Hierarchical Design and Test of MEMS

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Introduction

Microelectromechanical Systems (MEMS) has existed as a technical field since the early 1980's. Past research has primarily focused on developing new process technologies to support specific applications. As stable process technologies have emerged, many research efforts have shifted towards the design of systems containing hundreds or even thousands of mixed-domain components. As a result, there is a growing need for CAD tools that shorten the design and development time for MEMS-based products. Success in this area depends greatly on new design methodologies that allow complex microsystems of mechanical, electrical, thermal, fluidic, and optical components to be hierarchically represented and simulated. In addition, CAD tools capable of assessing and preventing faulty MEMS behavior are also necessary to ensure the end quality of complex MEMS-based products.

One relatively mature design area is the surface-micromachined suspended MEMS, as exemplified by the recent success of commercial microaccelerometers for automotive airbag deployment and digital mirror displays for high-fidelity video. The existence of acculmulated design expertise, stable fabrication services, and electromechanical modeling tools has made the suspended-MEMS technology a good candidate for initial development of design and test tools for MEMS. Carnegie Mellon University, most notable the Department of Electrical and Computer Engineering and the Robotics Institute, have been intensely investigating the design and test of suspended MEMS. Our MEMS CAD effort has three main thrusts that focus on a schematic environment for MEMS design, MEMS component synthesis and test of this technology.

Schematic-level MEMS design

Typically, MEMS enfineers begin design of a new component with a rough sketch and very basic equations to ensure feasibility. This stage usually leads directly to a physical layout, which, in many cases, is sent to fabrication with little verification, and frequently results in non-functional devices. In the past, the MEMS designer had two choices for the analysis of design: numerical silumlation (e.g., finite-element analysis), and behavioral simulation. Tools for both approaches exist, but none meet the designers needs of simple design entry coupled with rapid design analysis. Numerical simulation tools for MEMS are available from several companies, but tend to be prohibitively slow for tight iterative design. Behavioral simulation can be accomplished using many different commercial tools, such as SPICE, MATLAB, and Saber (1). Although some groups [2,3] have started to contruct geometric parameterized component libraries of MEMS components to support

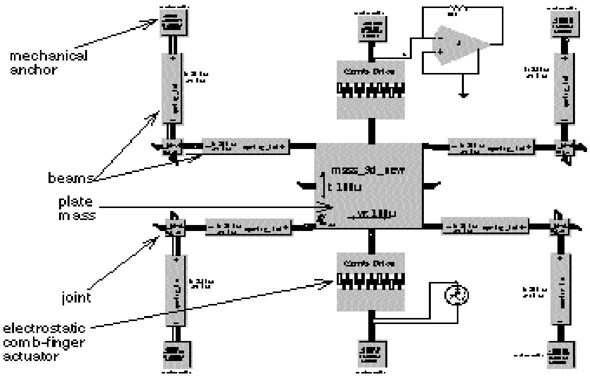

Figure 1: MEMS schematic of a crab-leg-flexure microresonator, implemented in Saber. The device is represented as an interconnected set of MEMS elements, such as beams, plates, and anchors. The electrostatic comb-finger actuators are hierarchical elements which, in turn, may be represented by beams and movable air-gap capacitors

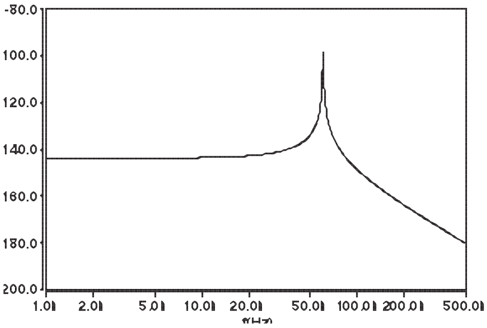

Figure 2: AC analysis of the crab-leg-flexure microresonator. The resonant peak in displacement of the central plate mass occurs at 50 kHz

behavioral simulation, their approach has been to encapsulate the entire MEMS „component“, requiring time-consuming model development based on numerical simulation, which therefore, cannot be placed in the iterative design loop.

