Universität Stuttgart

Workshop on

Adaptive Fast Boundary Element Methods in Industrial Applications

Söllerhaus, 29.9.–2.10.2004

U. Langer, O. Steinbach, W. L. Wendland (eds.)

Berichte aus dem Institut für Angewandte Analysis und Numerische Simulation

Book of Abstracts 2004/015

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Programm

Mittwoch, 29.9.2004	
15.00–16.00	Kaffee
16.00–16.05	Eröffnung
16.05–16.50	M. Bebendorf (Leipzig) Fast iterative or fast direct solution of boundary element systems
16.55–17.40	D. Pusch (Linz) Comparison of geometric and algebraic multigrid for data–sparse boundary element matrices
17.45–18.30	K. Straube (Stuttgart) Hierarchische Cholesky–Zerlegung für FE–Systeme in der Elektrodynamik
18.30	Abendessen
Donnerstag, 30.9.2004	
9.00–9.45	M. Maischak (Hannover) Numerical simulation of electrostatic spray painting
10.00–10.45	G. Of (Stuttgart) Adaptive boundary element methods in industrial applications
10.45–11.30	Kaffee
11.30–12.15	B. N. Khoromskij (Leipzig) Data–sparse Schur complement domain decomposition
12.30	Mittag
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16.30–17.15	J. Breuer (Stuttgart) The coupling of electrical eddy current heat production and air cooling
17.30–18.15	B. Cranganu–Cretu (Daettwil) A direct boundary integral equation method for mixed dielectric–PEC scatterers
18.30	Abendessen
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Freitag, 1.10.2004	
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	Numerical aspects of a poroelastic time domain boundary element formulation
10.00–10.45	R. Grzibovskis (Saarbrücken)
	Fast boundary element method for linear elasticity problems
10.45–11.30	Pause
11.30–12.15	S. Börm (Leipzig)
	$\mathcal{H}^2$–matrices with adaptive cluster bases
12.30	Mittag
13.30–18.00	Wanderung
18.30	Abendessen
Sonnabend, 2.10.2004	
9.00–9.45	L. Grasedyck (Leipzig)
	Adaptive coarsening of hierarchical matrices
9.45–10.30	J. Djokic (Leipzig)
	Efficient update of $\mathcal{H}$–matrices
10.30–11.00	Pause
11.00–11.45	C. Pechstein (Linz)
	Coupled FETI/BETI for nonlinear potential problems
11.45	Ende des Workshops

Fast iterative or fast direct solution of boundary element systems

M. Bebendorf[1], J. Ostrowski[2]
[1]Universität Leipzig, [2]ABB Schweiz

Besides wavelet techniques, for the efficient numerical solution of boundary element systems fast summation schemes like fast multipole or panel clustering can be used. These methods have the disadvantage that a complete recoding of existing computer codes is necessary. We will use a more sophisticated method which adaptively generates a data-sparse approximant from few of the original matrix entries. With this so called ACA (adaptive cross approximation) we will be enabled to generate, store and multiply the approximant by a vector with logarithmic-linear complexity. Since ACA treats blocks of the coefficient matrix separately, the parallelization of it is obvious.
Rather than only accelerating the matrix-vector multiplication, ACA approximates the whole operator in the format of hierarchical matrices ($\mathcal{H}$-matrices). Therefore, it is possible to apply the $\mathcal{H}$-versions of the usual matrix operations to the approximant. In particular, the LU decomposition can be generated with linear complexity. This gives rise to efficient, provably spectrally equivalent black-box preconditioners or to a direct solver using forward/backward substitution.
Numerical examples for realistic electromagnetic/electrostatic problems show that the whole solution phase can be done with logarithmic-linear complexity without special adaptation to the respective problem. (Joerg Ostrowski's part)

