Chapter 2. Computational Prototyping Tools and Techniques

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2.1 Free-Surface Hydrodynamics for Offshore Structure Analysis

Sponsors

Industry Consortium (Mobil, Statoil, DNV Software, Shell, OTRC, Petrobras, NorskHydro, Exxon, Chevron, SAGA, NSWC)
U.S. Navy - Office of Naval Research

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The free-surface hydrodynamics subgroup invents and implements algorithms for boundary-element prototyping tools used in offshore engineering. Work is done on linear and nonlinear approaches in the time and frequency domains. The current focus is on the advancement of high-order element techniques and the acceleration of solutions by sparsification. The high-order boundary element algorithms offer a continuous representation of the solution and gains in efficiency over the low-order approach. The sparsification algorithms (both multipole acceleration and precorrected-FFT acceleration) reduce the computational complexity of the solution while preserving the accuracy. The group has had considerable success in both of these areas: advancing both time- and frequency-domain high-order element prototyping tools, and applying precorrected-FFT acceleration to the low-order element tool WAMIT. More importantly, we are presently generating results from a combination of the high-order element and precorrected-FFT sparsification algorithms from frequency domain analysis. This combination will allow efficient coupled linear hydrodynamic/structural analysis. For a similar nonlinear time-domain analysis this combination is absolutely necessary, and work is being done in that area as well.

2.2 Numerical Techniques for Integral Equations

Sponsors

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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 disciplines 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 becomes 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 cubically with the number of unknown tiles needed to accurately discretize the problem. Over the last decade, algorithms that 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 that can work for general Greens functions and wavelet based techniques. These, in turn, generate extremely effective preconditioners that 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. We have developed second-kind formulations for the electrostatics problem that directly yields the surface charge distribution on conductors. We have developed techniques that ensure accuracy in the numerically computed capacitances given arbitrarily shaped dielectric materials of arbitrarily high permitivity.

2.3 Simulation Algorithms for RF Circuits

Cadence Design Systems
Harris Semiconductor
MAFET Consortium
Motorola Semiconductor

Project Staff

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RF-integrated circuit designers make extensive use of simulation tools that perform nonlinear periodic steady-state analysis and their extensions. However, the computational costs of these simulation tools have restricted users from examining the detailed behavior of complete RF subsystems. Recently, algorithmic developments, based on matrix-implicit iterative methods, are rapidly changing this situation, providing new faster tools which can easily analyze circuits with hundreds of devices. We have investigated these new methods by describing how they can be used to accelerate finite-difference, shooting-Newton, and harmonic-balance-based algorithms for periodic steady-state analysis.

2.4 Efficient 3-D Interconnect Analysis

Sponsors

Defense Advanced Research Projects Agency
Harris Semiconductor
IBM Corporation
MAFET Consortium
Semiconductor Research Corporation

Project Staff

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We have developed multipole-accelerated algorithms for computing capacitances and inductances of complicated 3-D geometries and 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 use Krylov subspace iterative algorithms with a multipole approximation to compute the iterates, reducing the complexity. 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 are available from our web site (http://rle-vlsi.mit.edu).

In more recent work, we have developed an alternative to the fast-multipole approach to potential calculation. This 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, because 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 been 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 the Krylov-subspace technique called the Arnoldi iteration, reformulates the system of linear ODEs resulting from the FASTHENRY equation into a state-space form and produces a reduced-order model directly 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. It may also present some other advantages because in the Arnoldi-based algorithm each set of iterations produces an entire column of the inductance matrix rather than a single entry. 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.

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

The design of single-chip mixed-signal systems that combine both analog and digital functional blocks on a common substrate is now an active area of our research, driven by the relentless quest for high-level integration and cost reduction. 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 are working on a sparsification method based on eigendecomposition that handles edge effects more accurately than previously applied multipole expansion techniques. Then we combine the sparsification approach with a multigrid iterative method which converges more rapidly than previously applied Krylov-subspace methods. Results on realistic examples demonstrate that the combined approach is up to an order of magnitude faster than the sparsification plus a Krylov-subspace method and orders of magnitude faster than not using sparsification at all.

2.5 Publications

2.5.1 Journal Articles

Kamon, M., N. Marques, L.M. Silveira, and J. White. "Automatic Generation of Accurate Circuit Models of 3-D Interconnect." *IEEE Trans. Compon., Packag., Manufact. Tech.* Part B: Advanced Packaging 21(3): 225-40 (1998).

Korsmeyer, F.T., and H.B. Bingham. "The Forward Speed Diffraction Problem." *J. Ship Res.* 42(2): 99-112 (1998).

Kring, D.C. "Ship Seakeeping through the τ = 1/4 Critical Frequency." *J. Ship Res.* 42(2): 113-19 (1998).

Newman, J.N. "Radiation and Diffraction Analysis of the McIver Toroid." *J. Eng. Math.* Special Issue on Ocean Mechanics. Forthcoming.

