Design Methodology for Mixed-Domain Systems-on-a-Chip

Tamal Mukherjee[†] *and Gary K. Fedder*[†*]

[†]Department of Electrical and Computer Engineering and [*]The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA, 15213-3890

Abstract

Digital design tools such as logic synthesis, semicustom layout and behavioral simulation have drastically changed the digital IC design process, enabling design of complex "systems on a chip". The usefulness of such chips are limited in a world dominated by information that is not represented by 0s and 1s. Overcoming these limitations has led to *mixed-signal*, and *mixed-domain* technologies. We focus on design methodologies and tools to aid the design of complex microelectromechanical systems (MEMS) having large numbers of *mixed-domain* components. We propose a hierarchically structured design approach that is compatible with standard IC design involving a schematic approach to MEMS design, a layout synthesis strategy for cell-level design automation, and a feature-recognition based device extractor for layout verification. We present emerging results on our design methodology and tools.

1. Introduction

Microelectromechanical Systems (MEMS), are µm to mm sized systems integrating electrical and mechanical elements. They are fabricated using microelectronic batch processing techniques and can sense, control and actuate on the micro scale. Moreover, arrays of MEMS devices can be used for macro scale sensing and actuation. Researchers are using MEMS in diverse application areas such as inertial navigation systems, digital mirror displays, DNA analysis systems, RF distributed sensor networks, and probe-based data storage systems. These systems incorporate truly mixed technology, integrating combinations of digital and analog electronics, mechanical structures, electromechanical actuators, and fluidic chambers.

The advent of stable, VLSI-compatible MEMS fabrication technologies has led to the development of increasingly complex and integrated MEMS-based systems. Future systems are expected to contain hundreds or even thousands of mixed-domain devices. This has led to a desperate demand for CAD tools to support rapid design of systems involving physical interactions between mechanical, electrostatic, magnetic, thermal, fluidic, and optical domains. As in pure electronic design, hierarchical cell design methodologies, mixed-technology simulators, layout synthesis tools, and layout extraction will enable MEMS engineers to build larger systems and allow them to concentrate on system-level design issues.

One relatively mature mixed-domain design technology is surface-micromachined suspended MEMS, as exemplified by the recent success of commercial microaccelerometers for automotive airbag deployment [1][2] and digital mirror displays for high-fidelity video projection [3]. The availability of accumulated design expertise, integrated MEMS/electronics fabrication capabilities, and electromechanical CAD modeling tools has made the suspended-MEMS technology a suitable candidate for initial development of design methodologies for MEMS. Our discussion of structured design will be restricted to suspended MEMS, however the concepts should apply to other technologies as they mature.

After describing the current MEMS design practice, we introduce our mixed-domain systems-on-a-chip design methodology, and then describe the individual areas within this methodology, and present results for simulation, synthesis and extraction.

2. Current MEMS Design Practice

Today, MEMS-based designs either involve a single micromechanical sense element surrounded by traditional electronic signal conditioning or arrays of identical micromechanical devices. Therefore the focus of MEMS design is typically at the device-level. Currently, MEMS engineers begin design of a new device with a rough sketch and very basic equations to ensure feasibility. This stage usually leads directly to a physical layout, due to the tight integration of form and function in mechanical devices. The designer has two choices for design verification: numerical simulation (*e.g.,* finite-element analysis), and behavioral simulation. Tools exist for both kinds of analysis, however each method has drawbacks which researchers are working to eradicate.

Numerical simulation involves self-consistent mechanical finite-element analysis coupled with electrostatic boundary element analysis. Tools that cater to the MEMS community are available from several companies [4][5][6]. The modeling of the design (solid model and meshing) for numerical simulation, and the subsequent interpretation of simulation results requires domain expertise and quickly becomes tedious. Furthermore, these simulation strategies can only verify device operation, and do not allow the complete simulation of the MEMS device with its attendant electronics. Additionally, the computation time and memory resources required for numerical simulation require the designer to partition the design, and to determine the best simulation strategy. Effectively, this prohibits the use of numerical simulation for tight iterative design. Therefore, numerical simulation is primarily seen as critically important for MEMS modeling and verification, analogous to the role that electronic technology CAD plays with device and interconnect modeling.

