Fast, accurate MEMS simulation with SUGAR 0.4

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CAD for MEMS has become synonymous with cumbersome unwieldy finite element analysis (FEA) packages [1]. These CPU hogs often won't even run on a machine with less than a quarter Gigabyte of RAM! While these FEA systems are critically important for analysis of some types of MEMS devices, they are overkill for the vast majority of surface micromachined devices.

We have developed a simulation program for planar MEMS devices which is simple to use, executes quickly, and gives results identical to FEA for common MEMS designs. The approach is based on nodal analysis to solve coupled nonlinear differential equations. Nodal analysis is essentially the same method used by SPICE to analyze electronic circuits. Initial work in this area was done using SPICE itself as the simulation engine for 1D systems [2]. Similar nodal analysis work for 2D and 3D simulation is in progress at CMU [3]. We report here the first public release of the (free) software, and demonstrate accuracy equivalent to FEA.

The software is simple to use. Planar MEMS devices composed of beams, electrostatic gaps, and anchors are described in a simple text file (Fig. 1). Arbitrary forces and moments may be applied at any or all nodes. Voltages across electrostatic gaps must be specified. Novice users (even faculty!) can typically have working simulations in minutes. The software has been used successfully in the graduate MEMS design course at UCB, and is in regular use by the inertial sensor design group at UCB.

Suspension design/analysis is still a major challenge in MEMS. UCB dissertations by Mike Judy and Gary Fedder in 1994 both contain major sections on suspension analysis and simulation. SUGAR analysis of folded flexure suspension (Fig. 2) agrees exactly with the ABAQUS finite element simulations done by Judy [4]. Similarly, SUGAR analysis of serpentine suspensions (Fig. 3) is identical to FEA simulations done by Fedder [5]. SUGAR analysis of crab leg suspensions from [5] is equally accurate.

SUGAR simulations of the multi-mode resonators reported by Brennan et al. [6] show the mode shapes and Bode plot of the semaphore mass displacement (Fig. 4). These simulations use a simple Couette flow model for damping under all moving structures. Simulations of the first three modes agree with Brennen's experimental data to within 5%.

In an ADXL05-like design, the primary (vertical) resonant frequency decreases as roughly the square-root of proof mass. The second resonance, however, is only a weak function of the proof mass (Fig. 5), as verified by a more detailed hand analysis. This behavior, not well known in the MEMS community, was discovered by a student using SUGAR 0.3 .

Fig. 6 shows frequency tuning with electrostatic springs in a simplified model of the gyro presented by Clark et al. [7]

The simulation algorithms are implemented in MATLAB and are portable across all Unix and PC platforms tested to date. The MATLAB source files will be available on the web at the time of publication.

497 words. Topic Area: Modeling/CAD.

[1] Gilbert, Legtenberg, Senturia, "3D Coupled Electromechanics for MEMS", MEMS 1995
[2] Berg, Lo, Simon, Lee, Pister, "Synthesis and Simulation for MEMS Design", ACM SIGDA Physical Design Workshop, 1996
[3] Vandemeer, Kranz, Fedder, "Nodal Simulation of Suspended MEMS with Multiple Degrees of Freedom", DSC-Vol. 62/HTD-Vol. 354, MEMS ASME 1997
[4] Judy, "Micromechanisms Using Sidewall Beams", Ph.D. dissertation, UCB, 1994.
[5] Fedder, "Simulations of Microelectromechanical Systems", Ph.D. dissertation, UCB, 1994.
[6] Brennen, Pisano, Tang, "Multiple Mode Micromechanical Resonators", MEMS 1990
[7] Clark, Howe, Horowitz, "Surface Micromachined Z-Axis Vibratory Rate Gyroscope", Hilton Head 1996

