Towards Bridging a Gap between Simulation and Experiment

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ABSTRACT

We present a pioneering effort into bridging a gap between simulation and experiment. We are creating an online tool called SugarX (version 0.1) that extracts mechanical properties from MEMS through electronic probing, and imports the properties into a corresponding computer model in attempts to investigate the performance of simulation against experiment. SugarX is an integrated system consisting of our Sugar-based modeling and simulation engine, our micro electro metrology (EMM) test bed, and Labview which couples the real and simulated domains. SugarX is available online at nanoHUB.org for remote experimental control and simulation. A goal with SugarX is to have both the real device and computer model share the same electromechanical properties. It is expected that EMM will be able to extract more than three dozen mechanical properties through electronic probing. In this initial version of SugarX, the user is able to automatically extract the displacement, comb drive force, and stiffness of the real device, and then export these properties into the model. The user is then able to control applied voltages of the real and simulated devices simultaneously. What else is interesting is that users are able to investigate Casimir and van der Waals forces within SugarX in real-time over the web.

Keywords: SugarX, EMM, Electro Micro Metrology, nanoHUB, Experiment, Simulation, Casimir, van der Waals.

1. INTRODUCTION

One of most difficult stages in the MEMS design-and-test cycle is model validation. As a consequence, model validation is usually ignored. A widely desired goal is to create a device that behaves like its prerequisite computer model. Although this goal remains elusive due to unpredictable variations in fabrication processes, what we are doing is working in the opposite direction. That is, our objective is to create a computer model that behaves like its post-requisite device. We are investigating this objective by extracting mechanical properties from the fabricated device and substituting those properties back into its computer model. One proposed outcome of this investigation is to validate the computer model. That it, it is often assumed that the chosen analytical or computer models are correct, but this assertion has yet to be completely validated or the limits of the models have yet to be completely explored. Another proposed outcome is to create experimentally-accurate models that can be used to increase our understanding of new or subtle micro or nanoscale phenomena.

Some previous efforts to extract geometric and material properties of fabricated devices include the following. Ostensberg and Senturia [1] use large arrays of devices to extract Young's modulus and residual stresses. Gupta [2] uses computer modeling along with electric probing to help extract process offsets and sidewall angles. Garmire [3] uses complementary comb drives to extract planar overcut and comb-drive forces. And Gasper [4] uses optics to extract in-plane displacements. What we propose to do differently is provide a methodology for automatic property extraction, a much greater number of properties, quantifiable measurements of uncertainty, and the importation of these properties into the prerequisite models.

Our theory called electro micro metrology (EMM) that can be used to measure force, geometry, displacement, and numerous other properties is proposed in [5] and [10]. Using EMM, measurements of geometry are reported in [6]. Advancements to EMM have been demonstrated in [7] that make it more practical.

SugarX integrates an EMM test bed and Labview [11] to automatically measure real device properties and substitutes those properties into a computer model for side by side comparisons. For demonstration purposes, SugarX is available online at nanoHUB.org. That is, any novice user with internet access can log into the nanoHUB and investigate MEMS device performance for various kinds of actuation parameters.

The rest of the paper is organized as follows. In Section 2 we present EMM theory that is used by SugarX to extract real properties. In Section 3, we describe SugarX framework and interface. We provide an experimental demonstration of SugarX actuating a displacement sensor in Section 4. In Section 5, we discuss potential applications of SugarX. Finally we conclude our discussion in Section 6.

2. EMM THEORY

Electro micro metrology (EMM) is a theory that we have created to practically measure geometric and material properties of MEMS in terms of electronic measurands. We show a simplified EMM device in Figure 1. The key features of the device are its comb drive and two unequal gap stops. The two gaps from layout are necessarily unequal and related by $gap_{2,layout} = n\, gap_{1,layout}$ where n is a proportionality parameter [7]. We define Δgap to be geometrical difference between layout and fabrication; that is, the real gap is effectively $gap = gap_{layout} - \Delta gap$. Although EMM theory addresses the measurement dozens of properties [5], here we

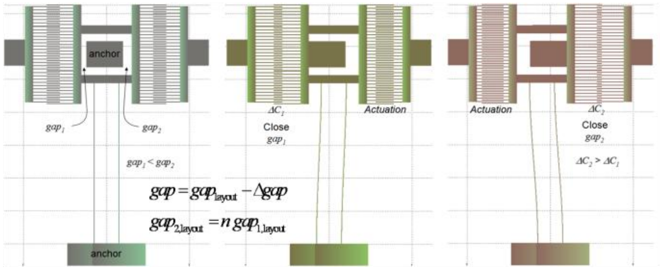


Figure 1: Metrology method. A sequence of capacitance measurements is shown. A change in capacitance is measured to close two unequal gaps. These changes in capacitance characterize the comb drive and lead to measurements of geometry, comb drive force, stiffness, and displacement.

implement the extraction of displacement, comb drive force, stiffness, and geometry as described below.

