MICROELECTROMECHANICAL SYSTEMS (MEMS) IN MILITARY SYSTEMS:
LESSONS LEARNED AND REMAINING TECHNICAL CHALLENGES

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ABSTRACT
Like commercial system applications, MEMS-based components used in military systems must meet
reliability and lifetime requirements. Testing to ensure that MEMS-based components meet these
requirements is a critical step in their development for use in military systems. If an efficient approach
for developing test and characterization methods is established, the use of MEMS-based components
in military systems may be accelerated. Our proposed approach uses a “design for reliability” approach
combined with an approach that uses analytical and computational methods. An example is included.

Introduction
Several military systems currently use microelectromechanical systems (MEMS) technology. Munitions guidance, navigation,
and control (GN&C) systems use MEMS-based inertial measurement units; display systems for ships and aircraft use MEMS-
based projection systems; and MEMS-based infrared (IR) imaging systems use MEMS-based thermal sensors. MEMS-based
fuze/safety and arming (F/S&A) systems, unattended sensor systems, communications systems, and instrumentation systems
are under development for use in military systems.

Manufacturers have learned that if component reliability for the application is not demonstrated, MEMS-based components will
not be used. As a result, practices to develop and produce reliable MEMS products have evolved [1, 2, 3]. These practices
entail designing for product reliability early in the development process [1, 2, 4]. Designing for reliability involves testing and
characterization throughout development and production. Manufacturers perform a combination of MEMS device and
component-specific tests and “standard” tests to develop reliable products and demonstrate that the product meets
specifications [1, 2, 5]. Manufacturers have discovered that testing and characterization tool and method development is a
critical part of the development and production process for MEMS-based components.

Manufacturers establish component specifications to show that the component will meet the requirements for the intended
application. Compared with commercial applications for MEMS-based components, military system applications usually
involve a greater required component lifetime and exposure to more environments during the component lifetime. Because of
these differences, MEMS developers and military system developers will have to develop test and evaluation practices to
ensure repeatable, reliable performance of MEMS-based components in military systems [6, 7, 8].

Since successful component developers employ a “design for reliability” approach, this paper begins with a review of MEMS
reliability. Next, commercial MEMS design and development practices based on the design for reliability approach are
discussed. This is followed by a discussion of testing and characterization performed during design and development. We then
propose an approach for identifying and facilitating development of testing and characterization methods and follow this with
an example illustrating the proposed approach.

MEMS Reliability
“Reliability is the probability that a system, component, or device will perform without failure for a specified period of time under
specified operating conditions” [9]. Failure may be separated into two distinct categories:

- Degradation failure, which consists of device operation departing far enough from normal conditions that the
  component no longer meets component performance requirements; and
- Catastrophic failures, the complete end of device operation [10].

Early in the development of MEMS technologies and components, the emphasis of many research and development (R&D)
programs was on device design, process development, and prototype performance demonstration in the laboratory [4]. The
processes and devices were not developed to ensure device manufacturability, reliability, or ability to be packaged. Packaging and reliability efforts were relegated to the later stages of product development [5].

Most Armed Service development programs do not have sufficient funding to take an unpackaged prototype MEMS device to an acceptable maturity level. Consequently, many prototype devices targeted for use in military systems are taking longer to develop than initially planned. To facilitate transition of MEMS-based components into military systems, developers should adopt practices that establish the foundation for MEMS-based component manufacturability, packaging, and reliability. The same is true for MEMS-based component transition into commercial system applications: MEMS-based components must have proven manufacturability (i.e., high yield) and proven final component (i.e., packaged device) reliability to be commercially feasible. Manufacturability, packaging, and reliability are inseparable. The experience of MEMS product manufacturers indicates that reliability must be designed into the product using an approach that begins at the product concept phase and continues through the production phase [1, 2, 4].