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% Substrate Anchor
a  1  2  5e-6   180  10e-6
% Horizontal Beam
b  1  3  34e-6  0    2e-6
% Vertical Beam .
b  3  4  70e-6  -90  2e-6
% Gap Capacitor
g  4  5  6  7  50e-6  0  4e-6  4e-6  10e-6  445
b  7  8  70e-6  0    2e-6
a  8  9  5e-6   0    10e-6
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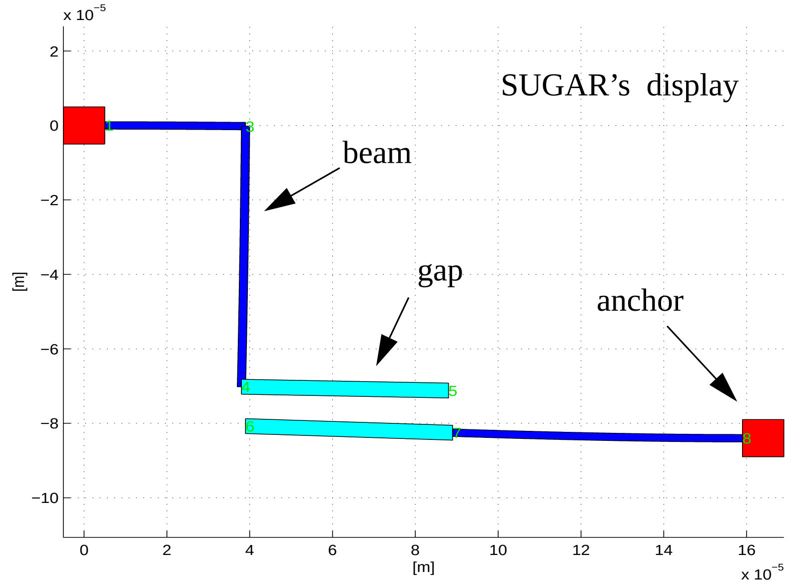

Figure 1: The input netlist file, above, is SPICE-like. A typical line of text for a beam is [b(eam) Node1 Node2 Length Angle Width]. The SUGAR display, right, shows bending due to a voltage applied across the capacitor gap. A separate process file contains information about Young's modulus and layer thickness.

