Electrical Calibration of Spring-Mass MEMS Capacitive Accelerometers

Lingfei Deng*, Vinay Kundur*, Naveen Sai Jangala Naga*, Muhlis Kenan Ozel*, Ender Yilmaz+, Sule Ozev*, Bertan Bakkaloglu*, Sayfe Kiaei*, Divya Pratab+, and Tehmoor Dar+

*School of Electrical, Computer, and Energy Engineering
Arizona State University

+Freescale Semiconductor

Abstract

Testing and calibration of MEMS devices require physical stimulus, which results in the need for specialized test equipment and thus high test cost. It has been shown for various types of sensors that electrical stimulation can be used to facilitate lower cost calibration. In this paper, we present an electrical stimulus based test and calibration technique for overdamped spring-mass capacitive accelerometers which require the characterization of stationary and dynamic calibration coefficients. We show that these two coefficients can be electrically obtained.

1. Introduction

Micro-Electron Mechanical Systems (MEMS) transfer a mechanical stimulus to an electrical response [1], which can then be measured with electronic circuitry and the attributes of the physical stimulus can be obtained using mathematical relations. In the case of a spring-mass MEMS accelerometer, the measured quantity is the capacitance, or the difference of the two capacitances, and analytical relation between capacitance and internal device parameters can be used to convert this information to acceleration, which is the actual measurement goal. However, the accuracy of this information depends on two factors: (a) measurement accuracy of the capacitance difference, and (b) knowledge on the parameters of the internal MEMS structure. To enhance the accuracy of the capacitance measurements, many circuit-level techniques can be applied, such as correlated double sampling and chopper stabilization. Multiple sense fingers can be used, the measurements can be repeated multiple times, and the sensitivity can be increased to 155mV/fF [2] or 300mV/fF [3].

In contrast, the internal parameters of the MEMS structure, such as, permittivity, mass, and spring constant, cannot be directly measured. As with any manufacturing process, these parameters are subject to process variations. After manufacturing, the only information that is available is the nominal value of these parameters.

In order to facilitate accurate readings from the MEMS devices, it is essential that these devices are calibrated. Moreover, similar to any other manufacturing process, MEMS devices are subject to manufacturing defects, which alter the complete structure and result in loss of functionality or shift in the internal parameters of the device. In order to prevent any defective device from being shipped to the customer, these devices also need to be tested for manufacturing defects.

978-3-9815370-0-0/DATE13/©2013 EDAA
This work is supported by SRC by contract number 2164.001

Testing and calibration of MEMS devices is an important component of the overall manufacturing cost. In order to obtain calibration parameters, these devices need to be excited with physical stimulus, which requires specialized, expensive equipment. Moreover, in order to prevent defective devices from being integrated with functional ASICs, MEMS devices need to be dynamically tested at the wafer-level.

During the MEMS product testing, there are two phases. The first phase is the wafer level testing that includes two types: simple static and quasi-static tests and dynamic measurements. In the first type, tests such as continuity tests or capacitance measurements, are currently in use in the industry. The main goal is to eliminate defective MEMS dies to save costs associated with packaging and/or ASICs that go along with them. Dynamic measurements are currently used in a limited capacity in the industry. Greater use of dynamic measurements is desired not only to eliminate defective MEMS devices but also to enable a detailed characterization at the wafer-level. Examples of dynamic measurements include frequency-dependent characteristics such as resonant frequency, damping factor, poles and zeros.

The second phase of testing occurs after packaging where the goal is to evaluate the full MEMS system functionality and performance. Due to process variations, the MEMS response varies, calibration parameters in terms of coefficients that relate the actual response to the desired response are determined in this phase. Characterization and calibration of MEMS devices require specialized, high cost testing equipment such as high-gravity shakers (up to 40g) [4].

This work aims at lowering the production cost of spring-mass capacitive accelerometers by addressing these test/calibration challenges. Specifically, the aim of this work is to develop a unified framework for testing and calibration of these devices using a small number of electrical measurements, thereby eliminating the need for physical stimulus.

In order to achieve these goals, analytical derivations are used to determine a small set of electrical measurements that can help in measuring the calibration coefficient without a physical stimulus. However, relying on these analytical relations is not advisable since there are secondary unmodeled effects that might change the behavior slightly. Thus, a statistical modeling framework is used to facilitate the mapping between electrical measurements and the calibration parameters. A MATLAB Simulink platform for the accelerometer developed in-house by the designers is used to experimentally verify that the selected set of specifications are adequate in determining the calibration coefficients accurately.