Behavioral simulation can be accomplished using many different commercial tools, such as SPICE [7] and MATLAB [8]. Although geometric parametrized cell libraries to support behavioral simulation have been constructed [9][10], this process is manual, requiring specific device expertise which is often lacking in a system designer. Model construction requires numerical simulation and, therefore, cannot be placed in the iterative design loop.

No rapid design process is available today for MEMS. Few design verification iterations are usually attempted during prototype design, resulting in fabrication replacing simulation in the iterative design loop. This is very expensive, since fabricated prototypes often do not meet performance specifications and, sometimes, are not even functional. These problems inhibit the use of MEMS for low-cost, low-volume application specific sensors, integrated on the same chip with electronic information processing and communication capabilities. Furthermore, these approaches are geared for systems involving arrays of identical MEMS devices, and become even more cumbersome for the design of integrated microsystems with large numbers of unique MEMS devices.

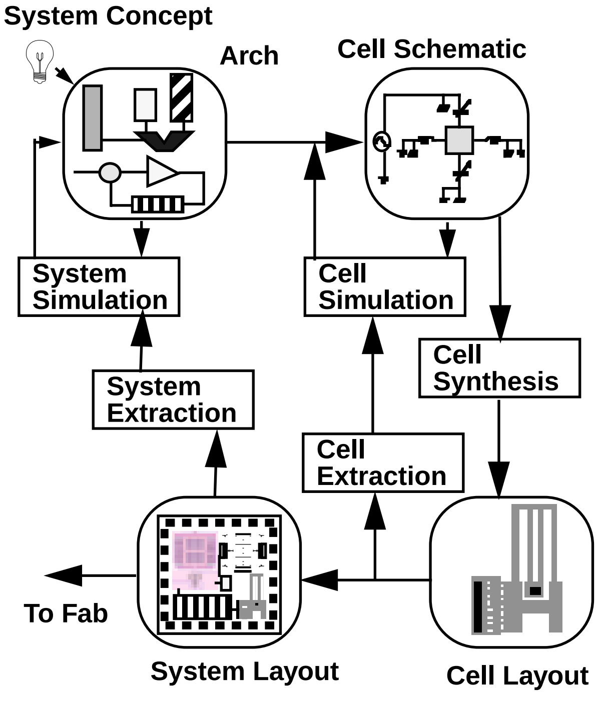

Fig. 1. Mixed-domain design methodology

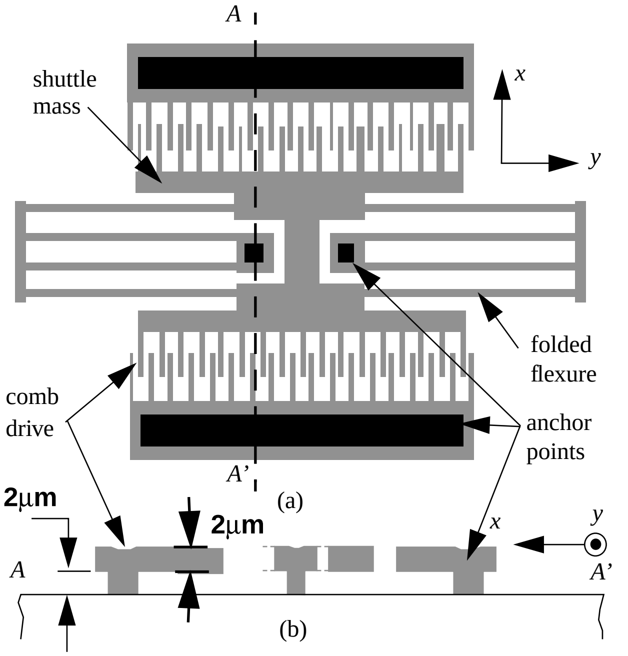

Fig. 2. A folded-flexure comb-drive microresonator fabricated in the MUMPs process. (a) Layout. (b) Cross-section *A-A'*.

3. Proposed Design Methodology

To enable the design of mixed-domain systems-on-a-chip, we have been developing a design methodology [11] based on existing digital and analog design methodologies. The system-level engineer begins by creating a system architecture that implements the desired system concept, as shown in Fig. 1. This architecture will include digital electronics for computation, analog electronics for signal conditioning and control, RF electronics for communication, and MEMS for sensing, control, and actuation. A traditional digital design approach can be followed for the digital portion of the design. Emerging analog design methodologies [12], and RF design tools can be applied for the analog and RF portion of the design problem. In this paper we will focus on the remaining part of the design problem: surface-micromachined suspended MEMS.