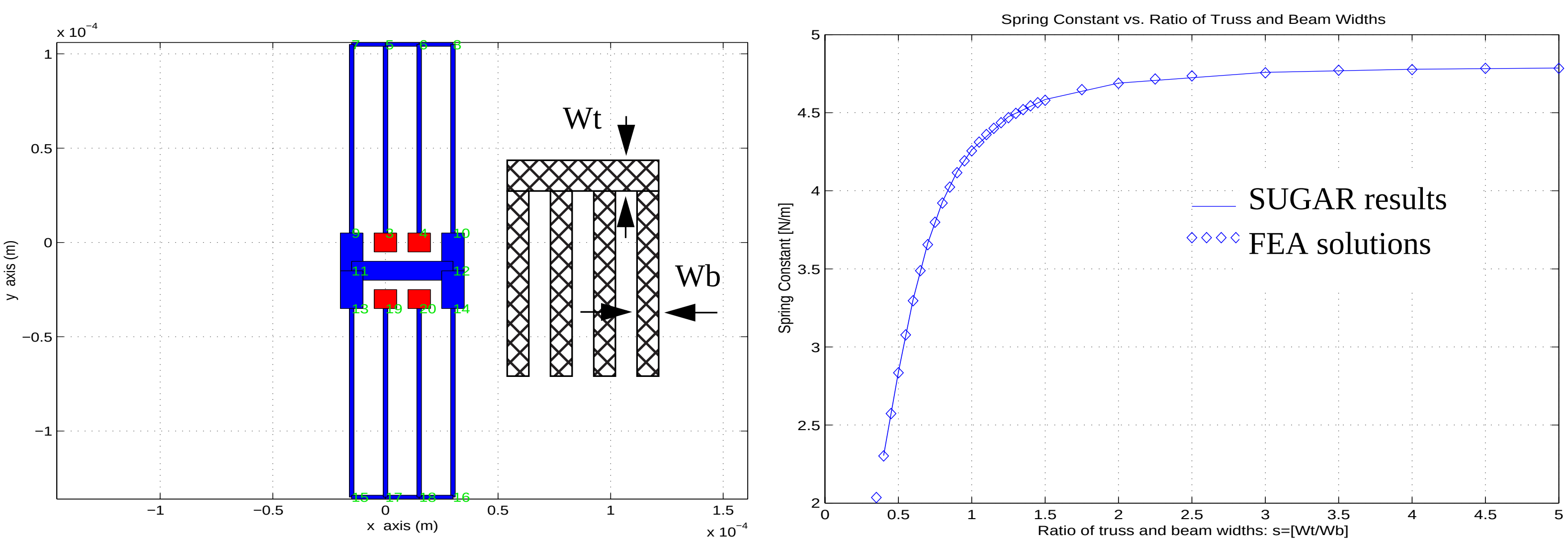

Figure 2: Comparison of SUGAR 0.4 results and FEA solution for the lateral spring constant of a folded-flexure (from Judy [4]) versus the ratio of the truss and beam widths. Wb and Wt are spring and truss widths respectively.

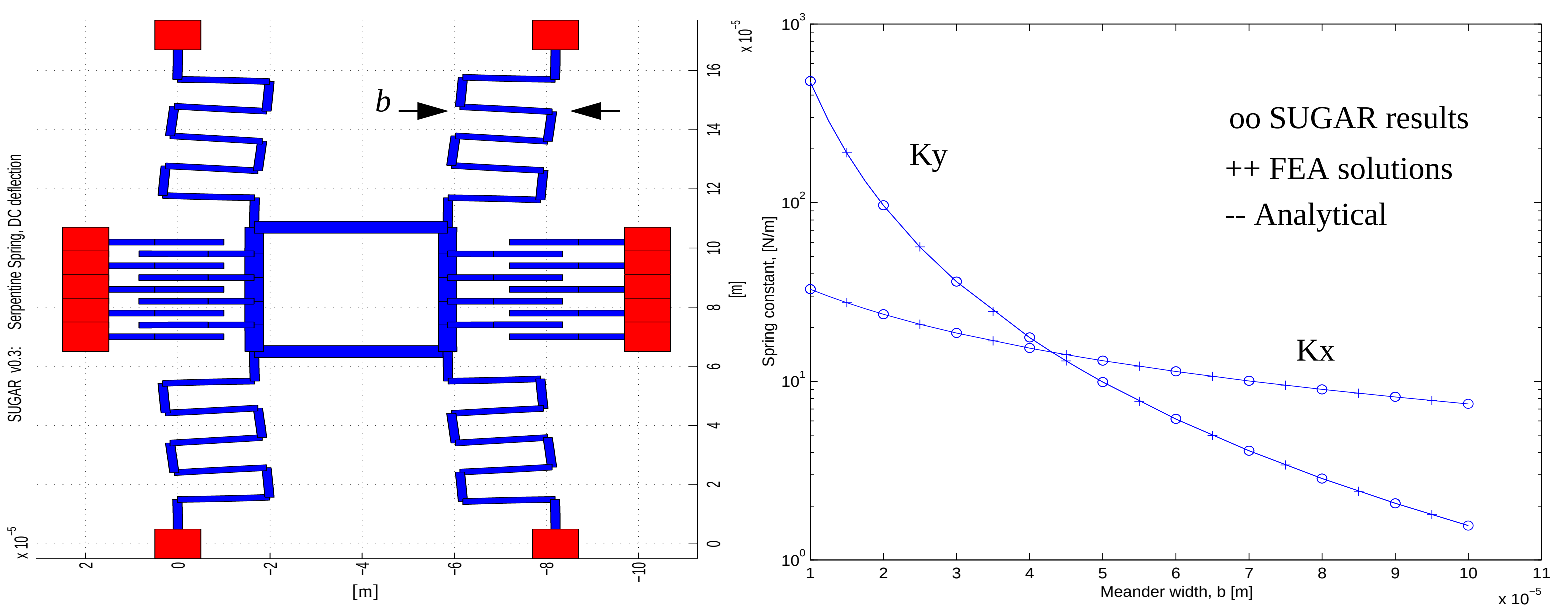

Figure 3: Horizontal and vertical spring constants for a serpentine spring structure (Fedder [5]). The graph shows stiffness k in the x and y directions as a function of meander length b.