2. Related Work

Over the past several decades, many testing and calibration methodologies have been proposed for the MEMS sensors. In [5], the authors characterize contamination fault behavior of a MEMS resonator. They develop a process simulator with the contamination fault injection and a mechanical simulator generating mechanical parameters. In [6], the testing of the MEMS flow sensor and the optical sensor have been discussed, including the customized ATE and a test setup for detecting the faults (misalignment of the flow sensor, voids in the waveguide of the optical sensor). In [7], the faults caused by micro-machining defects have been targeted. A circuit level approach is used to model the behavior of MEMS sensors, as well as the fault behavior.

Electrical-only test solutions for three types of MEMS have been proposed in [8]. Regarding the BIST solution, [9] introduces a dual-mode BIST technique for the capacitive MEMS devices. Capacitor partitioning of fixed capacitance plates enables the operation of different BIST modes for symmetry and sensitivity tests. In [10] and [11], the authors use the impulse response evaluation technique to implement BIST response to the digital domain. They both use polynomial linear feedback shift register (LFSR) based pseudo-random test sequence.

Another trend of MEMS testing and calibration is to use a statistical framework for test compaction, parameter prediction, and calibration. A two-class support vector machine (SVM) is used in [12] for the specification test compaction of analog circuits and MEMS. Based on the data of a training set, the two-class vector is able to pass or fail the device when it goes through a pruned test set. Multivariate adaptive regression splines (MARS) model is used in [13] for the prediction of the capacitive accelerometer parameters, such as proof mass, spring constant, and damping coefficient. MARS model is also used in [14-16] for the test and calibration of the convective accelerometer. Artificial Neural Networks (ANN) are also one of the regression-based models, used in [17] for the testing and diagnosis of MEMS pressure sensors. A specified testing and calibration method has been proposed in [18] for MEMS capacitive accelerometers.

Our work is conceptually similar to other techniques in MEMS testing [13-16,18]. Compared to the state of art, our contributions include determination of a full set of electrical measurements, which can be conducted with simple on-chip circuitry, for the characterization of the MEMS device as well as for the estimation of calibration coefficient, and using an outlier analysis technique to prevent defective devices from polluting the statistical estimation process.

3. Spring-Mass Capacitive Accelerometer Structure and its Calibration

The operation principle for the accelerometer that we study are based on the response of a movable finger with respect to physical stimulus and the electrical property that it generates, namely capacitance. In this section, we will review the operation principle of the accelerometer and determine the set of necessary measurements to characterize and calibrate the device.

A spring-mass capacitive MEMS accelerometer structure is shown in Figure 1. The movable shuttle is connected by two springs with the spring constant, K. Two fixed plates, together with the movable plate, form two capacitors. If there is no acceleration, the movable plate is at the center of two fixed plates, so that both capacitors have the same capacitance value (Eqn.1).

$$C_1 = C_1 = \varepsilon \frac{A}{d} \quad \text{(Eqn.1)}$$

where ε is the dielectric constant, A is the overlap area between movable and fixed plates, and d is the gap between the plates. If a vertical acceleration is applied to this system, the MEMS accelerometer will be

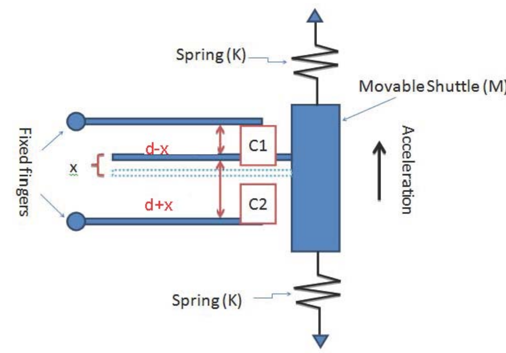

Figure 1: Spring-Mass Capacitive Accelerometer Structure

activated by this stimulus which contributes to a certain amount of small displacement of x, then, C1 and C2 will be altered as in Eqn.2.

$$C_1 = \varepsilon \frac{A}{d - x} \quad C_2 = \varepsilon \frac{A}{d + x} \quad \text{(Eqn.2)}$$