The MEMS cells in the system architecture then need to be refined into a schematic, which helps the designer understand the effect of cell-level design trade-offs on the system level design. We will focus on the details of our approach in Section 5. Once a cell-level topology (connection of mechanical and electrostatic elements) is chosen, a cell-synthesis tool can translate the cell's performance specifications into layout, as will be detailed in Section 6. Alternately, custom-cells can also be designed via traditional device-level MEMS strategies. The next step is the verification of the cell layout, which can be accomplished via layout extraction, detailed in Section 7, into a simulation netlist, that can be verified for functionality via our schematic-level simulation. Finally, the cell-layouts can be integrated into a system layout (using a traditional electronics floorplanner and chip-level router for now, until a better understanding is obtained of the demands that integrated microsystems place on these issues). System-level extraction and simulation for the integrated microsystem will then be used to verify functional correctness, and may result in design iterations, prior to fabrication.

4. The Microresonator

We will use the microresonator, shown in Fig. 2, to describe our approach to MEMS device design. The specific resonator topology was first described and analyzed by Tang [13]. It is used in resonator oscillators, in filters, and as a mechanical characterization test structure to measure Young's modulus of thin films. The central shuttle mass is suspended by two folded-beam flexures to form a mechanical mass-spring-damper system. The resonator can be fabricated via a surface-micromachining fabrication service such as the Multi-User MEMS Process service (MUMPs) from MCNC [14]. The structural elements in this process are formed using a homogeneous, conducting, polysilicon film. The movable microstructure is fixed to the substrate at only two anchor points, which also act as electrical vias. Wet etching of the sacrificial oxide under the structure results in the spacer gap.

The electrostatic actuators used to drive the resonator in the x-direction are called 'comb drives,' and are made from a set of interdigitated comb fingers. The generated electrostatic force, due to the application of a voltage across the comb fingers, does not depend upon the displacement of the resonator (to first order). The folded flexure suspension is designed to be compliant in the x direction of motion and to be stiff in all other direction (e.g., y and θ) to keep the comb fingers aligned.

The simplified schematic view of the resonator, shown in Fig. 3, represents the device as an interconnected set of mixed-domain lumped-parameter elements: the shuttle mass, two folded-flexure springs, and two comb-finger actuators which are displayed as time-varying capacitors. Each of these elements serves both an electrical and mechanical role. A voltage source that drives one actuator and mechanical anchor points, designated by notation similar to electrical ground, are also included in the schematic. The link between form and function in the mechanical representation of the device requires that the mechanical schematic include details such as the physical attachment point of the springs to the shuttle mass. This point affects functional parameters such as the system modal frequencies. Therefore, physical placement parameters must be included in the element models and ultimately linked to the mechanical nodal equations.

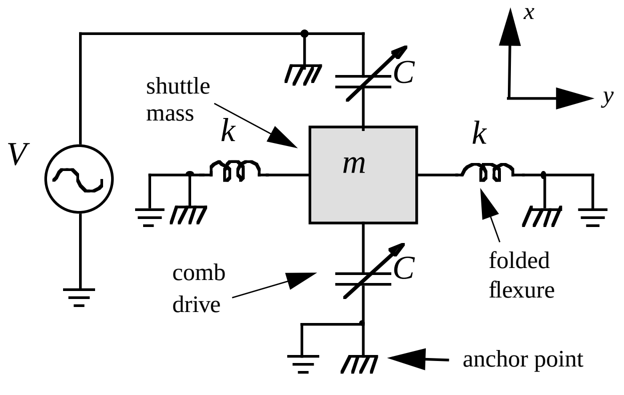

Fig. 3. Mixed-domain schematic of the lateral folded-flexure comb-drive microresonator, including a voltage source, *V*, for comb-drive actuation.