$\mathcal{H}^2$-matrices with adaptive cluster bases

S. Börm, W. Hackbusch
Max-Planck-Institut für Mathematik in den Naturwissenschaften, Leipzig

$\mathcal{H}^2$-matrices can be used to find data-sparse representations of the densely populated matrices occurring, e.g., in boundary element methods.
The basic idea of hierarchical matrix techniques is to split the index set I into a hierarchy of subsets, the *cluster tree* $\mathcal{T}_I$, and to split the matrix into a hierarchy $\mathcal{T}_{I\times I}$ of subblocks $\tau \times \sigma$ corresponding to $\tau, \sigma \in \mathcal{T}_I$ that contains only small blocks and blocks that admit a separable approximation. The latter blocks are called *admissible*.
In a hierarchical matrix, an admissible block $\tau \times \sigma$ is approximated by a factorized rank-k-matrix. In an $\mathcal{H}^2$-matrix, a modified factorized representation is used that leads to algorithms with *linear* complexity in the number of degrees of freedom n.
While constructing an $\mathcal{H}^2$-matrix approximation of an integral operator by Lagrangian interpolation leads to a relatively general, simple and fast method, this approach also requires a large amount of storage, since polynomial bases are not adapted to the special characteristics of a given operator or a given geometry. The storage requirements can be reduced significantly by using local singular value decompositions in order to eliminate redundant expansion functions. This optimization procedure increases the computing time only by a small amount and allows us to treat boundary element problems with more than $100,000$ degrees of freedom on standard PCs.

The coupling of electrical eddy current heat production and air cooling

Z. Andjelic[1], J. Breuer[2], O. Steinbach[2], W. L. Wendland[2]
[1]ABB Corporate Research, [2]Universität Stuttgart

We consider an industrial electric device which is driven by an alternating current. The amperage and the frequency are given on some contact areas of the device.
Starting with the eddy current model for the Maxwell equations one can derive boundary integral equations for the unknown traces of the electric and the magnetic fields on the boundary. The given amperage on the contacts translates into a given normal component of the electric field inside the device. This yields a special jump condition for the tangential components of the magnetic field. The unknown magnetic trace can then be restricted to its divergence free part. The jump can be computed by solving an auxiliary problem, the Laplace–Beltrami equation for some surface potential. For its discretization we derive a stabilized mixed Galerkin finite element method on the boundary which leads to a sparse system and gives quasioptimal convergence rates. The discretization of the main system is done via Raviart–Thomas elements on the boundary. The divergence constraint on the magnetic trace is incorporated by using Lagrangian multipliers. The case of multiple materials with different conductivity is handled via a domain decomposition approach. The corresponding discrete system contains fully populated boundary element matrices. So the adaptive cross approximation approach is used to approximate the Laplace and Helmholtz kernels which leads to a sparse boundary element method for the eddy current scheme.
The electrical field then enters as a source field into the heat conduction inside the device. For the cooling air flow we assume that it is not affected by the heat production, but can be considered as a given velocity field. This can be the result of the stationary Navier–Stokes equations or of the Prandtl boundary layer equations and a far field potential flow. For the temperature outside the device the energy equation has to be solved. As a simplified model the nonlinear heat conduction equation is considered. Via the Kirchhoff transformation the resulting system can be handled with boundary integral equations.

FMM based solution of electrostatic and magnetostatic field problems on a PC cluster

A. Buchau, W. Hafla, F. Groh, W. M. Rucker
Universität Stuttgart

The solution of electrostatic and magnetostatic field problems on a PC cluster is discussed in this paper. The use of problem oriented meshes in the context of fast multipole boundary element methods (FM–BEM) is examined along with parallelization strategies for PC clusters. Especially parallelization at different levels is investigated. This includes vectorization, multi–threading, and multi–processing. In all cases special properties of the FM–BEM are exploited. Furthermore limits of parallelization methods in combination with efficient matrix compression techniques are shown and their consequences are discussed. All proposed methods are numerically tested with real–life problems. There, a main focus is set on the combination of modern numerical techniques and their practical application. This includes choice of numerical formulation, direct or indirect, meshing strategy, hardware platform, and postprocessing.

