finger to the ground plane	7.560E-07	2.768E-05	35.61
10	Noise in sensor output	1.071E-06	5.351E-05	48.96
11	Sensor output variation with temperature	1.134E-06	5.535E-05	47.81
12	Mechanical obstruction of the fingers	7.875E-07	2.214E-05	27.11
13	Internal aging of polysilicon	9.450E-07	3.690E-05	38.05

Table 5.7
Failure Modes Increment Index (I_I) Ranking from 50°C to 100°C

Item ID	Failure Mode	Increment Index (I_I)	Ranking
7	Internal structural stress	103.13	1
8	Collapse of electrodes due to excessive deformation	62.90	2
1	Wear debris between rubbing surfaces	51.71	3
10	Noise in sensor output	48.96	4
11	Sensor output variation with temperature	47.81	5
6	Cracks and pores on the surface	47.24	6
2	Sticking of finger structures due to surface forces	42.29	7
4	Finger and substrate adhesion	38.05	8
13	Internal aging of polysilicon	38.05	9
9	Welding of the polysilicon finger to the ground plane	35.61	10
12	Mechanical obstruction of the fingers	27.11	11
3	Internal fracture on structure	24.47	12
5	Surface adhesion	22.96	13

Table 5.8 shows the failure mode’s Increment Index (I_I) values from the Second Scenario (100 °C) to the Third Scenario (150°C). Table 5.9 shows the rankings for the failure modes with the highest Increment Index (I_I). The highest I_I corresponds to that of Item 10 with an I_I of 26 times the criticality number at 100°C. In this case, the I_I indexes were lower than the ones showed in Table 5.7. This effect occurs because the failure mechanisms acceleration factor is

more aggressive when the device is changing from normal operations temperatures to values closed to the absolute maximum temperature value.

Table 5.8
Failure Modes Increment Index (I_I) from 100°C to 150°C

Item Id	**Failure Mode**	**Scenario 2**	**Scenario 3**	**I_I**
1	Wear debris between rubbing surfaces	3.321E-05	3.611E-04	9.87
2	Sticking of finger structures due to surface forces	6.273E-05	1.445E-03	22.03
3	Internal fracture on structure	1.845E-05	2.408E-04	12.05
4	Finger and substrate adhesion	5.904E-05	9.630E-04	15.31
5	Surface adhesion	1.661E-05	1.204E-04	6.25
6	Cracks and pores on the surface	5.166E-05	4.334E-04	7.39
7	Internal structural stress	5.904E-05	1.083E-03	17.35
8	Collapse of electrodes due to excessive deformation	6.642E-05	1.445E-03	20.75
9	Welding of the polysilicon finger to the ground plane	2.768E-05	4.815E-04	16.40
10	Noise in sensor output	5.351E-05	1.445E-03	26.00
11	Sensor output variation with temperature	5.535E-05	1.083E-03	18.57
12	Mechanical obstruction of the fingers	2.214E-05	4.815E-04	20.75
13	Internal aging of polysilicon	3.690E-05	7.223E-04	18.57

Table 5.9
Failure Modes Increment Index (I_I) Ranking from 100°C to 150°C

Item ID	**Failure Mode**	**Increment Index (I_I)**	**Ranking**
10	Noise in sensor output	26.00	1
2	Sticking of finger structures due to surface forces	22.03	2
8	Collapse of electrodes due to excessive deformation	20.75	3
12	Mechanical obstruction of the fingers	20.75	4
11	Sensor output variation with temperature	18.57	5
13	Internal aging of polysilicon	18.57	6
7	Internal structural stress	17.35	7
9	Welding of the polysilicon finger to the ground plane	16.40	8
4	Finger and substrate adhesion	15.31	9
3	Internal fracture on structure	12.05	10
1	Wear debris between rubbing surfaces	9.87	11
6	Cracks and pores on the surface	7.39	12
5	Surface adhesion	6.25	13

5.3 Face Validation of the Conceptual Framework

Face validation is a commonly used technique for the validation of conceptual studies. It is used about thirty percent of the time. Face validation is an approach for checking a model by inquiring domain experts about a specific problem situation, and contrasting their answers against those provided by the developed prototype system (O'Leary, 1987).