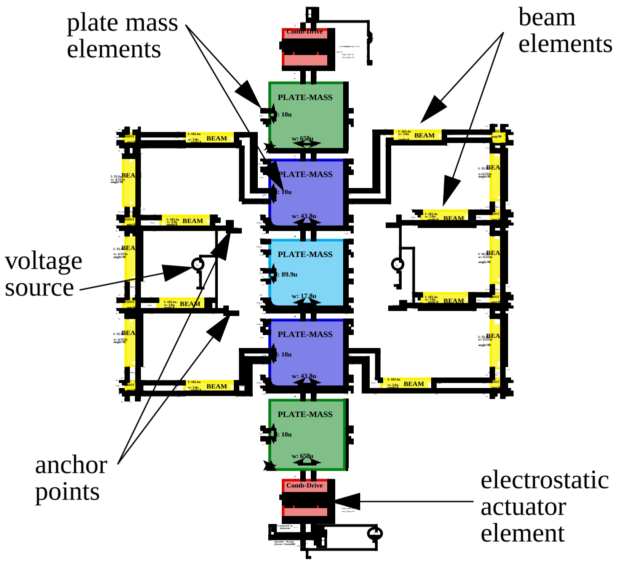

Fig. 4. Layout-based schematic representation of a MEMS resonator

5. Nodal Simulation

MEMS simulation is typically performed using numerical simulation (*e.g.,* finite element analysis), or signal flow analysis. Due to its abstraction detail, finite element analysis is more appropriate for device modeling than for system simulation. Most previous work on higher-level MEMS simulation has focused on behavioral simulation of individual devices (*e.g.,* microresonators) with abstract macromodels [15][16].

Our nodal simulation [17][18] approach uses a hierarchical set of MEM elements, which can be interconnected in a general way to create more complicated sub-components, devices and systems. Pister *et.al.* [19] are developing a similar hierarchical representation as part of a larger research collaboration. The resulting schematic view provides a direct linkage between the physical layout and behavioral simulation, as is the case with standard integrated-circuit design. A example schematic is shown in Fig. 4 of the microresonator from Fig. 2. A key feature is the one-to-one correspondence of components to layout,

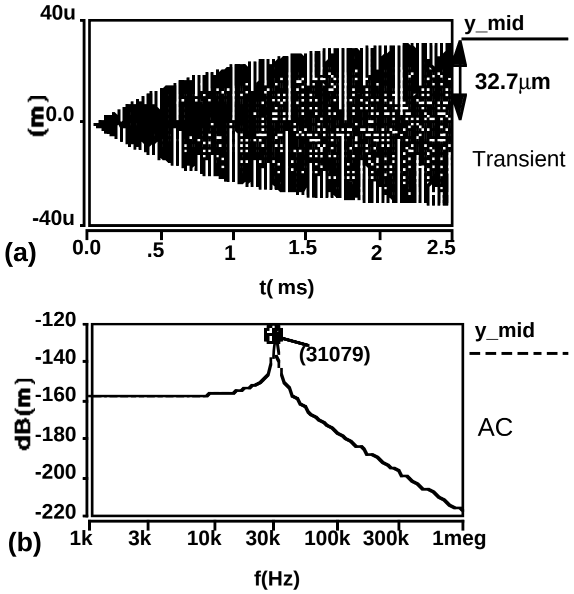

Fig. 5. (a) Transient and (b) A.C. analysis of MEMS microresonator

which provides an intuitive interface for the designer. We have coupled the layout-based schematic methodology with existing IC schematic capture tools enabling MEMS design to be quick and efficient.

To overcome the need for custom MEMS device models, we are working on a simulation methodology that treats atomic MEMS elements (such as beams and gaps) as the fundamental simulation entities, enabling the simulation of interconnections of beams. The transient and a.c. simulation of the microresonator is shown in Fig. 5 indicating that the resonant frequency for that resonator is 31 kHz with a steady-state drive amplitude of 32.7 μm.

Currently, work is progressing on extending these device-level simulations based on the interconnection of MEMS elements and electronics to system-level simulation, via analog HDL representations [20]. Integrating multiple suspended-MEMS devices, MEMS behavioral simulation must support a combination of signal-flow analysis and electrical nodal analysis.

6. MEMS Cell Synthesis

System-level design for MEMS requires the use of mixed-technology cells. MEMS devices tend to have a large number of design specifications coupled by the large ranges for each specification. For example, acceleration performance specifications for microaccelerometer applications range from 1 G for inertial sensors to greater than 100,000 G for munitions fuzing. Additional specifications, including bandwidth, resolution, sensitivity, linearity, and cross-axis rejection, must be simultaneously satisfied for a specific application. This prevents us from using a fixed-cell library in our design methodology.