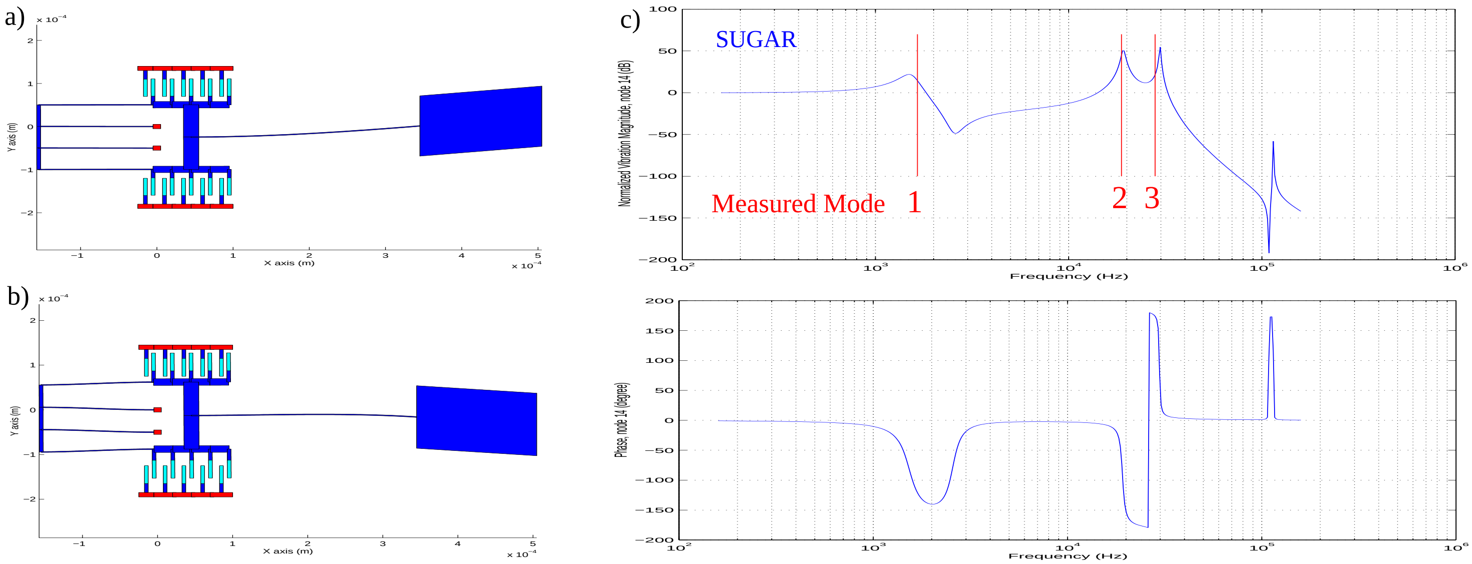

Figure 4: *:* Simulations of the linear-drive multimode resonator structure of Brennen [6] depict: a) the first resonant mode shape, corresponding to the peak at 1.531kHz; b) the second resonant mode shape, at 19.177 kHz; and c) the Bode magnitude and phase plot of the displacement at the base of the semaphore mass as a function of driving frequency. Third frequency = 29.736 kHz. Experimental data from [6] match the predicted three modes to within 5%.