Face validation was used in this conceptual framework for the assessment of the criticality of key failure modes in MEMS accelerometers. An expert with broad experience in MEMS devices reviewed and validated the results of this research.

Dr. Nima Mahmoodi, Assistant Professor of the Department of Mechanical Engineering at The University of Alabama conducts research in the areas of dynamics, vibrations, and control of mechanical systems. His current research is focused on piezoelectrically-actuated nanomechanical biosensors, nonlinear vibrations and controls with application to MEMS, energy harvesting using smart materials, active vibration control of structures with piezoelectric actuators, and vibration control of alternative energy sources such as wind turbine and solar concentrator. Dr. Mahmoodi serves as the Director of the University of Alabama's Nonlinear Intelligent Structures laboratory (NIS).

Dr. Mahmoodi commented that the methodology followed in this study is highly applicable to MEMS. He found the project's promising for future applications to other MEMS devices. He also pointed out that the results obtained in this investigation agree with the results reported by previous studies e.g., (Sandia National Laboratories, 2000; Tanner, 1999; Hartzell et al., 1999).

5.4 Summary

This chapter discussed the results obtained by the application of the developed conceptual framework for the assessment of key failure modes in MEMS accelerometers. The results for the three scenarios were analyzed and discussed. In addition, a Theoretical Maximum Criticality

Number (C_{Mmax}) was calculated to evaluate the Item Criticality Number (C_r) values from the three studied scenarios.

An Increment Index (I_I) was calculated to study the effect of the temperature on each identified failure mode. Finally, this chapter described the validation phase of the project by an expert in MEMS from the University of Alabama.

The results of this investigation show agreement with the reported results by other studies such as Sandia's National Laboratories accelerated life tests in MEMS accelerometers. Thus, it was established that the developed conceptual framework is applicable to the MEMS domain.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

The main objective of this research was the development of a conceptual framework for the assessment of the criticality of key failure modes in MEMS accelerometers. This conceptual framework represents a straightforward step by step methodology that can be easily applied to other MEMS devices. It represents a new approach for the criticality analysis of failures in microsystems.

The results obtained in this investigation were conclusive. MEMS failure modes are dependent on temperature variation. Temperature affects MEMS failure mechanisms in a different manner though. The failure modes related to stiction, wear, and adhesion were the most impacted. The attained results were in agreement with those reported by Sandia National Laboratories (2000) through Accelerated Life Testing.

6.1 Key Benefits of the Study

The developed conceptual framework represents a step forward in reliability engineering applied to microsystems. The most important breakthrough from this study is the implementation of a methodology commonly used in macrosystems to the microsystems domain.

The proposed conceptual framework can be used to evaluate failure mode criticality under various performance conditions by adjusting the involved parameters accordingly. Also, This FMECA methodology is also suitable for the design and manufacturing of MEMS devices if probabilistic reliability models for the mechanisms that make up the analyzed device are available.

This method represents a new approach to determine the criticality of failure modes in MEMS. Contrary to Accelerated Life Testing (ALT), the developed FMECA framework provides a mathematical means to understand how given variables such as temperature, vibration and shock can affect a micro device.

6.2 Recommendations for Future Research

Although this research represents a first attempt to apply a conceptual framework for the assessment of the criticality of key failure modes in MEMS, the achievements of this study can be enhanced through the following recommendations.

This project considered only three scenarios originated from different operational temperatures. Nonetheless, there are several other factors such as vibration and humidity that can be incorporated in a later effort.

The application of the proposed FMECA framework in either the design or the micromachining stages of MEMS devices should be investigated. Techniques such as Accelerated Life Testing (ALT) or stochastic reliability models should be used to determine more accurate mechanism failure rates that the ones used in this study.

