Computational Prototyping Tools and Techniques

Academic and Research Staff
Professor Jacob K. White**,** Dr. Bjarne Buchmann, Dr. F. Thomas Korsmeyer, Jinfang Huang

Graduate Students
Luca Daniel, Suvranu De, Joseph D. Kanapka, Thomas J. Klemas, Shihhsien Steve Kuo, Jing-Rebecca Li, Deepak Ramaswamy, Michal Rewienski, Ben Song, Xin Wang, David Willis, Zhenhai Zhu

1. Nonlinear Model-Order Reduction

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Project Staff
M. Rewienski, J. Li, D. Ramaswamy and J. White

Integrated circuit fabrication facilities are now offering digital system designers the ability to integrate analog circuitry and micromachined devices, but such mixed-technology microsystems are extremely difficult to design because of the limited verification and optimization tools available. In particular, there are no generally effective techniques for automatically generating reduced-order system-level models from detailed simulation of the analog and micromachined blocks. Research over the past decade on automatic model-reduction has lead to enormous progress in strategies for linear problems, such as the electrical problems associated with interconnect and packaging, but these techniques have been difficult to extend to the nonlinear problems associated with analog circuits and micromachined devices.

We have been working on several approaches to the nonlinear model reduction problem. Initially, we developed an approach based on a global quadratic representation of the system nonlinearity. In addition, we developed specialized methods for micromachined electromechanical devices. These specialized methods exploited the quadratic relationship between voltage and electrostatic force, as well as the fact that these micromachined devices are mostly rigid.

Our most recent effort is based on representing the nonlinear system with a piecewise-linear system and then reducing each of the pieces with a Krylov Projection. However, rather than approximating the individual components as piecewise-linear and then composing hundreds of components to make a system with exponentially many different linear regions, we instead generate a small set of linearizations about the state trajectory which is the response to a "training input". At first glance, such an approach would seem to work only when all the inputs are very close to the training input, but examples have shown that this is not the case. In fact, the method easily outperforms recently developed techniques based on quadratic reduction.

2. Numerical Techniques for Integral Equations

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Project Staff
J. Huang, B. Song, X. Wang Z. Zhu, and J. White

Finding computationally efficient numerical techniques for simulation of three dimensional structures has been an important research topic in almost every engineering domain. Surprisingly, the most numerically intractable problem across these various discplines can be reduced to the problem of solving a three-dimensional potential problem with a problem-specific Greens function. Application examples include electrostatic analysis of sensors and actuators; electro- and magneto-quasistatic analysis of integrated circuit interconnect and packaging; and potential flow based analysis of wave-ocean structure interaction.

Although the boundary element method is a popular tool to solve the integral formulation of many three-dimensional potential problems, the method become slow when a large number of elements are used. This is because boundary-element methods lead to dense matrix problems which are typically solved with some form of Gaussian elimination. This implies that the computation grows as cubically with the number of unknowns tiles needed to accurately discretize the problem. Over the last decade, algorithms with grow linearly with problem size have been developed by combining iterative methods with multipole approximations. Our work in this area has been to develop precorrected-FFT techniques, which can work for general Greens functions, and Wavelet based techniques, which generate extremely effective preconditioners which accelerate iterative method convergence.

The development of fast boundary-element based solvers has renewed interest in developing well-conditioned integral formulations for a variety of engineering problems. Previously, we had developed a novel surface-only formulation for quasistatic and full-wave analysis of interconnect. The new approach eliminated some of the low-frequency ill-conditioning problems associated with previous efforts. However, even though the formulation showed promise, it was plagued with numerical difficulties of poorly understood origin. Over the past year we have identified problems in the formulation and the schemes used to numerically evaluate the integrals.

3. Simulation Tools for Micromachined Device Design

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S. De, D. Ramaswamy, M. Rewienski, X. Wang, J. White

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.

Our most recent work is on extending the FastStokes solver to the incompressible fluid case. In particular, recent modeling and experimental work has demonstrated that the out-of-plane motion of certain micro-machined devices is strongly influenced by fluid compression. For simple structures, such as a plate over a substrate, the fluid compression effects can be determined by solving the Reynolds equation but such an approach can not be extended to more geometrically complicated structures. Instead, we have developed a modification of the algorithms in FastStokes that incorporates the compression effects.

4. Efficient 3-D Interconnect Analysis

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Project Staff
L. Daniel, J. Kanapka, T. Klemas, J. Li, B. Song, Z. Zhu, and J. White.

We have developed multipole-accelerated algorithms for computing capacitances and inductances of complicated 3-D geometries, and have implemented these algorithms in the programs FASTCAP and FASTHENRY. The methods are accelerations of the boundary-element or method-of-moments techniques for solving the integral equations associated with the multiconductor capacitance or inductance extraction problem. Boundary-element methods become slow when a large number of elements are used because they lead to dense matrix problems which are typically solved with some form of Gaussian elimination. This implies that the computation grows as N cubed, where N is the number of panels or tiles needed to accurately discretize the conductor surface charges. Our new algorithms, which use Krylov subspace iterative algorithms with a multipole approximation to compute theiterates, reduces the complexity so that accurate multiconductor capacitance and inductance calculations grow nearly as NM where M is the number of conductors. For practical problems which require as many as 10,000 panels or filaments, FASTCAP and FASTHENRY are more than two orders of magnitude faster than standard boundary-element based programs. Manuals and source code for FASTCAP and FASTHENRY areavailable from our web site (http://rle-vlsi.mit.edu).