Although geometric parametrized cell libraries have been developed (e.g., CaMEL from MCNC [10]), the cell generators are purely geometric, therefore the designer must manually evaluate numerous iterations to generate a design which satisfies performance requirements. Our approach [21][22] overcomes these limitations by translating the user-specified device specifications (e.g., accelerometer sensitivity) directly into cell geometrical layout parameters. We are developing synthesis modules for commonly used MEMS devices in the suspended-MEMS area, such as accelerometers, gyroscopes, resonators, and positioners. Instead of redesigning these components each time a new system is proposed, engineers will benefit from cell synthesizers which tackle the routine design of frequently-used components.

The development of a synthesis module involves determining the design variables, the numerical design constraints, and the quantitative design objective. As a starting point, we have developed and tested a synthesis tool for the surface-micromachined resonator topology of Fig. 2. The lowest nine lateral translational and rotational modes (both in-plane and out-of-plane) of the mass-spring-damper system are modeled by second-order equations of motion. All of the design variables are structural parameters of the folded flexure and comb drive elements, with the exception of the comb-drive voltage. Technology-driven design rules constrain the minimum geometries, such as beam widths and minimum spaces between structures. Maximum values of structural parameters are primarily constrained by manufacturing constraints such as

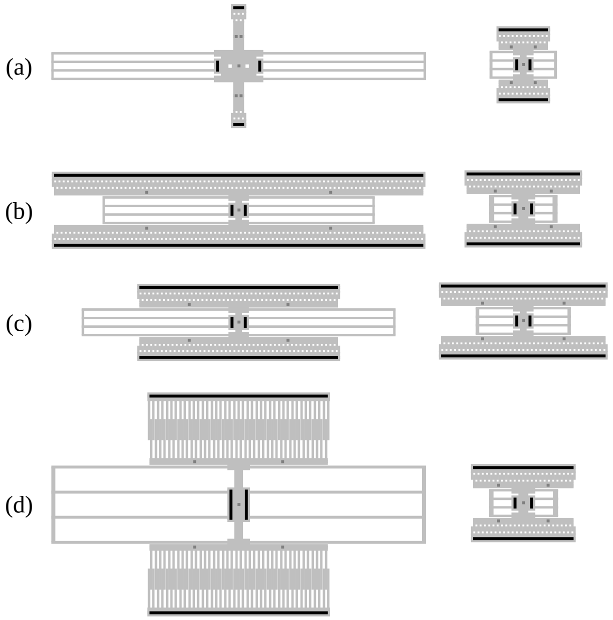

Fig. 6. Resonators synthesized for four different design objectives: (a) min active area, (b) min drive voltage, (c) min combination of active area and drive voltage , and (d) max displacement. Resonant frequencies are 10kHz (left) and 300k(Hz) right)

sticking of the structural film to the substrate during sacrificial oxide etching. The functional constraints include resonant frequency, stroke, quality factor, and electromechanical stability.

The complete design problem is represented as a constrained non-linear optimization problem, and solved by an off-the-shelf solver [23]. A gridded-multistart approach is used to overcome local minima, and a branch-and-bound approach is used for handling the integer variables (e.g., number of comb fingers). Various design objectives such as minimization of area, drive voltage, combination of area and voltage, and maximization of displacement have been used to explore the resonator design space. Various engineering specifications such as resonator frequency were used to understand the constraint space for each microresonator objective. Results for low-frequency (10 kHz) and high-frequency (300 kHz) resonators are shown in Fig. 6. As expected, the high frequency devices are much smaller than their low frequency counterparts. Smaller devices have less mass, and smaller flexures are stiffer. Both effects increase the resonant frequency.

7. MEMS Layout Extraction

Layout correctness can only be accomplished by extracting the layout into a schematic netlist and simulating for functional correctness, or by comparing the layout to a golden design netlist to ensure geometric connectivity. Unlike VLSI, where extraction is also used for checking layouts, the shape, size and position of a MEMS object is of utmost importance and plays a crucial role in deciding the MEMS element corresponding to that object.

The objective of the extraction tool is to recognize the layout elements based on its features (shape, size and placement) to enable subsequent rapid simulation-based verification. To achieve this, we first detect the atomic elements then commonly used device components such as comb-drives. We begin by converting the layout into a canonical representation, to ensure a unique recognition. Feature based recognition then detects the various atomic elements (beams, plates, gaps and anchors). Information from other layers, like location of anchor cuts is used to help in this phase (such technology specific information comes from a process description file). The final recognized set of elements is then optimized to reduce the total number of nodes required for netlist generation. Using the information contained in the recognized set we generate a netlist which can then be compared with the original design netlist. Thus our primary objective of having a check on the designed layout can be achieved. Device function can also be confirmed by running a lumped parameter simulation on this netlist.