A design for reliability approach requires a multidisciplinary design team consisting of personnel with experience: chip design, chip-level processing, packaging, system design, manufacturability, and reliability [11]. To determine product reliability, a methodical approach to relate final product reliability to reliability at each of the earlier development and production phases is needed [4]. Another way to look at the relationship between final product reliability and the reliability at each development and production phase is to understand that there is a hierarchy from the chip reliability, to packaged device reliability, to subsystem reliability, to system reliability [11].

MEMS Design and Development Practices

Figure 1 shows, in flowchart form, a general component development cycle incorporating a design for reliability approach. To design for reliability, a reliability design goal should be one of the initial design goals established [1]. The requirements for the proposed system application for the product are used to establish product design goals, including a reliability design goal. This is true for military systems. The design goals, including reliability and lifetime goals, should be based on the system requirements.

A process flow, a device design, and a component design are generated after the design goals are established. Then, a Failure Mode and Effects Analysis (FMEA) is performed on the process and design [1, 11]. The FMEA approach is a disciplined, systematic procedure designed to identify potential process and product weaknesses that could lead to failure [11]. In the FMEA approach, a group of experts from various technology and manufacturing areas suggest possible failure modes, considering processing methods, design constraints, packaging concerns, test procedures, and other possible factors that could contribute to failure [1]. The group identifies the consequences, or risks, of failures [11]. Based on the possible failures and the related associated consequences, the list of failure modes is ranked according to their effect on the “customer.” This list establishes a priority system for in-process testing, developmental testing, and design improvements [12].

Simulation and analysis is performed to investigate potential failure modes and to introduce possible process and design changes. Once the simulation and analysis is completed, the predicted performance of the device and component is compared to the design goals. If the performance does not meet the design goals, one or more of the following are modified: the process flow, the device design, or the component design. The modifications are based on insight gained from the FMEA and from the simulation and analysis. Compared with approaches that do not use FMEA, the FMEA approach has enabled a faster time to market with lower risk of failures for a new device design [1].

Testing and Characterization

Testing and characterization is a critical part of the design for reliability approach [1, 12]. (See Figure 1, which shows that FMEA and test and characterization are part of the development process.) However, test and characterization planning, including the development of test and characterization methods, is not stated explicitly as part of the development process. As noted above, the FMEA identifies and establishes priorities for in-process testing and characterization and for post-process developmental testing and characterization. The experience of MEMS-based component manufacturers indicates that MEMS process-, device-, and component-specific test methods combined with established, accepted test methods are needed to develop reliable components [1–3].

One example of MEMS-based process-, device-, and component-specific testing is the Deformable Mirror Display (DMD) test system developed by Texas Instruments, Inc., for testing of the DMD [1]. In addition, many test and characterization techniques have been developed by researchers in academe, in national laboratories, or in other government laboratories. These researchers typically attempt to gain a general, fundamental understanding of MEMS materials, processes, and device behavior. Testing and characterization research on MEMS materials, processes, and devices has increased over the past 5 years based on the number of presentations at conferences and symposiums sponsored by organizations such as SPIE, the Society for Experimental Mechanics (SEM), the American Society of Mechanical Engineers (ASME), and the Materials Research Society (MRS). Many researchers utilize a combination of analytical and computational techniques to develop testing and characterization tools and methods for advancing the fundamental understanding of MEMS materials, processes, and device behavior [13, 14, 15, 16]. Continued development of MEMS-based process-, device-, and component-specific test methods is needed as existing MEMS-based components are used in new applications, such as military systems, or as new
components are developed. The challenge is to identify and develop the testing and characterization tools and methods needed for the new application or the new component.

Proposed Test and Characterization Method Development Approach
The proposed approach is to use FMEA to identify potential failure modes and to identify the data developers need to reduce the probability of failure for the identified failure modes. Once the FMEA is performed, an “ACES-like” methodology would be used to aid in the development of testing and characterization tools and methods used to generate the needed data. (Coordinated analytical, computational, and experimental solutions, or ACES, methodology has been developed to obtain solutions to design problems [13].)