The offset between the two capacitors is given by Eqn.3. This non-linear equation can be solved assuming x<<d. Thus, one can obtain a linear relation between capacitor offset and displacement, and hence, acceleration (Eqn.3-6).

$$x \cong \frac{d^2}{2\varepsilon \cdot A} \Delta C \quad \text{(Eqn.3)} \qquad a = \frac{k}{m} x \quad \text{(Eqn.4)}$$

$$\Delta C \cong \frac{2\varepsilon \cdot A \cdot m}{k \cdot d^2} a \quad \text{(Eqn.5)} \quad S = \frac{\varepsilon \cdot A \cdot m}{k \cdot d^2} \quad \text{(Eqn.6)}$$

Where k is the spring constant and m is the mass, and S is the linear coefficient (sensitivity) between the measurable quantity (ΔC) and acceleration, which is also referred to as the untrimmed sensitivity of the system. Unfortunately, the sensitivity is a function of the internal parameters of the MEMS structure, namely, permittivity, mass, and spring constant, area, and gap. In order to facilitate accurate readings from the MEMS devices, it is essential that these devices are calibrated with respect to their internal parameters. Moreover, MEMS devices are subject to manufacturing defects, which alter the complete structure and result in loss of functionality or shift in the internal parameters of the device. In order to prevent any defective device from being shipped to the customer, these devices also need to be tested for manufacturing defects.

3.1 Calibration of MEMS devices

The calibration process for MEMS devices for the most part entails determination of the sensitivity term (Eqn.7). However, process variations do not only alter this sensitivity but also generate a stationary offset between the two capacitors due to the variations in the gap between C_1 and C_2. This stationary offset (ΔC_{off}) can be electrically measured when the part is stationary and it is the first step in calibration. The next phase of the calibration process entails applying a known physical stimulus to the device (in case of the accelerometer, it is a known acceleration (a_{app})), and measuring the capacitor offset (ΔC_{meas}). This offset includes the stationary offset and it has to be removed from the measured dynamic capacitance offset. Then, the sensitivity can be determined as the ratio of the dynamic capacitance offset and acceleration. The ratio between the actual sensitivity and the nominal sensitivity is also known as the calibration coefficient (CC). Calibration coefficient is more informative in the sense that it provides a device-independent metric to assess how close the device behavior is to the expected behavior. This process is outlined in Eqn.7-8, where p_{nom} indicates the nominal value of parameter p, which is known for the given process.

$$S = \frac{\Delta C_{meas} - \Delta C_{off}}{a_{app}} \text{ (Eqn.7)}$$

$$CC = \frac{S_{nom}}{S} = \frac{\frac{k}{k_{nom}} \cdot \left(\frac{d}{d_{nom}}\right)^2}{\frac{\varepsilon}{\varepsilon_{nom}} \cdot \frac{A}{A_{nom}} \cdot \frac{m}{m_{nom}}} \text{ (Eqn.8)}$$

4. Electrical Stimulus-based Calibration of the Accelerometer

It is desirable to determine this calibration coefficient using electrical measurements. The first and foremost goal of this work is therefore to determine the necessary set of measurements to achieve this goal.

Eqn.5 reveals that the calibration coefficient depends on the ratio k/m and the two capacitors formed by the parallel plates, C1, and C2. C1 and C2 are directly accessible through electrical measurements. The ratio k/m determines the natural frequency of the spring-mass system. This natural frequency may be altered by the parasitics; yet a strong correlation still exists with the natural frequency observed from the overall electrical equivalent of the system and the calibration coefficient. However, for some designs, direct measurement of the natural frequency may not possible due to overdamping of the response. Thus, we need to devise a set of measurements that will be representative of the natural frequency without actually measuring or calculating it. These measurements need to be simple enough so that they can be measured with simple ATE or on-chip by the ASIC.