To calibrate a device using EMM, changes in capacitances (ΔC_1 and ΔC_2) required to close its two unequal gaps ($gap_{1,layout}$ and $gap_{2,layout}$) are measured. See Figure 1. Since the change in capacitance is proportional to the size of the gap traversed, we have:

$$\frac{\Delta C_1 \propto \; gap_{1,layout} + \Delta gap}{\Delta C_2 \propto \; ngap_{1,layout} + \Delta gap} \Rightarrow \Delta gap = gap_{1,layout} \frac{n\Delta C_1 + \Delta C_2}{\Delta C_1 + \Delta C_2} \quad (1)$$

Changes in capacitance have the added benefit of canceling parasitic capacitance.

Since comb drives have a large linear operating range, we define a comb drive constant Ψ as

$$\Psi \equiv \frac{\Delta C_1}{gap_{1,layout} - \Delta gap} = \frac{\Delta C_1}{gap_1}. \quad (2)$$

Using our measurements of Δgap and Ψ, we measure comb drive displacement Δx, force F, and system stiffness k as:

$$\Psi \equiv \frac{gap_1}{\Delta C_1} = \frac{\Delta x}{\Delta C} \Rightarrow \Delta x = \frac{\Delta C}{\Psi}, \quad (3)$$

$$F \equiv \frac{1}{2}\frac{\Delta C}{\Delta x}V^2 = \frac{1}{2}\Psi V^2, \text{ and} \quad (4)$$

$$k \equiv \frac{F}{\Delta x} = \frac{1}{2}\Psi^2 \frac{V^2}{\Delta C}. \quad (5)$$

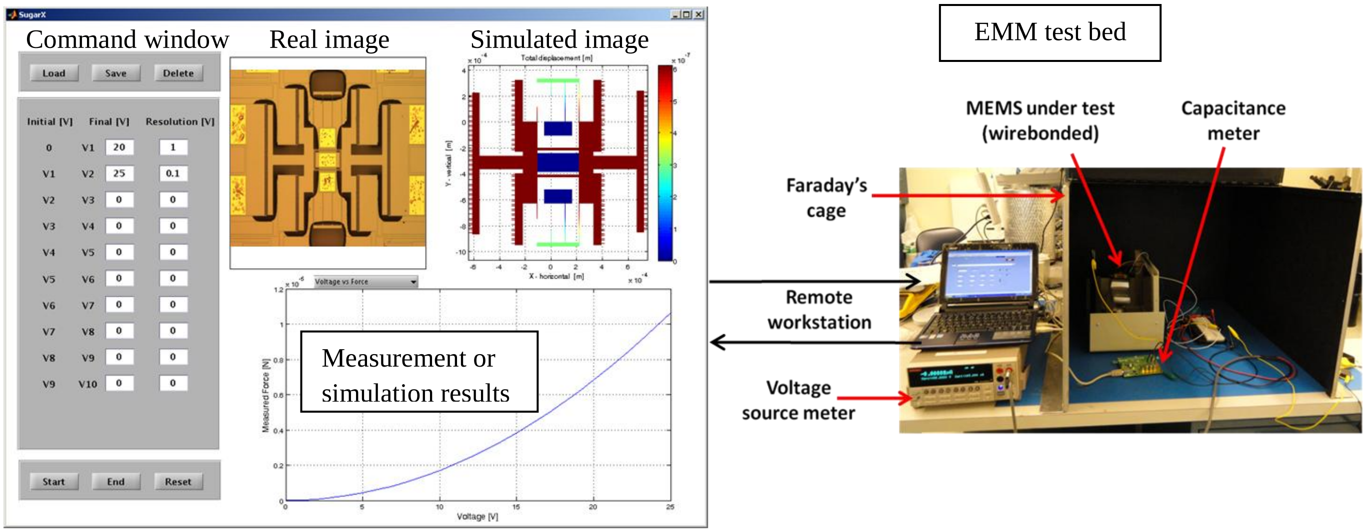
Derivations of above expression and their uncertainties are provided in [7].

3. SUGARX FRAMEWORK

In SugarX, the remote user is able to control a laboratory experiment through the nanoHUB.org. Although calibration by EMM is automatic, the user is able to define a sequence of subsequence applied voltages across the comb drives. With the integration of Labview, voltages are applied and changes in capacitances are measured. The applied and sensed data is recorded. The SugarX interface and its accompanying EMM test bed are shown in Figure 2. SugarX's four main windows include applied voltage sequence, optical image of the real MEMS, simulated image of the MEMS model, and a plot of the performance data from the experiment or simulation.

3.1 Command Window

Within the parameter window, the user is able to perform the following operations: Start, stop, end, or reset an experimental run; enter a sequence of actuation voltages; or load or save measurement data.