Silveira, L.M., I. Elfadel, M. Kamon, and J. White. "A Coordinate-Transformed Arnoldi Algorithm for Generating Guaranteed Stable Reduced-Order Models of RLC Circuits." Special Issue on Advances in Computer Methods in Electromagnetics of *Comp. Meth. Appl. Mech. Eng*. 169(3-4): 377-89 (1999).

Tausch, J., and J. White. "Second-Kind Integral Formulations for the Capacitance Problem." *Adv. Comput. Math.* 9: 217-32 (1998).

Tausch, J., and J. White. "Capacitance Extraction of 3-D Conductor Systems in Dielectric Media with High Permittivity Ratios." *IEEE Trans. Microwave Tech.* 47(1): 18-26 (1999).

2.5.2 Meeting Papers Presented

Farina, L., and C.-H. Lee. "An Effective Treatment of Corner Singularities in Higher-order Integral Equation Methods for Water Wave Diffraction." Paper presented at the Day on Diffraction, St. Petersburg, Russia, 1998.

Lee, C.-H., and J.N. Newman. "An Assessment of Hydroelasticity for Very Large Hinged Vessels." Paper presented at Hydroelasticity '98, Fukuoka, Japan, 1998.

Lee, C.-H., L. Farina, and J.N. Newman. "A Geometry Independent Higher-order Panel Method and its Application to Wave-body Interactions." Paper presented at the Engineering Mathematics and Applications Conference, Adelaide, Australia, 1998.

Marques, N., M. Kamon, J. White, and L. M. Silveira. "An Efficient Algorithm for Fast Parasitic Extraction and Passive Order Reduction of 3D Interconnect Models." Paper presented at the Design, Automation and Test in Europe, Exhibition, and Conference (DATE'98), Paris, France, February 1998, pp. 538-48.

Wang, F., and J. White. "Automatic Model Order Reduction of a Microdevice using the Arnoldi Approach." Paper presented at the International Mechanical Engineering Congress and Exposition, Anaheim, California, November 1998.

Yang, Y.-J., F.T. Korsmeyer, V. Rabinovich, M. Ding, S.D. Senturia, and A.I. Akinwande. "An Efficient Three-dimensional CAD Tool for Field-emission Devices." Paper presented at the IEEE International Electron Devices Meeting, San Francisco, California, 1998.

2.5.3 Meeting Papers Published

Aluru, N.R., and J. White. "A Fast Integral Equation Technique for Analysis of Microflow Sensors Based on Drag Force Calculations." Paper published in the *Proceedings of the International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators,* Santa Clara, California, April 1998, pp. 283-86.

Chou, M., and J. White. "Multilevel Integral Equation Methods for the Extraction of Substrate Coupling Parameters in Mixed-Signal IC's." Paper published in the *Proceedings of the 35th Design Automation Conference,* San Francisco, California, June 1998, pp. 20-25.

Kamon, M., F. Wang, and J. White. "Recent Improvements to Fast Inductance Extraction and Simulation." Paper published in the *Proceedings of the Seventh Topical Meeting on Electrical Performance of Electronic Packaging*, West Point, New York, October 1998, pp. 281-84

Marques, N., M. Kamon, J. White, and L.M. Silveira. "A Mixed Nodal-Mesh Formulation for Efficient Extraction and Passive Reduced-Order Modeling of 3-D Interconnects." Paper published in the *Proceedings of the 35th Design Automation Conference,* San Francisco, California, June 1998, pp. 297-302.

Massoud, Y., and J. White. "Fast Inductance Extraction of 3-D Structures with Non-constant Permeabilities." Paper published in the *Proceedings of the International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators*, Santa Clara, California, April 1998, pp. 190-93.

Massoud, Y., S. Majors, T. Busami, and J. White. "Layout Techniques for Minimizing On-Chip Interconnect Self Inductance." Paper published in the *Proceedings of the 35th Design Automation Conference,* San Francisco, California, June 1998, pp. 566-71.

Newman, J.N. "Hydrodynamic Analysis of the McIver Toroid." Paper published in the *Proceedings of the 13th International Workshop on Water Waves and Floating Bodies,* Alphen, The Netherlands, 1998, pp. 115-18.

Ramaswamy, D., N.R. Aluru, and J. White. "A Mixed Rigid/Elastic Formulation for Efficient Analysis of Electromechanical Systems." Paper published in the *Proceedings of the International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators,* Santa Clara, California, April 1998, pp. 304-07.

Wang, J., and J. White. "Automatic Model Order Reduction of a Microdevice using the Arnoldi Approach." Paper published in the *Proceedings of the International Mechanical Engineering Congress and Exposition,* Ananheim, California, November 1998, pp. 527-30.

Wang, J., J. Tausch, and J. White. "Improved Integral Formulations for Fast 3-D Method-of-Moments Solvers." Paper published in the *Proceedings of the Seventh Topical Meeting on Electrical Performance of Electronic Packaging,* West Point, New York, October 1998.