The use of well-known decision-making models based in risk-assessment theory such as the Analytical Hierarchical Procedure (AHP) and Fuzzy Logic (FL) as an alternative to FMECA should be explored. In addition, The findings of this study should be extended to the assessment of key criticality failure modes beyond Class 1 MEMS (i.e. classes 2, 3 and 4). Finally, more complex mathematical paradigms such as Entropy Theory and Markovian Reasoning might be considered for the evaluation of the effects of operational variables (vibration, and mechanical/electrical shock particularly) in MEMS.

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FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA) SCENARIO 1

SYSTEM: MEMS Airbag Deployment System
PART NAME: ADXL180 (Analog Device)
REFERENCE DRAWING : N/A
MISSION : Deployment of airbag system

DATE: 2/10/2011
SHEET: 1 of: 1
COMPILED BY: M.Sequera
APPROVED BY: D.Fonseca

ITEM NUMBER	ITEM FUNCTIONAL ID	POTENTIAL FAILURE MODE	FAILURE MECHANISM (CAUSE)	SEVERITY (S)	FAILURE RATE (λp)	FAILURE EFFECT PROBABILITY (β)	FAILURE MODE RATIO (α)	OPERATING TIME (t)	FAILURE MODE CRITICALITY NUMBER (Cm)	ITEM CRITICALITY NUMBER Σ (Cm)	REMARKS
ADXL180	1	Wear debris between rubbing surfaces	Humidity, Wear	10	0.00028E-6	0.25	0.10	90000.00	6.300E-07	6.300E-07	
ADXL180	2	Sticking of finger structures due to surface forces	Stiction	10	0.00028E-6	0.25	0.23	90000.00	1.449E-06	2.079E-06	
ADXL180	3	Internal fracture on structure	Fatigue Stress	10	0.00028E-6	0.25	0.115	90000.00	7.245E-07	2.804E-06	
ADXL180	4	Finger and Substrate Adhesion	Stiction	10	0.00028E-6	0.25	.24	90000.00	1.512E-06	4.316E-06	
ADXL180	5	Surface Adhesion	Shock	10	0.00028E-6	0.25	.11	90000.00	6.930E-07	5.009E-06	
ADXL180	6	Cracks and Pores on the surface	Humidity , Temperature	10	0.00028E-6	0.25	.17	90000.00	1.071E-06	6.080E-06	

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA) SCENARIO 1

SYSTEM: MEMS Airbag Deployment System | DATE: 2/10/2011
PART NAME: ADXL180 (Analog Device) | SHEET: 2 of: 2
REFERENCE DRAWING : N/A | COMPILED BY: M.Sequera
MISSION : Deployment of airbag system | APPROVED BY: D.Fonseca

ITEM NUMBER	ITEM FUNCTIONAL ID	POTENTIAL FAILURE MODE	FAILURE MECHANISM (CAUSE)	SEVERITY (S)	FAILURE RATE (λp)	FAILURE EFFECT PROBABILITY (β)	FAILURE MODE RATIO (α)	OPERATING TIME (t)	FAILURE MODE CRITICALITY NUMBER (Cm)	ITEM CRITICALITY NUMBER Σ (Cm)	REMARKS
ADXL180	7	Internal structural stress	Humidity, Wear	10	0.00028E-6	0.25	0.09	90000.00	5.670E-07	6.647E-06	
ADXL180	8	Collapse of electrodes due to excessive deformation	Temperature	10	0.00028E-6	0.25	0.165	90000.00	1.040E-06	7.686E-06	
ADXL180	9	Welding of the polysilicon finger to the ground plane	Fatigue Stress	10	0.00028E-6	0.25	0.12	90000.00	7.560E-07	8.442E-06	
ADXL180	10	Noise in sensor output	Stiction	10	0.00028E-6	0.25	0.17	90000.00	1.071E-06	9.513E-06	
ADXL180	11	Sensor output variation with temperature	Temperature	10	0.00028E-6	0.25	0.18	90000.00	1.134E-06	1.065E-05	
ADXL180	12	Mechanical obstruction of the fingers	Contamination	10	0.00028E-6	0.25	0.125	90000.00	7.875E-07	1.143E-05	
ADXL180	13	Internal aging of Polysilicon	Humidity , Temperature	10	0.00028E-6	0.25	0.15	90000.00	9.450E-07	1.238E-05	