A Direct Boundary Integral Equation Method for mixed dielectric–PEC scatterers

B. Cranganu–Cretu[1], R. Hiptmair[2]
[1]ABB Schweiz, [2]ETH Zürich

We present a new variational direct boundary integral equation approach for solving the scattering and transmission problem for dielectric objects partially coated with a PEC layer. The main idea is to use the electromagnetic Calderón projector along with transmission conditions for the electromagnetic fields. This leads to a symmetric variational formulation, which lends itself to Galerkin discretization by means of divergence–conforming discrete surface currents.
A partial PEC coasted dielectric gives rise to a transmission (aperture) problem. The transmission problem received extensive attention in the engineering community (see [1] and the references cited therein). Approaches based on the expansion into spherical harmonics are also present in the literature, however, this only works for very special geometries. More flexibility is offered by the scheme proposed in [1], which is based on the equivalence principle introduced by Harrington. Yet, this method is of little practical value, because it entails inverting a large dense matrix. In this article we outline an approach that is based on the Poincaré-Steklov operators associated with Maxwell's equations in free space. These operators are also known as the electric–to–magnetic mappings. They will be expressed through boundary integral operators and give rise to a coupled variational problem featuring traces of the electric and magnetic field on Γ as unknowns.
Our focus we be on both the derivation of the coupled variational problem and its Galerkin discretization and the performance of the resulting scheme in numerical experiments. We will sketch the theoretical justification for the validity of the coupled problem, but details will be skipped. A comprehensive exposure of the theoretical techniques is given in [2]. Several numerical experiments confirm the efficacy of the new method [3].

[1] T. Wang, R. F. Harrington, J. R. Mautz: Electromagnetic scattering from and transmission through arbitrary apertures in conducting bodies. IEEE Trans. Antennas and Prop. 38 (1990) 1805–1814.

[2] A. Buffa, R. Hiptmair: Galerkin boundary element methods for electromagnetic scattering. In: Topics in Computational Wave Propagation. Direct and Inverse Problems (M. Ainsworth, P. Davis, D. Duncan, P. Martin, B. Rynne eds.), Lecture Notes in Computational Science and Engineering vol. 31, Springer, Berlin, 2003, pp. 83–124.

[3] B. Cranganu–Cretu, R. Hiptmair, Z. Andjelic: Transmission through arbitrary apertures in metal–coated dielectric bodies. Digest book of the 11th Biennial IEEE Conference on Electromagnetic Field Computation CEFC 2004, 6–9 June, 2004, Seoul, p. 142.

Efficient Update of $\mathcal{H}$-Matrices

J. Djokić

Max Planck Institute for Mathematics in Sciences, Leipzig

$\mathcal{H}$-matrices have been used for solving various kinds of problems that require large matrices. The discretisation of an integral equation leads to a full matrix that can be approximated by an $\mathcal{H}$-matrix. The natural question that arises in the context of adaptive grid refinement is: if the discretisation becomes *locally* finer, is it possible to update an existing $\mathcal{H}$-matrix instead of constructing a new one.

In this talk we will present an efficient method for updating an $\mathcal{H}$-matrix that arises from the boundary element method applied to the single-layer (or double-layer) potential operator.

This is a joint work with Lars Grasedyck, Wolfgang Hackbusch and Sabine Le Borne.

Adaptive Coarsening of Hierarchical Matrices

L. Grasedyck
Max Planck Institute for Mathematics in Sciences, Leipzig

In this talk we give a brief introduction to the hierarchical matrix format which is used for the efficient storage of BEM stiffness matrices. The basic building block of the format is the cluster tree T_I of the index set I which is constructed, e.g., by binary space partitioning. Via the admissiblity condition the block-cluster tree $T_{I\times I}$ is built, which describes the subdivision of the matrix into admissible blocks. Each of the admissible blocks is represented by a matrix of low rank.
In the second part of the talk we introduce a coarsening strategy that aims at finding an *optimal* block-cluster tree and thus an optimal admissiblity condition. Optimality can be gained with respect to storage or arithmetic complexity.
In the third part of the talk we use the coarsening procedure and the $\mathcal{H}$-matrix arithmetic in order to define an $\mathcal{H}$-LU preconditioner for BEM stiffness matrices. Complexity estimates for the setup, storage and evaluation of the preconditioner close the talk.

Fast boundary element method for linear elasticity problems

R. Grzibovskis
Universität des Saarlandes, Saarbrücken

We develop a fast boundary element method for the system of Lamé equations. Single and double layer potential operators are discretized and approximated using the hierarchical clustering and the Adaptive Cross Approximation techniques. This leads to matrix compression factor of order 10 and makes it possible to consider problems with about 20000 elements. We present results of calculations that come from BEM and FEM coupling in the framework of the DFG Project "Modelling of Incremental Metal Forming".