Our approach aims at providing a rapid MEMS design process by taking advantage of the hierarchical nature of MEMS. At the lowest level of this hierarchy are such MEMS elements as beams and air gaps that can be interconnected in a general way to create more complicated MEMS devices. Interconnected MEMS devices form higher-level components which come together to form systems. The resulting schematic view provides a direct linkage between both physical layout and behavioral simulation, as is the case with standard integrated-circuit design. A key feature is the one-to-one correspondence of micromechanical components to layout, which provides an intuitive interface for the designer. Coupling the schematic methodology with existing schematic capture tools that are compatible with elctrical circuit analysis enables MEMS design to be quick and efficient.

Exploiting hierarchy allows us to avoid the bottleneck of MEMS device model development. Our simulation methodology [4] treats simple MEMS elements (such as microstructural beams and air-gap capacitors) as the fundamental simulation entities. These elements may be interconnected in a device-level schematic enabling the simulation of the new design of flexures, air-gap electrostatic actuators, and air-gap capacitive sensors. To highlight this capability, the schematic representation of a ‘crab-leg’ MEMS resoncator, implemented in Saber, is shown in Figure 1. the crab-leg suspension is a popular MEMS spring device, created by joining two beams at 90∞. Seperate macromodeling of the complete resonator device is not necessary to conduct the simulation. In a manner analogous to circuit cimulation, general models of the beams and gaps are interconnected in the netlist to build the device-level macromodel hierarchically (and automatically). The a.c. simulation of the microresonator is shown in Figure 2, indicating that the resonant frequency for this resonator is 50 kHz.

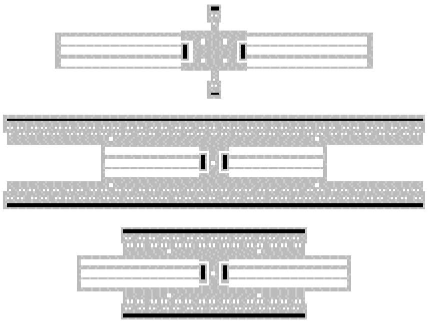

Figure 3: 20 kHz resonators synthesized for three different design objectives: (a) active area, (b) drive voltage, and (c) combination of active area and drive voltage

Currently, work is progressing on elemental-level simulation, in which fundamental MEMS beam and gap elements are interconnected to creat MEMS devices, as well as device-level simulation, in which device macromodels (e.g., comb-finger electrostatic actuator and folded-flexure suspension are interconnected to simulate a complete system application (e.g., a microresonator oscillator).

MEMS Component Synthesis

System-level design for MEMS required the use of mixed-technology components. As is the case with other technologies, the MEMS components for a particular design may come from fixed-libraries, parmetrizable libraries, or from on-the-fly component systhesis.We beliebe that synthesis is the best choice, providing a flexiable and extensible way to generate MEMS components.

Our synthesis approach involves rapid translation of design specifications (such as accelerometer sensitivity) into a design that both functions as an accelerometer, and can meet the desired specifications. This design is then translated into layout using a parametrizable layout generator. This approach involves modeling the design problem as a formal numerical synthesis problem, and then solving it with powerful optimization techniques, a philosophy that has been successful in analog circuit synthesis[5]. Although universal building blocks have not been discoverd for MEMS, components frequently used in systems designs can be easily identified. In the suspended-MEMS area , reusable topologies include several kinds of accelerometers, gyroscopes, resonators, x-y positioners, and micromirrors. Instead of redesigning these components each time a new system is proposed, engineers will benefit from synthesizers which tackle the routine design of frequently-used components.