Here, we note that the frequency domain gain magnitude response of the MEMS device is directly related to the natural frequency. Since the spring-mass system is a second order system, at least two frequency domain measurements are needed to be able to characterize its behavior. In addition to the magnitude information, the frequency at which the input and output present with 90° phase shift is directly correlated to the natural frequency of the system. While

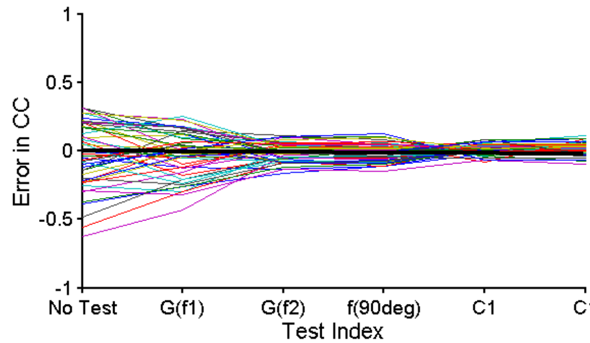

Figure 2: Progression of estimation error after each measurement

under ideal circumstances, the magnitude measurements suffice in establishing a good correlation, the response will be altered by parasitics in the device, the device-to-ASIC connection, and the loading by the ASIC or tester. Thus, using the phase information provides us with additional tools to establish a better correlation.

In summary, our test plan includes the gain at two different frequencies, one very low frequency (several hundred Hz, f0), and one at relatively higher frequencies (1-3kHz range, f1), the frequency at which the phase difference between the input and output signals equals 90°, and two stationary capacitances formed by the parallel plate structure, C1, C2. These measurements can easily be done with bench or automatic equipment as well as on-chip implementation.

Due to their ease of use and the ease of transfer into the probability domain, we use the neural network approach based on reproducing Hilbert kernel space formulation (RHKS) [**Error! Reference source not found.**,**Error! Reference source not found.**]. In this statistical learning and mapping methodology, information on each sample device is embedded as a node with a Gaussian Kernel function around it.

5. Results

In order to evaluate the feasibility of the proposed test flow on the available accelerometer design, we used the MATLAB/Simulink model of the MEMS device developed by the designers of the overall MEMS/ASIC system. This model captures the ideal behavior, as well as the secondary non-linear effects of the spring-mass system. This device can accept acceleration or voltage as input; the two capacitor outputs are accessible. No other access point exists in for this device. Process variables for this device include mass (m), spring constant (k), area (A), gap (d), and damping constant (q). The process engineers also specify the variation range of each of these parameters. Monte-Carlo samples are generated with process variations only within the ±3σ range.

Calibration coefficients of devices within the verification set are estimated as explained in Section 4. Figure 2 shows the progression of error for the calibration coefficient after each measurement for 50 randomly picked sample device instances. Here, the training set size is 150 devices. The first datapoint corresponds to no test, which means the mean value of the calibration coefficients in the training set is used as the estimate. The second and third points correspond to the gain magnitude at two frequencies, G(f1) and G(f2). The fourth point is the phase measurement (f(90deg)), and the final two points correspond to the stationary capacitance measurements, C1 and C2.

Acceptable error in calibration coefficient is within 0.1. With no test, some of the devices display errors beyond this limit. Thus, we can conclude, even from this small sample set that testing and calibration are absolutely necessary for correct operation.

In order to evaluate the dependency of the estimation accuracy to the training set size, we have also run various experiments with differing training set sizes.

Table 1 summarizes the accuracy/training set size dependency. Clearly, having a higher number of devices in the training set provides a better snapshop of process variations and thus better estimation accuracy. However, it is clear that several hundred devices suffice to get a good estimate of the calibration coefficient.

Table 1: RMS Error over the sample devices in the verification set.

Training set size	RMS error after frequency measurements	RMS error after C1 measurement	RMS error after C2 measurement
500	0.051	0.032	0.021
400	0.052	0.032	0.023
300	0.053	0.033	0.024
200	0.056	0.034	0.026
100	0.058	0.037	0.031

6. Conclusions

Due to process variations, the response of spring-mass MEMS sensors needs to be calibrated. This process generally requires a physical stimulus. However, electrical excitation can be used to facilitate the estimation of the calibration coefficients provided that a model relating the electrical response to the physical response is developed. In this paper, we have derived the necessary analytical relations to analyze the response of an accelerometer and used this analysis to determine a set of low-cost electrical measurements to characterize these devices. Due to access limitations and the overdamped response of the accelerometer, we have selected to use two gain magnitude measurements, one phase measurement, along with the stationary capacitances to characterize the MEMS device and estimate the calibration coefficient.