Data-Sparse Schur Complement Domain Decomposition

W. Hackbusch, B. N. Khoromskij, R. Kriemann
Max-Planck-Institute for Mathematics in the Sciences, Leipzig

A class of hierarchical matrices ($\mathcal{H}$-matrices) allows the data-sparse approximation to integral and more general nonlocal operators (say, the Poincaré-Steklov operators) with almost linear cost. We consider the $\mathcal{H}$-matrix-based approximation to the Schur complement on the interface [2] corresponding to the FEM discretisation of an elliptic operator $\mathcal{L}$ with jumping coefficients in $\mathbb{R}^d$. As with the standard Schur complement domain decomposition methods, we split the elliptic inverse $\mathcal{L}^{-1}$ as a sum of local inverses associated with subdomains (this can be implemented in parallel), and the corresponding Poincaré-Steklov operator on the interface.
Using the hierarchical formats based on either standard or weakened admissibility criteria (cf. [1]) we elaborate the *approximate Schur complement inverse* in an explicit form that is proved to have a linear-logarithmic cost $O(N_\Gamma \log^q N_\Gamma)$, where N_Γ is the number of degrees of freedom on the interface. The $\mathcal{H}$-matrix-based preconditioner can be also applied.
Numerical tests confirm the almost linear cost of our *parallel direct Schur complement method*. In particular, we consider examples with brick and mortar structure of the coefficients.

Literatur

[1] W. Hackbusch, B.N. Khoromskij and R. Kriemann. *Hierarchical Matrices Based on Weak Admissibility Criterion.* Preprint MPI MIS no. 2, Leipzig, 2003; Computing (to appear).

[2] W. Hackbusch, B.N. Khoromskij and R. Kriemann. *Direct Schur Complement Method by Domain Decomposition based on Hierarchical Matrix Approximation.* Preprint MPI MIS no. 25, Leipzig, 2004 (submitted).

Numerical simulation of electrostatic spray painting

M. Maischak
Universität Hannover

We investigate the electrostatic subproblem of the electrostatic spray painting process. Between the target and at least one electrode a high voltage is applied. Due to the small diameter of the tip of the electrode a hugh electrical field strength leads to the existence of a charge cloud around the electrod, i.e. to the corona emission of electrons from the metal surface. This charges are transported in a convection process along the electrical field lines. The boundary condition for the charge transport problem is given indirectly by the Peek field strength, which means that the charge density on the emitting surface takes a value such that the electrical field strength on the surface equals the Peek field strength, which is determined by the geometry. We solve this nonlinear coupled problem iteratively by modeling the electrostatic problem by Poissons equation discretized by FEM or a FEM-BEM coupling procedure and the charge transport problem by a nonlinear convection equation discretized by a Least-Squares approach or the Method of Characteristics. We will present numbers for both cases and compare.

Adaptive boundary element methods in industrial applications

G. Of, O. Steinbach, W. L. Wendland
Universität Stuttgart

The Galerkin variational formulation of the symmetric formulation of the boundary integral equations is considered for the solution of mixed boundary value problems of the Laplace equation. Complex structures with a large number of degrees of freedoms can be treated by the use of fast boundary element methods as the fast multipole method, for example.

Some special features of different problems, as for example very small distances between two substructures or extreme values in potential and flux, make a very high resolution of the corresponding subareas necessary. Therefore the use of adaptively refined meshes is necessary for a solution which is as good as possible and is achieved with rather low costs.

For this purpose an adaptive version of the fast multipole method is considered in which great importance is attached to the maintenance of the symmetry. The preconditioners used in the case of the symmetric formulation, as the boundary integral operators of opposite orders and an artificial multilevel boundary element preconditioner, can be extended to adaptive meshes.

The examples to be shown are the computation of the potential and the electric field for a spray painting equipment and in an experimental setup. Thereby different adaptive meshes are used. In this connection the evaluation of the solution by the representation formula in a huge number of evaluation points is also an important issue.

Coupled FETI/BETI for Nonlinear Potential Problems

C. Pechstein

Johannes Kepler Universität Linz

The Finite Element Tearing and Interconnecting (FETI) method has become a well–established Domain Decomposition method allowing intense parallel computing. Recently, its boundary element counterpart, namely the Boundary Element Tearing and Interconnecting (BETI) method, and the coupling of both methods, FETI and BETI, have been introduced.