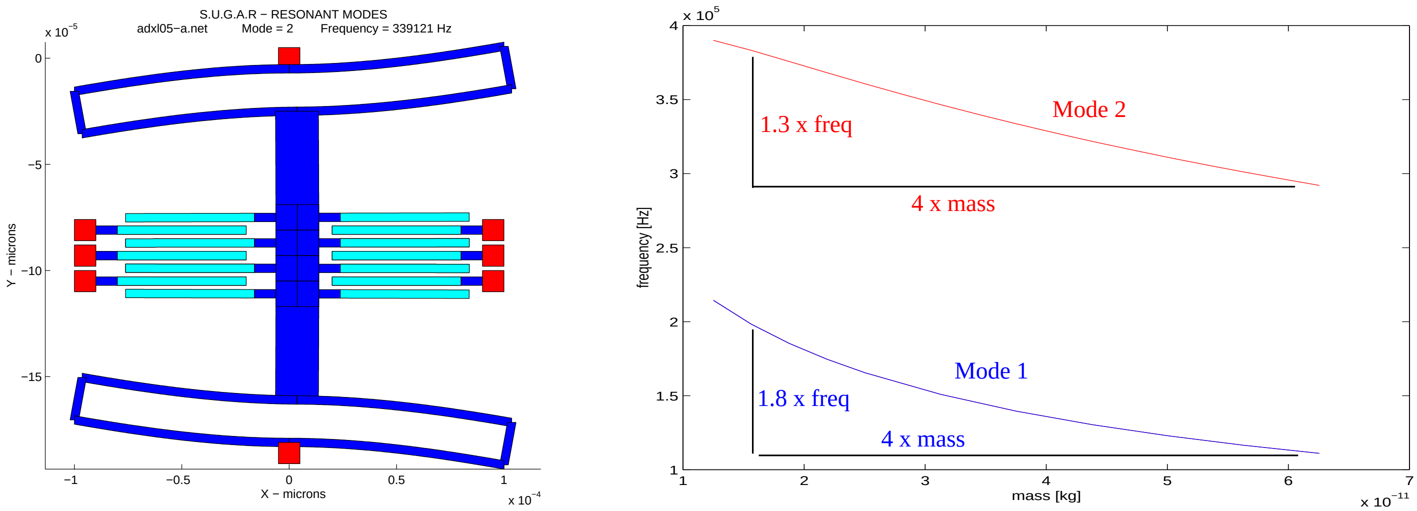

Figure 5: Using Sugar v0.3, graduate students discovered a previously unknown property of ADXL05-like suspensions. The resonant frequency of the second planar mode is a very weak function of *m*--certainly much weaker than $m^{-1/2}$ due to displacement amplification of the suspension tips.

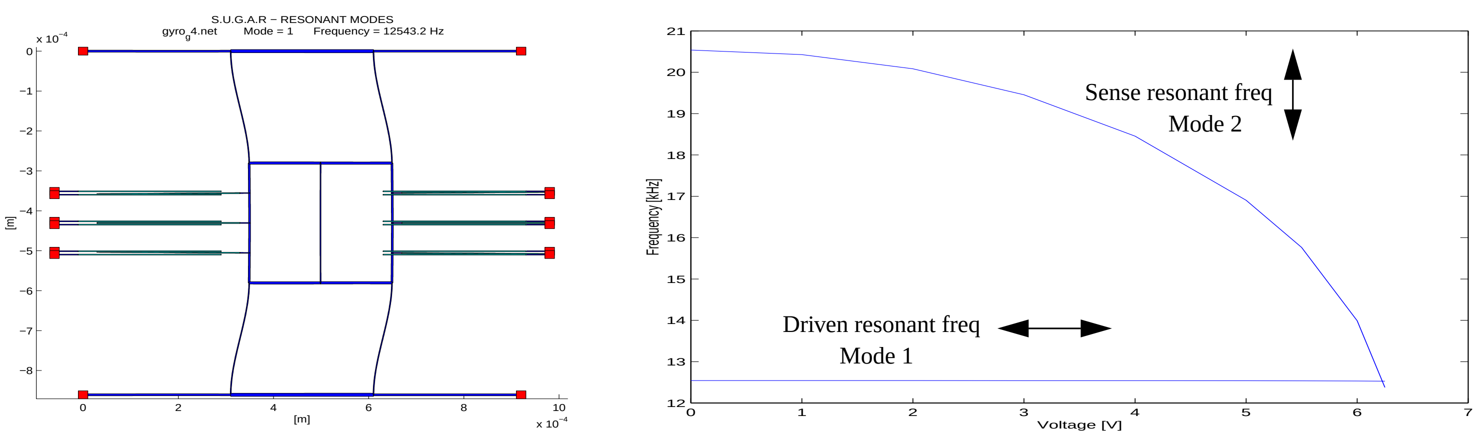

Figure 6: A simplified model of the z-axis vibratory rate gyroscope described by Clark *et al* [7] is characterized by two planar resonant modes: the driving mode, depicted on the left, and the sensing mode, middle. Simulations predict that the sensing mode resonant frequency *decreases* as a function of applied voltage, while that of the driving mode remains unchanged. Mode matching occurs for a comb-drive voltage of 6.2 V.