Computer-Aided Design Tools for Microelectromechanical Systems

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1. Simulation Tools for Micromachined Device Design

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Micromachining technology has enabled the fabrication of several novel microsensors and microactuators. Because of the specialized processing involved, the cost of prototyping even simple microsensors, microvalves, and microactuators is enormous. In order to reduce the number of prototype failures, designers of these devices need to make frequent use of simulation tools. To efficiently predict the performance of micro-electro-mechanical systems these simultion tools need to account for the interaction between electrical, mechanical, and fluidic forces. Simulating this coupled problem is made more difficult by the fact that most MEMS devices are innately three-dimensional and geometrically complicated. It is possible to simulate efficiently these devices using domain-specific solvers, provided the coupling between domains can be handled effectively. In this work we have developed several new approaches and tools for efficient computer aided design and analysis of MEMS.

One of our recent efforts in this area has been in developing algorithms for coupled-domain mixed regime simulation. We developed a matrix-implicit multi-level Newton methods for coupled domain simulation which has much more robust convergence properties than just iterating between domain-specific analysis programs, but still allows one to treat the domain analysis programs as black boxes. In addition, we developed another approach to accelerating coupled-domain simulation by allowing physical simplifications where appropriate. We refer to this as mixed regime simulation. For example, self-consistent coupled electromechanical simulation of MEMS devices face a bottleneck in the finite element based nonlinear elastostatic solver. Replacing a stiff structural element by a rigid body approximation which has only 6 variables, all variables associated with the internal and surface nodes of the element are eliminated which are now a function of the rigid body parameters. Using our coupled domain approach has made it possible to perform coupled electromechanical analysis of an entire comb drive accelerometer in less than 15 minutes.

Analysis of the resonance behavior of micromachined devices packaged in air or fluid requires that fluid damping be considered. Since the spatial scales are small and resonance analyses are typically done assuming a small amplitude excitation, fluid velocities can often be analyzed by ignoring convective and inertial terms and then using the steady Stokes equation. For higher frequency applications, the convective term may still be small, but the inertial term rises linearly with frequency. Therefore, analyzing higher frequency resonances requires the unsteady Stokes equations, though the small amplitudes involved make it possible to use frequency domain techniques. We have developed a fast Stokes solver, FastStokes, based on the precorrected-FFT accelerated boundary-elment techniques. The program can solve the steady Stokes equation or the frequency domain unsteady Stokes equation in extremely complicated geometries. For problems discretized using more than 50,000 unknowns, our accelerated solver is more than three orders of magnitude faster than direct methods.

2. Enhancing MEMS Design Using Statistical Process Information

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Micro Electro-Mechanical Systems (MEMS) design is often done using circuit design rules for layout and complex synthesis or mechanical simulation for actual device structure. The problem with this approach is that devices that work well in simulation often have high sensitivity to process variation and therefore can have properties that differ substantially from projected values. These effects lead to both poor performance and lower yields.

Figure 1 shows a picture as well as a diagram of a comb-drive resonator. This device is ideal for process sensitivity analysis because its resonant frequency is a key system parameter that can be easily computed in simulation and is directly affected by the process and underlying geometries.

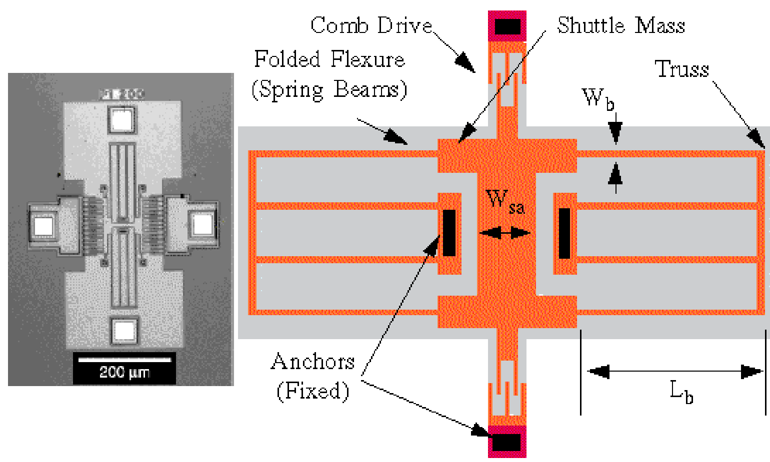

Figure 1. *Comb-Drive Resonator*

As an example of the importance of process variation to device performance, Figure 2 compares a 50Khz resonator based on a 2 mm folded beam flexture to a 50Khz resonator using a 4 mm beam. The graph shows that for a 1 s manufacturing variation in beam width (taken from actual MEMS fabrication data), the 4 mm system experienced a 4.2 frequency variation compared to the 10 reduction in system variation (for frequency) would lead to higher yield and tighter system specifications.