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA) SCENARIO 2

SYSTEM: MEMS Airbag Deployment System
PART NAME: ADXL180 (Analog Device)
REFERENCE DRAWING : N/A
MISSION : Deployment of airbag system

DATE: 2/10/2011
SHEET: 1 of: 1
COMPILED BY: M.Sequera
APPROVED BY: D.Fonseca

ITEM NUMBER	ITEM FUNCTIONAL ID	POTENTIAL FAILURE MODE	FAILURE MECHANISM (CAUSE)	SEVERITY (S)	FAILURE RATE (λp)	FAILURE EFFECT PROBABILITY (β)	FAILURE MODE RATIO (α)	OPERATING TIME (t)	FAILURE MODE CRITICALITY NUMBER (Cm)	ITEM CRITICALITY NUMBER Σ (Cm)	REMARKS
ADXL180	1	Wear debris between rubbing surfaces	Humidity, Wear	10	0.0082E-6	0.50	.09	90000.00	3.32E-05	3.32E-05	
ADXL180	2	Sticking of finger structures due to surface forces	Stiction	10	0.0082E-6	0.50	0.17	90000.00	6.27E-05	9.594E-05	
ADXL180	3	Internal fracture on structure	Fatigue Stress	10	0.0082E-6	0.25	0.10	90000.00	1.85E-05	1.144E-04	
ADXL180	4	Finger and Substrate Adhesion	Stiction	10	0.0082E-6	0.50	0.16	90000.00	5.90E-05	1.734E-04	
ADXL180	5	Surface Adhesion	Shock	10	0.0082E-6	0.25	.09	90000.00	1.66E-05	1.900E-04	
ADXL180	6	Cracks and Pores on the surface	Humidity , Temperature	10	0.0082E-6	0.50	0.14	90000.00	5.17E-05	2.417E-04	

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA) SCENARIO 2

SYSTEM: MEMS Airbag Deployment System	DATE: 2/10/2011
PART NAME: ADXL180 (Analog Device)	SHEET: 2 of: 2
REFERENCE DRAWING : N/A	COMPILED BY: M.Sequera
MISSION : Deployment of airbag system	APPROVED BY: D.Fonseca

ITEM NUMBER	ITEM FUNCTIONAL ID	POTENTIAL FAILURE MODE	FAILURE MECHANISM (CAUSE)	SEVERITY (S)	FAILURE RATE (λp)	FAILURE EFFECT PROBABILITY (β)	FAILURE MODE RATIO (α)	OPERATING TIME (t)	FAILURE MODE CRITICALITY NUMBER (Cm)	ITEM CRITICALITY NUMBER Σ (Cm)	REMARKS
ADXL180	7	Internal structural stress	Humidity, Wear	10	0.0082E-6	0.50	0.16	90000.00	5.90E-05	3.007E-04	
ADXL180	8	Collapse of electrodes due to excessive deformation	Temperature	10	0.0082E-6	0.50	0.18	90000.00	6.64E-05	3.672E-04	
ADXL180	9	Welding of the polysilicon finger to the ground plane	Fatigue Stress	10	0.0082E-6	0.25	0.15	90000.00	2.77E-05	3.948E-04	
ADXL180	10	Noise in sensor output	Stiction	10	0.0082E-6	0.50	0.145	90000.00	5.35E-05	4.483E-04	
ADXL180	11	Sensor output variation with temperature	Temperature	10	0.0082E-6	0.50	0.15	90000.00	5.54E-05	5.037E-04	
ADXL180	12	Mechanical obstruction of the fingers	Contamination	10	0.0082E-6	0.25	0.12	90000.00	2.21E-05	5.258E-04	
ADXL180	13	Internal aging of Polysilicon	Humidity , Temperature	10	0.0082E-6	0.50	0.1	90000.00	3.69E-05	5.627E-04	