Using simulations based on a MATLAB model for the target sensor, we have shown that very accurate estimation of the calibration coefficient can be obtained with simple, feasible electrical stimulation only. We have also presented an outlier analysis technique which is essential in pruning away defective devices to avoid polluting the learning/estimation process. This outlier analysis has shown to be very effective in determining even the close-in outliers which have functional responses with variations outside the given process window.

References

1. L. S. Fan, Y. C. Tai and R. S. Muller, “IC-processed electrostatic micro-motors”, IEEE International Electron Devices Meeting, pp. 666-669, 1988.
2. T.C. Lu, Y.J. Huang, and H.P. Chou, “A novel interface circuit for capacitive sensors using correlated double sampling demodulation technique”, Second International Conference on Sensor Technologies and Application, pp. 396-400, August 2008.
3. B. V. Amini, and F. Ayazi, “A 2.5 V 14-bit Sigma-Delta CMOS SOI Capacitive Accelerometer”, IEEE J. Solid-State Circuits, vol-39, No. 12, pp. 2467-2476, 2004.
4. R. O'Reilly, H. Tang and W. Chen, "High-g testing of MEMS devices, and why", IEEE Sensors, pp. 148-151, 2008.
5. A. Kolpekwar, and R.D. Blanton, "Development of a MEMS testing methodology", International Test Conference, pp. 923-931, 1997.
6. H.G Kerkhoff, "Testing of MEMS-based microsystems", European Test Symposium, pp. 223- 228, 2005.
7. S. Mir, and B. Charlot, "On the integration of design and test for chips embedding MEMS", IEEE Design & Test of Computers, vol. 16, no. 4, pp. 28-38, 1999.
8. B.Charlot, S. Mir, F. Parrain, and B. Courtois, "Electrically induced stimuli for MEMS self-test", IEEE VLSI Test Symposium, pp. 210-215, 2001.
9. X. Xiong, Y. Wu, and W.-B. Jone, "A dual-mode built-in self-test technique for capacitive MEMS devices", IEEE Transactions on Instruments and Measurements, vol. 54, no. 5, pp. 1739- 1750, 2005.
10. M.F. Islam, and M.A.M. Ali, "On the use of a Mixed-Mode Approach For MEMS Testing", IEEE International Conference, pp. 62-65, 2006.
11. L. Rufer, S. Mir, E. Simeu, and C. Domingues, "On-chip testing of MEMS using pseudo-random test sequences", IEEE conference symposium, pp. 50- 55, 2003.
12. S. Biswas, L. Peng, R.D. Blanton, and L.T. Pileggi, "Specification test compaction for analog circuits and MEMS [accelerometer and opamp examples]", IEEE Design, Automation and Test in Europe, Vol. 1, pp. 164- 169, 2005.
13. V. Natarajan, S. Bhattacharya, and A. Chatterjee, "Alternate electrical tests for extracting mechanical parameters of MEMS accelerometer sensors", IEEE VLSI Test Symposium, pp. 6, 2006.
14. A.A. Rekik, F. Azais, N. Dumas, F. Mailly, and P. Nouet, "Investigations on electrical-only test setup for MEMS convective accelerometer", International Conference on Signals, Circuits and Systems (SCS), pp. 1-6, 2009.
15. A.A. Rekik, F. Azai□s, N. Dumas, F. Mailly, and P. Nouet, "An electrical test method for MEMS convective accelerometers: Development and evaluation", Europe Conference & Exhibition, pp. 1-6, 2011.
16. A.A. Rekik, F. Azais, N. Dumas, F. Mailly, and P. Nouet, "Test and calibration of MEMS convective accelerometers with a fully electrical setup", Latin American Test Workshop, pp. 1-6, 2011.
17. V. Litovski, M. Andrejevic, and M. Zwolinski, "ANN based modeling, testing and diagnosis of MEMS [capacitive pressure transducer example]," 7th Seminar on Neural Network Applications in Electrical Engineering, pp. 183- 188, 2004.
18. N. Dumas, F. Azais, F. Mailly, P. Nouet, "Evaluation of a fully electrical test and calibration method for MEMS capacitive accelerometers," IEEE International Mixed-Signals, Sensors, and Systems Test Workshop, pp. 1-6, 2008.
19. Y. Hailong, Y. Maofeng, D. Wang, J. Xinzhang, “Kriging Model combined with latin hypercube sampling for surrogate modeling of analog integrated circuit performance”, IEEE Symposium on Quality of Electronic Design, pp. 554-558, 2009.