In more recent work, we have been developing an alternative to the fast-multipole approach to potential calculation. The new approach uses an approximate representation of charge density by point charges lying on a uniform grid instead of by multipole expansions. For engineering accuracies, the grid-charge representation has been shown to be a more efficient charge representation than the multipole expansions. Numerical experiments on a variety of engineering examples arising indicate that algorithms based on the resulting “precorrected-FFT'” method are comparable in computational efficiency to multipole-accelerated iterative schemes, and superior in terms of memory utilization.

The precorrected-FFT method has another significant advantage over the multipole-based schemes, in that it can be easily generalized to some other common kernels. Preliminary results indicate that the precorrected-FFT method can easily incorporate kernels arising from the problem of capacitance extraction in layered media. More importantly, problems with a Helmholtz equation kernel have be solved at moderate frequencies with only a modest increase in computational resources over the zero-frequency case. An algorithm based on the precorrected-FFT method which efficiently solves the Helmholtz equation could form the basis for a rapid yet accurate full-wave electromagnetic analysis tool.

Reduced-order modeling techniques are now commonly used to efficiently simulate circuits combined with interconnect. Generating reduced-order models from realistic 3-D structures, however has received less attention. Recently we have been studying an accurate approach to using the iterative method in the 3-D magnetoquasistatic analysis program FASTHENRY to compute reduced-order models of frequency-dependent inductance matrices associated with complicated 3-D structures. This method, based on a Krylov-subspace technique, namely the Arnoldi iteration, reformulates the system of linear ODE's resulting from the FASTHENRY eqquation into a state-space form and directly produces a reduced-order model in state-space form. The key advantage of this method is that it is no more expensive than computing the inductance matrix at a single frequency. The method compares well with the standard Pade approaches and may present some advantages because in the Arnoldi-based algorithm, each set of iterations produces an entire column of the inductance matrix rather than a single entry, and if matrix-vector product costs dominate then the Arnoldi-based algorithm produces a better approximation for a given amount of work. Finally, we have shown that the Arnoldi method generates guaranteed stable reduced order models, even for RLC problems.

Another approach to computing these reduced order models are the truncated balanced realization (TBR) methods. These methods have largely been abandoned for the interconnect model-order reduction application, even though they produce optimal reduced-order models, because TBR requires the solution of a Lyapunov equation and has been believed to be too computationally expensive to use on large problems. We recently developed a new algorithm, Vector ADI, for approximately solving the Lyapunov equation. The new method is formulated in terms of finding an orthnormal basis for a Krylov subspace based on rational functions of the system matrix. The new method requires work comparable to the Arnoldi methods, but produces reduced-order models that are near the TBR optimum.

Additional recent work has focussed on fast techniques of model reduction which automatically generate low order models of the interconnect directly from the discretized Maxwell's equations under the quasistatic assumption. When combined with with fast potential solvers, the overall algorithm efficiently generates accurate models suitable for coupled circuit-interconnect simulation.

Also in this area, we have been investigating techniques analyzing coupling problems in single chip mixed-signal systems, where both analog and digital functional blocks share a common substrate. A major challenge for mixed-signal design tools is the accurate modeling of the parasitic noise coupling through the common substrate between the high-speed digital and high-precision analog components. We recently developed a wavelet-like approach which makes it possible to reduce the time and memory required to compute the interactions between N substrate contacts from order N squared down to order N log N.

5. Paper Publications

H. Levy, D. MacMillen, and J. White, "A Rank-One Update Method for Efficient Processing of Interconnect Parasitics in Timing Analysis", Proceedings of the Design Automation Conference, Los Angeles, June, 2000, pp 75-78.

J. Kanapka, J. Phillips and J. White, "Fast methods for extraction and Sparsification of Substrate Coupling", Proceedings of the 37th Design Automation Conference, Los Angeles, June, 2000, pp 738-743

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

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

W. Ye, X. Wang, W. Hemmert, D. Freeman and J. White, "Viscous Drag on a Lateral Micro-resonator: Fast 3-D Fluid Simulation and Measured Data", Proc. Solid-State Sensors and Actuators Workshop, Hilton Head Island, June, 2000 pp. 124-127

D. Ramaswamy and J. White, "Automatic Generation of Small-Signal Dynamic Macromodels from 3-D Simulation," International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators, Hilton Head, North Carolina, March 2001

L. Daniel, J. White, A. Sangiovanni-Vincentelli, "Electromagnetic Modeling using Conduction Modes as Global Basis Functions", Semiconductor Research Corporation TECHCON 2000 Conference, Phoenix AZ, 21-24 September 2000

L. Daniel, A. Sangiovanni-Vincentelli, J. White, "Electromagnetic Modeling using Conduction Modes as Global Basis Functions", IEEE 9th Topical Meeting on Electrical Performance of Electronic Packages: Scottsdale, AZ, 23-25 October 2000.

L. Daniel, A. Sangiovanni-Vincentelli, J. White, "Using Conduction Modes for Efficient Electromagnetic Analysis of on-Chip and off-Chip Interconnect" , Design Automation Conference, Las Vegas, 22-24 June 2001.

T. Mukherjee, G. Fedder and J. White, "Emerging Simulation Approaches
For Micromachined Devices", IEEE Trans. on Computer-Aided Design, December, 2000

X. Wang, P. Mucha and J. White, "Fast Fluid Analysis for Multibody Micromachined Device", International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators, Hilton Head, North Carolina, March 2001