Initial [V]	Final [V]		Resolution [V]
0	V1	20	1
V1	V2	25	0.1
V2	V3	0	0
V3	V4	0	0
V4	V5	0	0
V5	V6	0	0
V6	V7	0	0
V7	V8	0	0
V8	V9	0	0
V9	V10	0	0

Figure 2. SugarX framework. Due to unpredictable variations in fabrication processing and unvalidated modeling parameters, there has been a gap between measurement and simulation. As a consequence, real MEMS and their modeled counterparts have not shared the same properties. SugarX is bridging the gap between experiment and simulation. SugarX uses EMM [5] to extract geometric and material properties from the real device into a computer model. Bridging this gap is expected to help to uncover phenomena that simplified models have yet to account for.

The default starting voltage for actuation is 0V. Multiple input fields are provided where the user can enter multiple range of voltages and the resolution (or step-size) in that corresponding range, see Figure 2. For example, if the user wants to actuate the device from 0-20 V in steps of 1 V, and from 20-25V in steps of 0.1V, then 20 is entered in the first column (0V being the default starting voltage) and 1 in the second column (resolution). Similarly, in the second range, 25 is entered in the first column of the following line and 0.1 in the corresponding field of resolution column. The reason for providing multiple input fields is that, sometimes the user may require data with higher resolution in a particular voltage range compared to other ranges. This range may be close to closing a gap where interesting phenomena may occur. Once the voltage sequence is provided, the user clicks on *Start* button to start the SugarX experiment.

3.2 Real Image Window

This window displays an optical image of the device under test. The microscope installed in the EMM test bed (see Figure 2) is a miniature gooseneck USB microscope. The microscope image shown in Figure 2 is an offline placeholder. A live optical image of the experiment is in development.

3.3 Simulated Image Window

This window shows the deflected computer model of the device under test. The input voltage is applied to both the real and simulated model. The performance parameters of the model are imported from EMM, and the deflection of the model is computed using Sugar with user-defined voltages.

3.4 Results Window

This window displays various properties extracted using the formulation presented in Section 2. The properties are measured capacitance, displacement, force, stiffness, etc. A plot comparing experiment vs simulation properties may also be displayed in this window.

4. EXPERIMENTAL DEMONSTRATION

4.1 Experimental Setup

In this demonstration we used the same experimental setup described in [7]. An AD7746 capacitance meter chip from Analog Devices [8] is used for sensing differential capacitance changes. A Keithley 2400 digital source meter [9] is used to provide actuation voltages. A remote workstation running Labview is connected to the above setup and controls the two-way data transfer from nanoHUB to the experimental setup.

4.2 Device Description

The present MEMS device user test is identified in the optical image in Figure 2. This device was previously used in [7] to investigate EMM measurements of displacement, force, and stiffness. The device is an extension of a W. Tang folded flexure resonator. We make the design EMM capable by simply adding two unequal gap-stops. We also add sets of comb drives for simultaneous sensing with actuation. The dimensions of gaps in this device are $gap_{1,layout} = 2\mu m$ and $gap_{2,layout} = 4\mu m$. The layout width and length of each flexure are $2\mu m$ and $300\mu m$ respectively. Other layout dimensions of this device are: number of fingers of each comb drive sensor = 90, length of each finger = $25\mu m$, width of each finger = $3\mu m$, gap between two fingers = $3\mu m$, and layer thickness = $25\mu m$. A back side etch is used in order to eliminate the levitation effect.

4.3 SugarX Results

In this section we present our first results using SugarX. Here we use the following voltage sequence: 0 – 20V (resolution – 0.1V), and 20-25V (resolution = 0. 1V). We use a higher resolution near the close of the gap because we have found interesting phenomena occurring near gap closure. We present our results in Figure 3.