The process of modeling the design problem involves determining the design variables, the numerical de-

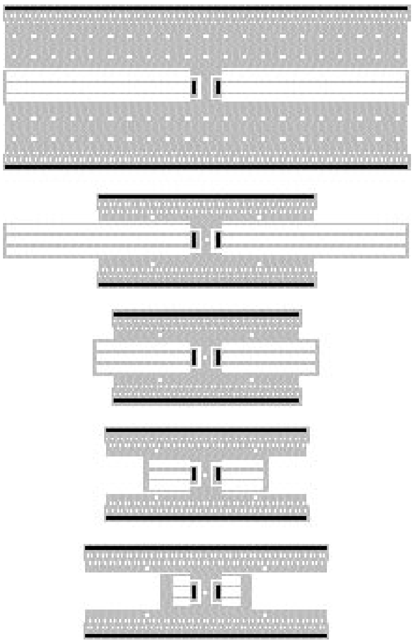

Figure 4: Layout of five resonators synthesized from specifications. (a) fr = 3 kHz, (b) 10 kHz, (c) 30 kHz, (d) 100 kHz, (e) 300 kHz

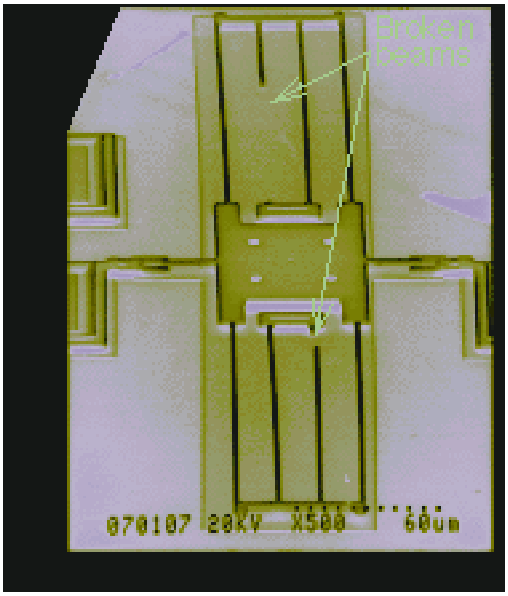

Figure 5: A single-finger comb drive resonator with broken flexure beams

sign constraints, and the quantitative design objective. As a starting point, we have developed and tested a synthesis tool for the surface-micromachined folded-flexure resonator [6].

The lowerst three lateral translational and rotational modes of the mass-spring-damper system are currently not modeled. 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 possible sticking of the structural film to the underlying substrate, which may occur during wet-etch processing of the microstructures. The functional constraints include resonant frequency, stroke, quality factor, and electromechanical stability. The complete design problem is therefore represented as a constrained nonlinear optimization problem, and solved by an off-the-shelf solver.

For our first attempt at encoding the MEMS component-level design problem as an optimization problem, we imported a first-order model of the deisgn objective, area minimization, from VLSI design. The resulting designs were clearly unexpected from the point of view of a MEMS designer. Essentially, the active area minimization was leading to singlecomb-finger resonators, which, while perfectly feasible in terms of operation, were undesirable due to their dependence on high drive voltages to ensure adequate resonant stroke. To highlight the differences, we show the layouts synthesized for the 20 kHz specificiation for three different objectives: area minimization, drive voltage minimization, and minimization of a combination of area and drive voltage (Figure 3). MEMS synthesis can be used for design space expoloration, was shown in Figure 4, where devices were generated to minimize a normalized combination of total layout area and drive voltage for five values of resonant frequency. Smaller devices have less mass, and smaller flexures are stiffer. Both effects increase the resonant frequency. These results span the approximate design range for this particular topology and process technology. For high-frequency resonators, the mass becomes limited by the lower bounds on the comb-drive dimensions to maintain adequate stroke. Very low frequency resonators are limited by the upper bounds imposed on geometry.

We are currently extending this synthesis approach to other MEMS components such as accelerometers and gyroscopes.

Test

Faulty MEMS behavior can result from process contaminations that effect the structure and material properties of a given microstructure. For example, Figure 5 shows the SEM of a defective folded-flexure comb-drive microresonator. This particular resonator has two broken beams which may be the result of the introduction of foreign particles into the fabrication process.