We use the coupled FETI/BETI method to solve boundary value problems for nonlinear potential problems of the form $-\nabla \cdot [\nu(|\nabla u|)\nabla u] = f$. One prominent application is the nonlinear magnetostatic problem in 2D, originating from Maxwell's equations. There, due to the underlying physics, the computational domain splits into such parts where the coefficient ν is constant (suitable for BEM), and subdomains where ν is nonlinear (treated with FEM).

Adressing the nonlinearity in a straight–forward approach, we linearize the entire PDE by Newton's method and solve the arising linear boundary value problems with coupled FETI/BETI. These linearized problems have the same structure as an originally linear problem, except for a matrix coefficient (instead of a scalar one) and nontrivial jumps in the Neumann trace on the subdomain interfaces.

Another approach is to apply the FETI/BETI concept directly to the nonlinear equation by replacing all linear operators, such as the Dirichlet to Neumann map, by their nonlinear counterparts.

Comparison of Geometric and Algebraic Multigrid for Data-Sparse Boundary Element Matrices [1]

U. Langer, D. Pusch
Johannes Kepler Universität Linz

We present geometrical (GMG) and algebraic multigrid (AMG) preconditioners for data-sparse boundary element matrices arising from the adaptive cross approximation (ACA) to dense boundary element matrices. Data-sparse matrix approximations schemes such as ACA yield an almost linear behavior in N_h, where N_h is the number of (boundary) unknowns. The treated system matrix represents the discretized single layer potential operator resulting from the interior Dirichlet boundary value problem for the Laplace equation. According to the continuous case, we present a convergence analysis for the ACA version.
Iterative solvers dramatically suffer from the ill-conditioness of the underlying system matrix for growing N_h. Our multigrid-preconditioners avoid the increase of the iteration numbers and result in almost optimal solvers with respect to the total complexity. The corresponding numerical 3D experiments are concentrated on the comparison of the GMG and AMG preconditioner approach.

[1] This work has been supported by the Austrian Science Fund 'Fonds zur Förderung der wissenschaftlichen Forschung (FWF)' under the grant P14953 'Robust Algebraic Multigrid Methods and their Parallelization'.

Numerical Aspects of a Poroelastic Time Domain Boundary Element Formulation

M. Schanz, D. Pryl, L. Kielhorn
TU Braunschweig

The dynamic responses of fluid–saturated semi–infinite porous continua subject to transient excitations such as seismic waves or ground vibrations are important in the design of soil–structure systems. The most powerful methodology to tackle semi–infinite domains is the Boundary Element Method (BEM). Based on Biot's theory the governing equations for a poroelastic continuum are given as a coupled set of differential equations for the unknowns solid displacements and pore pressure. Using the Convolution Quadrature Method (CQM) proposed by Lubich a boundary element time stepping procedure is established based only on the Laplace transformed fundamental solutions.
The implementation of this BE formulation is straight forward, however, the choice of dimensionless variables is crucial for the final numerical behavior of the method. Further, for poroelastic Finite Element formulations it is advantageous to use shape functions of different polynomial order for the displacement and the pore pressure. Here, the same is investigated for the above BE formulation.
In the presentation, the CQM based BE formulation is sketched briefly. Numerical studies concerning mixed shape functions for the pore pressure and the solid displacements are presented. Also, several choices of dimensionless variables are implemented and tested concerning their numerical behavior.

Hierarchische Cholesky-Zerlegung für FE-Systeme in der Elektrodynamik

K. Straube

Robert Bosch GmbH, Stuttgart

In der Praxis elektromagnetischer Simulationen treten zunehmend komplexe 3D-Probleme auf, die mit Hilfe der BEM-FEM-Kopplung bewältigt werden können. Für entsprechend feine FE-Netze wächst der Aufwand für die Lösung des groß dimensionierten, schwach besetzten Gleichungssystems. Im Zuge der Umsetzung der BEM-FEM-Kopplung für Kantenelemente gilt es unter anderem, einen geeigneten schnellen Solver für den FEM-Teil zu finden. Dazu soll eine auf rekursive Umsortierung basierende Cholesky-Zerlegung vorgestellt werden. Durch die entstehende Blockstruktur der Matrix wird dabei der Fill-in während der Zerlegung und somit der Aufwand gering gehalten. Aufbauend auf diese Herangehensweise eignet sich die ACA-Approximation zur Bestimmung guter Vorkonditionierer.

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