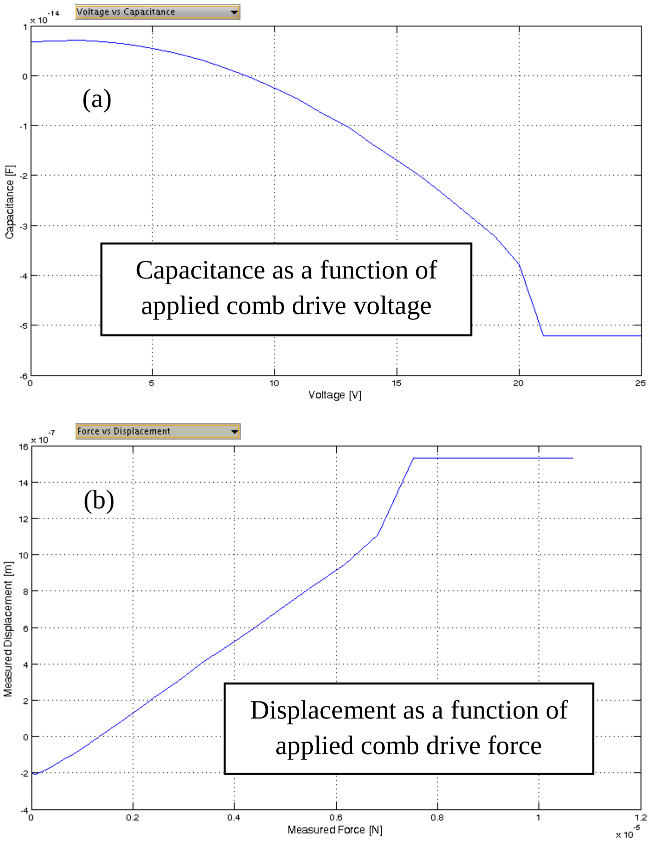


Figure 3: Results of SugarX. The figures show capacitance as a function of applied comb drive voltage (a), and the EMM-extracted displacement as a function of comb drive force (b). It can be seen that the real gap is less than the 2-micron layout gap. There can also be seen an increase in the rate of gap closer near the end of travel. Since the voltage across the gap-stop is zero, this additional force is expected to be due to the Casimir force. From these results, we measure system stiffness as 8.198N/m before gap closure.

As mentioned in Section 2, EMM requires capacitance measurements at left and right gap closing voltages to compute Δgap. SugarX provides two options to obtain the value of Δgap: In the first one, as the same device is continuously tested, SugarX stores the value of Δgap apriori obtaining subsequent measurements. The first option is to use the same value of Δgap for subsequent measurements, and the second option is to re-measure Δgap before each subsequent measurement. The first option provides quick results and is likely to be reasonable for most cases. For more rigorous studies, of say, surface modifications due to contact, repeated measurements of Δgap would be used. To measure Δgap, SugarX automatically closes the gaps by applying enough voltage, measuring the changes in capacitances to traverse the gaps, and extracts Δgap using (1).

4.4 SugarX Applications

An interesting application of the present device under test in SugarX is that it could be used to investigate short-range forces such as Casimir and van der Waals forces. This is possible due the capability of EMM-calibrated devices to measure forces and displacements. For example, in Figure 3 (a), we show the values of measured capacitance for a range of actuation voltages applied to close a gap. In this plot, the capacitance varies as the square of voltage until about 19V. It is important to note that the applied voltage is applied across the comb drive but not across the gap-stop. In fact, the single-crystal-silicon surfaces that come into contact at the gap-stop are both grounded. So there are no applied electrostatic forces acting across the gap. However, after the comb drive reaches ~19V, we observe an increase in the rate of capacitance change; i.e. an additional close-range force becomes significant and increases the rate of gap closure. Rough calculations performed by physicist Ricardo Decca suggest that this force is in the range of the Casimir force. SugarX is able to measure this additional force as follows.

At any position of the comb-drive actuator, the forces acting on the moving comb-drives are electrostatic force F_{Elec}, Casimir force $F_{Casimir}$, and mechanical restoring force F_{Mech}. At static equilibrium before gap closure, the force balance is

$$F_{Elec} + F_{Casimir} = F_{Mech} \,. \tag{6}$$

Since F_{Elec} is given by (4) and displacement and stiffness are given by (3) and (5), we can measure the suggested Casimir force as a function of x by

$$F_{Casimir}\ \ x\ \ = k\,\Delta x - \frac{1}{2}\,\Psi\, V^2 \,. \tag{7}$$

Not shown in Figure 3, when the voltage is decreased after gap closure, there is stiction that keeps the gap closed until a much lower voltage than gap-closing voltage is achieved. We suggest this stiction to be due a dominating van der Waals force. We measure this surface stiction force value as

$$F_{van\,der\,Waals} = k\ gap_1 - \frac{1}{2}\,\Psi\, V_{pull\,off}^2 \,, \tag{8}$$

where $V_{pull\,off}$ is the voltage upon release from stiction.

Another important application of SugarX is to achieve experimentally accurate models. In order to achieve these models, SugarX will use EMM to measure geometric, material, and dynamic properties and import these measured parameters into the model. Similar to how EMM is explained in Section 2 to extract force, displacement, and stiffness, other properties such as Young’s modulus, flexure width, layer thickness, etc. may be extracted (see [5]).

5. CONCLUSION

In this paper, we presented our pioneering online tool called SugarX, which we are using to bridge a gap between experiment and simulation. We presented SugarX’s framework, which consists a web interface to the nanoHUB for widespread dissemination, electro micro metrology (EMM) to measure mechanical properties like displacement, force, and stiffness, and labview for experimental control of both real and simulated devices. In the device presented, short-range interaction forces such as Casimir and van der Waals forces may be investigated.

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