We are developing a comprehensive testing methodolgy for surface-micromachined suspended MEMS. The first step involves understanding the failure modes for the components of concern. To this end, we are using process simulations to predict the effects that contaminations and process variations (later) have on the physical geometries and material properties of the surface-micromachined components [7]. Figure 6 shows the impact of different 2 mm-size contaminations occurring at different resonator locations, introduced at various steps of the MUMPS fabrication process [3]. Low-level electromechanical simulations of the defective resonators reveal an array of faulty behaviors depending on defect location and process step of introduction. we are currently condecting a Monte Carlo analysis using real contamination data at every step of the manufacturing process in order to produce a large spectrum of defective MEMS structures. Low-level mechanical simulations are then planned to categorize these defective structures into a smaller set of faulty behavior classes. These fault classes will form the basis of our MEMS fault models and enable: Fault model verification: we plan to verify the accuracy of teh developed fault models using actual fabricated systems. Our approach will use de-

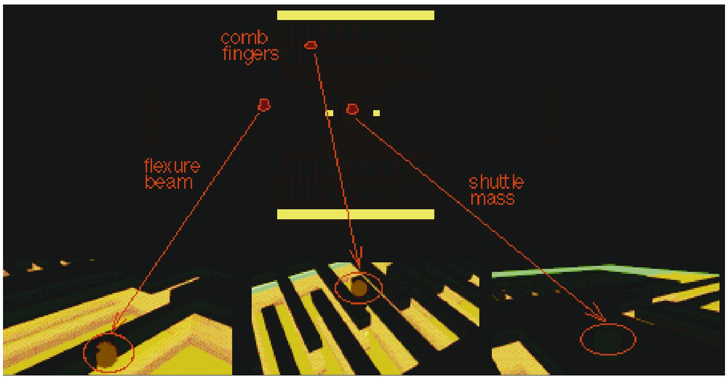

Figure 6: Structural impact of three different contaminations: (a) Flexure beam, (b) comb fingers, and (c) shuttle mass

fective devices to measure and compare actual and predicted faulty behaviors.

Test methodolgy grading: Any possible shortcomings in current testing methodologies will be exposed by test methodology grading. Even if shortcoming do not exist, knowledge about MEMS faulty behavior may lead to more effective test or design techniques that reduce cost and increase quality.

Yield Learning: Finally, more effective testing methodologies will undoubtedly lead to better diagnosis. We plan to create formal links between observed faulty behavior, testing methods, and process contaminations for diagnostic purposes.

Conclusion

Structured design methods for suspended MEMS promise 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 structured design methodology and in leveraging existing CAD tools.

A mixed-domain schematic representation will enable rapid exploration and alaysis of the design space for MEMS components. Many existing suspended-MEMS designs can be partitioned into discrete elements and devices, such as beam springs, plate masses, and electrostatic actuators, that are modeled as lumped-parameter elements. Conversely, new components can be created by connecting together these lumped elements. The development of component-level simulation capability that can stimulate novel interconnections of these MEMS elements and devices is critical for shortening the MEMS design cycle.

MEMS synthesis is a powerful tool for building common components that can then be used in larger systems. Our work on layout synthesis of microresonators has shown that a key prerequisite for synthesis is a set of lumped-parameter models that adequately link device behavior with physical design variables. Thes use of algebraic models of the MEMS components insead of a numerical simulation is essential in controlling the computation time required to generate synthesized results via an iterative improvement algorithm.

A comprehensive testing methodology for surface-micromachined suspended MEMS is required to ensure that the designs generated using the above methods will actually work in the presence of manufacturing contaminations and process variations. We are developing an understanding of the effect of manufacturing reality on the physical geometries and material properties of the surface-micromachined components, which can then be used to create robust MEMS designs.

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 reliable, low-cost, low-volume commonplace applications. Such a design environment is essential for designs in which sensors need to be integrated on the same chip as the attendant electronic information processing capability.

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