The circles in Figure 2 represent the “solution space” for each method used for the posed design problem. For example, the analytical method will yield several potential solutions depending on the assumptions regarding device geometry, material properties, loading conditions, and boundary conditions. The computational method will yield several potential solutions depending on these same factors and on the computational method employed. The experimental method will yield several potential solutions depending on the calibration, resolution, and sensitivity of each method and on the methods used. As experimentally measured values, instead of assumed or design input values, are used in the analytical and computational methods, a robust, self-consistent solution to the design problem is obtained that lies within the intersection of the three solution spaces shown in Figure 2 [17]. How can experimental tools and methods be developed using this approach?

Using the combination of analytical and computational methods to identify critical design parameters and possible device/component response will aid in the selection of experimental tools and methods. From the analytical method, in addition to identifying experimental tools and methods for testing and characterization, the resolution and range of measurements required will be identified. For example, the method a researcher uses to measure displacement as a function of loading will depend on the expected range of displacements to be measured and the loading method employed. That is, if expected displacements are on the order of 6 inches, a different experimental method would be used than if the expected displacements were on the order of a tenth of an inch. The computational method will provide further insight into additional experiments and measurements that may be needed to aid the designers. Once the testing and characterization are completed, the measured parameters (such as displacement) can be used to refine the input values and assumptions used in the analytical and computational methods. Providing the developer a means to refine input values and assumptions will aid in identifying needed process and design changes.
Test and Characterization Development Approach: An Example
The following hypothetical example demonstrates how the proposed approach can provide information used to guide experimental tool and method development. This example only applies this approach to the device design. In practice, this approach would be applied to the packaged device or component, as well to investigate potential failure modes due to the interaction between the package and the device. Consider a component that contains a sensor that uses the deflection of an array of polysilicon cantilever beams as the sensing mechanism and changes in capacitance between the beams and the substrate as the transduction mechanism. Once an initial process flow, device design, and component design are established, an FMEA is performed. Assume that the process flow is a surface micromachined polysilicon process in which a polysilicon cantilever beam array can be produced. The beams in the array are designed to have the same dimensions (reported below).

A potential failure mode for the array is the sticking of beams to the substrate during operation. This occurs when sufficient force is applied to deflect the beam so that the bottom of the beam contacts the substrate. Based on this failure mode, designers need data that will aid their efforts to reduce the probability of a beam touching the substrate. Such data include the average and statistical repeatability of:

- the force needed to cause beams to contact the substrate,
- the beam dimensions and geometry, and
- the Young's modulus for the polysilicon beam material.

Next, the ACES-like methodology will be used to generate additional information on the experimental tools and methods needed. For this example, the first step is to use analytical methods to predict the force-deflection response of the beams. The next step is to utilize computational methods to predict the force-deflection deflection response of the beams. From these methods experimental tools and methods will be identified and required tool capability (e.g., measurement range and resolution) will be discussed.

For this example, the analytical model used is a rectangular cantilever beam rigidly fixed at one end. The design is for the force to be applied at a single point at the free end of the cantilever beams. From the static beam equations for a rectangular cantilever beam fixed at one end with a point force applied at the free end, the equation for the force needed to deflect the beam a distance equal to the gap distance is given by [18]:

$$ F = \frac{Ewdt^3}{4L^3} $$  \hspace{1cm} (1)

The beam is designed to have the following dimensions:

- length \((L)\) of 100 \(\mu\)m,
- width \((w)\) of 20 \(\mu\)m,
- thickness \((t)\) of 2 \(\mu\)m,
- gap under the beam \((d)\) from the bottom of the beam to the top of the substrate of 3 \(\mu\)m.
A value of 169 GPa for the Young’s modulus ($E$) is used. A sensitivity analysis is then performed to establish the maximum range of predicted force values based on reasonable ranges of values for each input parameter. For this example, it assumed that during fabrication the beam dimensions can be controlled to 0.1 µm, and each input dimension is considered independently with all other input parameters; this introduces a range of predicted forces from 0.017 mN to 0.023 mN. If the dimensions are combined to provide a maximum range in the estimate for predicted force, keeping Young’s modulus constant, the predicted force range is from 0.017 mN to 0.024 mN. One researcher reported Young’s modulus for polysilicon as 169 ± 6.15 GPa [19]. Using this range resulted in predicted forces from 0.019 mN to 0.021 mN. If the dimensions and values for Young’s modulus are combined to provide a maximum estimate of the range in predicted force values, the range is from 0.016 mN to 0.025 mN. This maximum range of predicted force values is the solution space for the analytical method schematically represented in Figure 3. A line that has the length of the maximum predicted range of forces at a deflection of the gap value, d, represents the solution space.

The computational method consists of developing solid models used in finite-element methods. For MEMS devices, the solid models are usually generated by software that contains a solid-model-generation package that uses process-flow information and the mask layouts. The finite-element method then performs a sensitivity analysis based on reasonable ranges of values for each design parameter as described above. The range of predicted force values obtained is the solution space for the computational method shown in Figure 4. A finite-element method analysis of a polysilicon beam has not been completed. A maximum range of predicted force values would need to be computed in a manner similar to the example for the analytical method. When comparing analytical model predictions and computational model predictions, the developer typically will gain insight into the effect that the more realistic representation of the device structure (in this case a cantilever beam) has on the predicted response.

How can the above information from the analytical and computational methods be used in the development of test and characterization methods? For this example, by using the results from the FMEA, it is determined that measurements of
deflection of cantilever beams as a function of applied force are needed. Using the design values for beam dimensions and material properties, it will be necessary to be able to apply a point force to the free end of the beams having a maximum magnitude of 0.03 mN to ensure that sufficient force can be applied to cause contact. For the initial experimental tools and methods, it is assumed that the control and resolution required on the applied force should be at least an order of magnitude less than the minimum predicted applied force. Using the predicted force from the analytical method, this implies that a test method where the applied force can be controlled and has a resolution of at least 0.0017 mN (1.7 µN) is needed. While applying the force, the deflection of the beam must be measured. If the gap is on the order of 3.0 µm, the deflection measurement must be performed with a minimum resolution of 0.3 µm while the force is being applied. Based on the assumption that the dimensions can be controlled to within 0.1 µm, the characterization methods used to measure the dimensions would need to have a resolution of at least 0.01 µm for dimensions ranging from microns to hundreds of microns.

In addition to the information obtained from the analytical methods, differences in the predicted force ranges between the analytical method and the computational method will provide additional insight. For example, assume that the minimum predicted force value for the computational method is lower than the value predicted by the analytical method. The lower minimum predicted force indicates that when a more realistic representation of the beam is used, the beam is more compliant. One possible source of increased compliance may be a non-rigid response at the fixed end of the beam. This information can be used to refine the analytical model. Then, the experimental parameters to be controlled or measured can be updated.

The FMEA indicates the types of testing and characterization needed to support the development of a reliable component. Quantitative information (e.g., range and resolution) of experimental parameters to be controlled or to be measured is provided by the analytical method. Further refinement of quantitative information for these parameters is provided by the computational method. This is the information that experimenters will need to develop testing and characterization tools and methods. To reduce the amount of time needed to develop testing and characterization tools and methods, the proposed approach encourages a planned approach.

Summary
MEMS-based components must have proven manufacturability and reliability if they are to be used in military systems. Commercial MEMS developers have learned that to produce a component that is reliable and able to be manufactured with high yield, a design for reliability approach should be used. This approach involves identifying reliability design goals early in the development process; performing an FMEA on the process, device designs, and component designs; and establishing testing and characterization tools and methods to investigate process, device, and component reliability. The proposed methodology uses a design for reliability approach combined with an approach that uses analytical and computational methods. The example presented shows how the proposed methodology could be used to aid in the establishment of testing tools and methods.

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