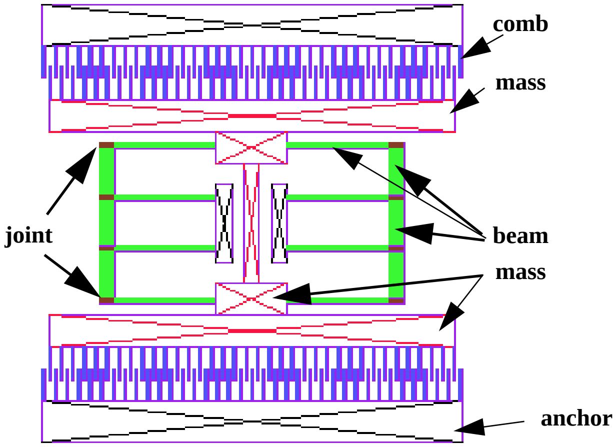

Fig. 7. Layout extraction of MEMS resonator showing element recognition

Fig. 7 shows an example of a microresonator extraction. Each type of recognized element (beam, joint) is shaded differently to indicate our ability to recognize the layout. Once each element is classified, a netlist can be generated for behavioral simulation. We are currently working on the recognition of commonly used MEMS components such as comb-drives and springs.

8. Conclusions

Mixed-domain Systems-on-a-Chip design methodology for suspended MEMS promises to shorten the development cycle to days, and enable design of more complex systems comprised of hundreds to thousands of micromechanical elements. Identification of reusable hierarchical representations of MEMS components is a critical first step in advancing toward a hierarchical design methodology and in leveraging existing CAD tools.

A mixed-domain schematic representation will enable rapid exploration and analysis of the design space for MEMS components. The identification and modeling of the fundamental MEMS elements, and the ability to interconnect these elements for new device designs will be critical for the shortening the MEMS design cycle.

MEMS cell synthesis is a powerful tool for building common components that can then be used in larger systems. The identification and modeling of sub-component level lumped-parameter models that adequately link device behavior with physical design variables, and the integration of these models with optimization will lead to automatic custom cell design capability for system-level design, as well as design-space exploration capability crucial for the system-level architecture decisions.

MEMS extraction is essential for layout verification of synthesized or custom layouts. The use of a common set of fundamental elements between the extraction and simulation methodologies enables the use of extraction output for behavioral verification, as well as for netlist comparison to ensure correct connectivity of the components.

Finally, we envision a MEMS design environment in which the expert MEMS designer can rapidly iterate on ideas for MEMS designs, in the same integrated environment where a system-level designer can use synthesized and custom-made MEMS components to develop monolithic mixed-technology chips for low-cost, low-volume commonplace applications. Such a design environment is essential for designs in which several unique MEMS sensors need to be integrated on the same chip with electronic information processing capability.

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10. References

[1] *ADXL50 Accelerometer Data Sheet*, Analog Devices, Inc., One Technology Way, P.O.Box 9106, Norwood, MA 02062-9106, 1996 (http://www.analog.com).

[2] *MMAS40G10D Accelerometer Data Sheet*, Motorola Sensor Products, 1996 (http://design-net.com/senseon).

[3] M. A. Mignardi, "Digital Micromirror Array for Projection TV," *Solid State Technology*, v.37, no.7, pp. 63-4, July 1994.

[4] *MEMCAD Web Page*, http://www.memcad.com, Microcosm Technologies, Inc., 201 Willesden Dr., Cary, NC 27513.

[5] *Intellisense Web Page*, http://www.intellis.com, IntelliSense Corporation, 16 Upton Dr., Wilmington, MA 01887.

[6] J. M. Funk, J. G. Korvink, J. Bühler, M. Båchtold, and H. Baltes, "SOLIDIS: A Tool for Microactuator Simulation in 3-D," *J. of Microelectromech. Sys.*, v. 6, no. 1, pp. 70-82, March 1997. (*SOLIDIS Web Page*, http://www.ise.ch/solidis)

[7] G. K. Fedder and R. T. Howe, "Multimode Digital Control of a Suspended Polysilicon Microstructure," *J. of Microelectromechanical Systems*, pp 283-297, Vol 5., No. 4, December 1996.