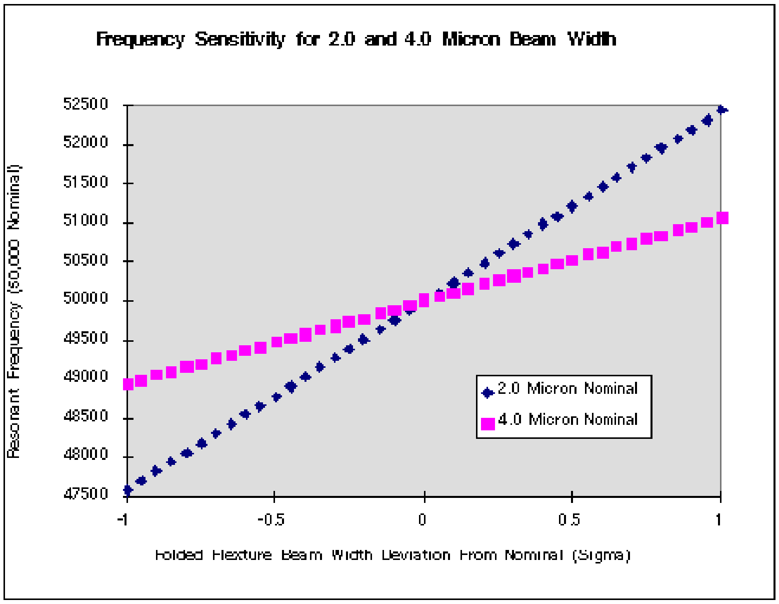

Figure 2. *2.0mm vs. 4.0mm Folded Beam Resonator*

A methodology for enhancing MEMS designs was developed using the property shown in figure 2. The comb-drive resonator was used as an example device. A tool for synthesizing resonators that are more robust to process variation was developed. Figure 3 shows the results of synthesizing three resonators using the tool. Figure 3.A shows a 50KHz resonator synthesized for area alone. Typical fabrication process variation would cause this device over 10variation. Figure 3.B shows the same resonator optimized for less than 95process robustness.

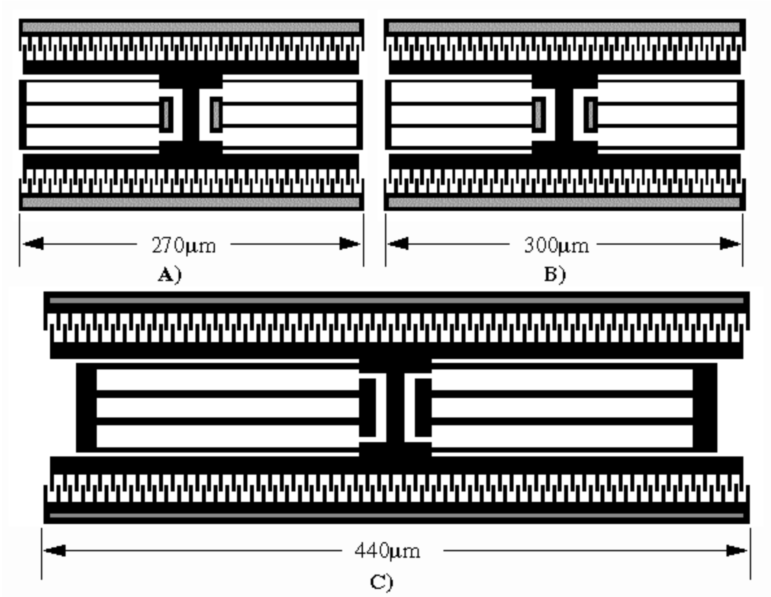

Figure 3. *Synthesized Resonators:* ***a)*** *10.22* ***c)*** *5*

3. Publications

Y. Chen and J. White, "A Quadratic Method for Nonlinear Model Order Reduction" (To appear, International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators), San Diego, March 2000

Lee, Z. K., M. B. McIlrath, and D. A. Antoniadis, " Two-Dimensional Doping Profile Characterization of MOSFET's by Inverse Modeling Using I-V Characteristics in the Subthreshold Region," IEEE Transaction on Electron Devices, Vol. 46, No. 8, 1640-1649, (Aug. 1999).

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X. Wang, J. N. Newman and J. White "Robust Algorithms for Boundary-Element Integrals on Curved Surfaces" (To appear, International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators), San Diego, March 2000

W. Ye, X. Wang, and J. White "A Fast Stokes Solver for Generalized Flow Problems" (To appear, International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators), San Diego, March 2000

Theses

Lin, Calvin J. "A New Lab for 6.111: A Coin Operated Vending Machine Controller," M. Eng., Dept. of Electr. Eng.and Comput. Sci., MIT May 1999

Pedersen, Erik J., "User Interface for MEMS Characterization System," M. Eng., Dept. of Electr. Eng.and Comput. Sci., MIT January 1999

Rodriguez, Ramon, "Performance Measurements for MEMS Analysis System," M. Eng., Dept. of Electr. Eng.and Comput. Sci., MIT May 1999