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA) SCENARIO 3

SYSTEM: MEMS Airbag Deployment System
PART NAME: ADXL180 (Analog Device)
REFERENCE DRAWING : N/A
MISSION : Deployment of airbag system

DATE: 2/10/2011
SHEET: 1 of: 1
COMPILED BY: M.Sequera
APPROVED BY: D.Fonseca

ITEM NUMBER	ITEM FUNCTIONAL ID	POTENTIAL FAILURE MODE	FAILURE MECHANISM (CAUSE)	SEVERITY (S)	FAILURE RATE (λp)	FAILURE EFFECT PROBABILITY (β)	FAILURE MODE RATIO (α)	OPERATING TIME (t)	FAILURE MODE CRITICALITY NUMBER (Cm)	ITEM CRITICALITY NUMBER Σ (Cm)	REMARKS
ADXL180	1	Wear debris between rubbing surfaces	Humidity, Wear	10	0.107E-6	0.75	.05	90000.00	3.611E-04	6.02E-05	
ADXL180	2	Sticking of finger structures due to surface forces	Stiction	10	0.107E-6	0.75	0.20	90000.00	1.445E-03	1.505E-03	
ADXL180	3	Internal fracture on structure	Fatigue Stress	10	0.107E-6	0.5	0.10	90000.00	4.815E-04	1.986E-03	
ADXL180	4	Finger and Substrate Adhesion	Stiction	10	0.107E-6	0.75	0.20	90000.00	1.445E-03	3.431E-03	
ADXL180	5	Surface Adhesion	Shock	10	0.107E-6	0.5	.05	90000.00	2.408E-04	3.671E-03	
ADXL180	6	Cracks and Pores on the surface	Humidity , Temperature	10	0.107E-6	0.75	0.18	90000.00	1.300E-03	4.971E-03	

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA) SCENARIO 3

SYSTEM:	MEMS Airbag Deployment System	DATE:	2/10/2011
PART NAME:	ADXL180 (Analog Device)	SHEET:	2 of: 2
REFERENCE DRAWING :	N/A	COMPILED BY:	M.Sequera
MISSION :	Deployment of airbag system	APPROVED BY:	D.Fonseca

ITEM NUMBER	ITEM FUNCTIONAL ID	POTENTIAL FAILURE MODE	FAILURE MECHANISM (CAUSE)	SEVERITY (S)	FAILURE RATE (λp)	FAILURE EFFECT PROBABILITY (β)	FAILURE MODE RATIO (α)	OPERATING TIME (t)	FAILURE MODE CRITICALITY NUMBER (Cm)	ITEM CRITICALITY NUMBER Σ (Cm)	REMARKS
ADXL180	7	Internal structural stress	Humidity, Wear	10	0.107E-6	0.75	0.15	90000.00	1.083E-03	6.055E-03	
ADXL180	8	Collapse of electrodes due to excessive deformation	Temperature	10	0.107E-6	0.75	0.2	90000.00	1.445E-03	7.499E-03	
ADXL180	9	Welding of the polysilicon finger to the ground plane	Fatigue Stress	10	0.107E-6	0.5	0.1	90000.00	4.815E-04	7.981E-03	
ADXL180	10	Noise in sensor output	Stiction	10	0.107E-6	0.75	0.2	90000.00	1.445E-03	9.425E-03	
ADXL180	11	Sensor output variation with temperature	Temperature	10	0.107E-6	0.75	0.15	90000.00	1.083E-03	1.051E-02	
ADXL180	12	Mechanical obstruction of the fingers	Contamination	10	0.107E-6	0.5	0.1	90000.00	4.815E-04	1.099E-02	
ADXL180	13	Internal aging of Polysilicon	Humidity , Temperature	10	0.107E-6	0.75	0.1	90000.00	7.223E-04	1.171E-02	