Computational Prototyping Tools and Techniques

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1. 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 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. In the past year, we have developed a novel surface-only formulation for quasistatic and full-wave analysis of interconnect. The new approach eliminates some of the low-frequency ill-conditioning problems associated with previous efforts. In addition, we developed an new formulation based on fictious magnetic charge for including nonconductive magnetic materials in an integral formulation for inductance extraction.

2. Efficient 3-D Interconnect Analysis

Sponsors:

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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 the iterates, 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 are available 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.

3. Paper Publications

L. M. Silveira, I. Elfadel, M. Kamon and J. White, ``A Coordinate-Transformed Arnoldi Algorithm for Generating Guaranteed Stable Reduced-Order Models of RLC Circuits, Special Issue of Comp. Methods in Appl. Mech. and Eng. on Advances in Comp. Methods in Electromagnetics, February 1999, Vol. 169/3-4, pp. 377-389

M. Kamon, N. Marques, L. M. Silveira and J. White, ``Automatic generation of Accurate Circuit Models of 3-D Interconnect'', IEEE Transactions on Components, Packaging, and Manufacturing Technology -- Part B: Advanced Packaging, August, 1998, vol. 21, no. 3, pp. 225-240

D. Ramaswamy, W. Ye, X. Wang and J. White, ``Fast Algorithms for 3-D Simulation,'' Journal of Modeling and Simulation of Microsystems, Vol. 1, No. 1, pp. 77-82, December, 1999.

Y. Massoud, J. Wang, and J. White, ``Accurate Inductance Extraction with Permeable Materials Using Qualocation,'' To appear International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators, San Juan, April 1999

J. Wang, J. Tausch, and J. White, ``A Wide Frequency Range Surface Integral Formulation for 3-D Inductance and Resistance Extraction,'' To appear International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators, San Juan, April 1999

J. White, ``Fast Algorithms for 3-D Simulation,'' To appear International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators, San Juan, April 1999

W. Ye, J. Kanapka, X. Wang and J. White, ``Efficiency and Accuracy Improvements for FastStokes, A Precorrected-FFT Accelerated 3-D Stokes Solver,'' To appear International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators, San Juan, April 1999

W. Ye, J. Kanapka, and J. White, ``A Fast 3D Solver for Unsteady Stokes Flow with Applications to Mi cro-Electro-Mechanical Systems,'' International Conference on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators, San Juan, April 1999

J Li and J. White ``Solution of Low Rank Input Lyapunov Equations by Vector Alternate Direction Implicit Iteration using a Rational Krylov Subspace Approach, with Application to Model Order Reduction,'' (Proceedings of the 35th Design Automation Conference), New Orleans, June 1999.

D. Ramaswamy, N. Aluru and J. White, Fast Coupled-Domain, Mixed-Regime Electromechanical Simulation Proc. Int'l Conference on Solid-State Sensors and Actuators (Transducers '99), Sendai Japan, June, 1999 pp. 314-317

J. Wang, J. Tausch, and J. White, A Wide Frequency Range Surface Formulation for 3-D RLC Extraction (Proceedings of the IEEE Conference on Computer-Aided Design), San Jose, November, 1999.

J. Li and J. White, Efficient Model Reduction of Interconnect Via Approximate System Grammians (Proceedings of the IEEE Conference on Computer-Aided Design), San Jose, November, 1999.

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

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