[8] G. K. Fedder, *Simulation of Microelectromechanical Systems*, Ph.D. Thesis, Dept. of Electrical Engineering and Computer Science, U. C. Berkeley, Sept. 1994.

[9] *Micromachines Program*, available from Multi-Project Circuits (CMP) Service, 46, avenue Felix Viallet, 38031 Grenoble Cedex, Oct. 1994, 29 pages.

[10] *CaMEL Web Page*, http://www.mcnc.org/camel.org, MCNC MEMS Technology Applications Center, 3021 Cornwallis Road, Research Triangle Park, NC 27709.

[11] T. Mukherjee and G. K. Fedder, "Structured Design of Microelectromechanical Systems," in *Proceedings of the 1997 Design Automation Conference*, Anaheim, CA, June 9-13, 1997, pp. 680-685.

[12] L. R. Carley, G. G. E. Gielen, R. A. Rutenbar and W. M. C Sansen, "Synthesis Tools for Mixed-Signal ICs: Progress on Frontend and Backend Strategies," *Proceedings of the IEEE/ACM Design Automation Conference*, pp 298-303, June 1996.

[13] W. C. Tang, T.-C. H. Nguyen, M. W. Judy, and R. T. Howe, "Electrostatic comb drive of lateral polysilicon resonators," *Sensors and Actuators A*, vol.21, no.1-3, pp. 328-31, Feb. 1990.

[14] D. A. Koester, R. Mahadevan, K. W. Markus, *Multi-User MEMS Processes (MUMPs) Introduction and Design Rules*, available from MCNC MEMS Technology Applications Center, 3021 Cornwallis Road, Research Triangle Park, NC 27709, rev. 3, Oct. 1994, 39 pages.

[15] J. M Karam, B. Courtois, H. Boutamine, P. Drake, A. Poppe, V. Szekely, M. Rencz, K. Hoffman, M. Glesner, "CAD and Foundries for Microsystems," in *Proceedings of the 1997 Design Automation Conference*, Anaheim, CA, June 9-13, 1997, pp. 674-679.

[16] J. Scholliers, T. Yli-Pietila, "Simulation of Mechatronic Systems Using Analog Circuit Simulation Tools", *Proc. IEEE Intl. Conference on Robotics and Automation*, Nagoya, Japan, 21-27May 1995, vol. 3, pp.2847-52.

[17] J. E. Vandemeer, M. S. Kranz, and G. K. Fedder, "Nodal Simulation of Suspended MEMS with Multiple Degrees of Freedom," *in Proc. of the 1997 International Mechanical Engineering Congress and Exposition: The Winter Annual Meeting of ASME in the 8th Symposium on Microelectromechanical Systems*, Dallas, TX, Nov. 16-21, 1997.

[18] J. E. Vandemeer, M. S. Kranz, and G. K. Fedder, "Hierarchical Simulation of Surface Micromachined Inertial Sensors," to appear in *1998 Int. Conf. on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators (MSM '98)*, Santa Clara, CA, April 6-8, 1998.

[19] E. C. Berg, N. R. Lo, J. N. Simon, H. J. Lee, K. S. J. Pister, "Synthesis and Simulation for MEMS Design", *ACM SIGDA Physical Design Workshop, Reston VA,April 1996*, pp. 66-70.

[20] I. Getreu, "Behavioral Modelling of Analog Blocks using the SABER Simulator,", Proc. Microwave Circuits and Systems, pp 977-980, August 1989.

[21] G. K. Fedder, S. Iyer, and T. Mukherjee, "Automated Optimal Synthesis of Microresonators," in *Technical Digest of the IEEE Int. Conf. on Solid-State Sensors and Actuators (Transducers '97)*, Chicago, IL, June 16-19, 1997, v. 2, pp. 1109-1112.

[22] S. Iyer, T. Mukherjee, and G. K. Fedder, "Multi-Mode Sensitive Layout Synthesis of Microresonators," to appear in *1998 Int. Conf. on Modeling and Simulation of Microsystems Semiconductors, Sensors and Actuators (MSM '98)*, Santa Clara, CA, April 6-8, 1998.

[23] P. E. Gill, W. Murray, M. A. Saunders and M. H. Wright, "User's Guide for NPSOL," Systems Optimization Laboratory, Dept. of Operations Research, Stanford University, SOL 86-2, January 1986.