Technische Universität Graz

12. Workshop on

Fast Boundary Element Methods in Industrial Applications

Söllerhaus, 25.–28.9.2014

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

Berichte aus dem Institut für Numerische Mathematik

Book of Abstracts 2014/8

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Program

Thursday, September 25, 2014	
15.30	Coffee
18.30	Dinner
Friday, September 26, 2014	
9.00–9.30	J. Dölz (Basel, Switzerland) $\mathcal{H}$–matrix accelerated second moment analysis for potentials with rough correlation
9.30–10.00	D. Lukas (Ostrava, Czech Republic) A boundary element method for homogenization
10.00–10.30	N. Salles (London, UK) New analytical results on the convergence of a convolution quadrature method
10.30–11.00	Coffee
11.00–11.30	E. van't Wout (London, UK) Simulation of high intensity focused ultrasoundwith BEM++ and the Laplace–Beltrami preconditioner
11.30-12.00	C. Urzua–Torres (Zürich, Switzerland) Dual–preconditioning for boundary integral equations on screens
12.00–12.30	T. Führer (Vienna, Austria) Optimal preconditioning for the coupling of adaptive finite and boundary elements
12.30	Lunch
15.00–15.30	Coffee
17.00–17.30	M. Aussal (Palaiseau, France) The sparse cardinal sine decomposition and its application to fast boundary element method
17.30–18.00	G. Gantner (Vienna, Austria) Reliable and efficient a posteriori error estimation for adaptive IGA boundary element methods for weakly singular integral equations
18.30	Dinner

Saturday, September 27, 2014	
9.00–9.30	S. Kurz (Tampere, Finland)
	Structure preserving mesh coupling for Maxwell's equations
9.30–10.00	D. Amann (Graz, Austria)
	Helmholtz transmission problem for composite structures
10.00–10.30	G. Unger (Graz, Austria)
	Boundary element methods for Maxwell's eigenvalue problem
10.30–11.00	Coffee
11.00–11.30	W. L. Wendland (Stuttgart, Germany)
	tba
11.30–12.00	Jan Zapletal (Ostrava, Czech Republic)
	Shape optimization based on BEM and subdivision surfaces
12.00–12.30	M. Bugeanu (Basel, Switzerland)
	A second order convergent trial method for free boundary problems
12.30	Lunch
13.30–18.00	Hiking Tour
18.30	Dinner
Sunday, September 28, 2014	
9.00–9.30	H. Harbrecht (Basel, Switzerland)
	The $\mathcal{H}^2$ wavelet method
9.30–10.00	O. Steinbach (Graz, Austria)
	Space–time finite and boundary element methods for parabolic initial boundary value problems
10.00–10.30	Closing and Coffee

13. Söllerhaus Workshop on

Fast Boundary Element Methods in Industrial Applications

September 27–30, 2015

Helmholtz transmission problem for composite structures

D. Amann, O. Steinbach
TU Graz, Austria

When solving transmission problems for the Helmholtz equation using boundary integral equations, eigenvalues of the interior Laplace operator, so called spurious modes, may cause difficulties. If they appear, certain boundary integral operators lose their injectivity. The existence of spurious modes depends on the wave numbers as well as on the domains.
In this work we consider the case of a Lipschitz domain with a piecewise constant wave number. For this model problem we review and discuss three formulations that overcome the problem mentioned above, which means we can establish unique solvability for all wave numbers. The presented formulations are the classic combined boundary integral formulation, the Steklov–Poincaré operator formulation and the local multitrace formulation. Since we want to efficiently apply iterative solvers, we examine if these approaches are compatible to preconditioning strategies and how preconditioners can be constructed. Finally numerical examples are presented to support our findings and compare the three formulations.

The sparse cardinal sine decomposition and its application to fast boundary element method

F. Alouges and M. Aussal
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Fast convolution algorithms on unstructured grids have become a well established subject. Algorithms such as Fast Multipole Method (FMM), adaptive cross approximation (ACA) or H-matrices for instance are, by now, classical and reduce the complexity of the matrix-vector product from $O(N^2)$ to $O(N \log N)$ with a broad range of applications in e.g. electrostatics, magnetostatics, acoustics or electromagnetics.
In this talk we describe a new numerical method [1] which is based on a suitable Fourier decomposition of the Green kernel, associated to sparse quadrature formulae. We show how the approach uses the so-called Type-III Non Uniform Fast Fourier Transform (NUFFT) [4,5], to perform efficiently the convolution. Applications for tri-dimensional Laplace and Helmholtz kernel are provided, both in collocation and Finite Element approximations. A comparison with the FMM [2,3] shows a similar complexity scaling. Eventually, we present the acoustics scattering by a human head, which is of particular importance for 3D- Audio solutions.

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A second order convergent trial method for free boundary problems

Mihaela Monica Bugeanu and Helmut Harbrecht
Universität Basel, Switzerland

In this talk, we will present a method for solving the Bernoulli free boundary problem using a trial method of second order convergence. For the free boundary, we impose the Neumann boundary condition and use the Dirichlet boundary data for the update. We will first present the method in question and then show numerical results that support the claim of a second order convergent method.

$\mathcal{H}$-matrix accelerated second moment analysis for potentials with rough correlation

Jürgen Dölz[1], Helmut Harbrecht[1], Michael Peters[1], Christoph Schwab[2]
[1]Universität Basel, Switzerland, [2]ETH Zürich, Switzerland

We consider the efficient solution of strongly elliptic potential problems with stochastic Dirichlet data by the boundary integral equation method. The computation of the solution's two-point correlation is well understood if the two-point correlation of the Dirichlet data is known and sufficiently smooth. Unfortunately, the problem becomes much more involved in case of rough data. We will show that the concept of the H-matrix arithmetic provides a powerful tool to cope with this problem. By employing a parametric surface representation, we end up with an H-matrix arithmetic based on balanced cluster trees. This considerably simplifies the implementation and improves the performance of the H-matrix arithmetic. Numerical experiments are provided to validate and quantify the presented methods and algorithms.

Optimal preconditioning for the coupling of adaptive finite and boundary elements

M. Feischl[1], T. Führer[1], D. Praetorius[1], E. P. Stephan[2]
[1]TU Vienna, Austria, [2]Leibniz University, Hannover, Germany

For many relevant applications, the coupling of the finite element method (FEM) and boundary element method (BEM) appears to be the appropriate numerical method to cope with unbounded domains. As the problem size increases, so does the strong need for effective preconditioners for iterative solvers. Most of the available literature on preconditioning of FEM-BEM coupling techniques deals with the symmetric coupling on quasi-uniform meshes. Often, however, non-symmetric coupling formulations are preferred, since they avoid the computation and evaluation of the hypersingular integral operator.
We present results [1] on block-diagonal preconditioning for the Johnson-Nédélec coupling on adaptively generated meshes. With an appropriate stabilization vector $\mathbf{S}$, which ensures positive defineteness of the coupling formulation, the Galerkin matrix of the Johnson-Nédélec coupling reads in block form

$$\begin{pmatrix} \mathbf{A} & -\mathbf{M}^T \\ \frac{1}{2}\mathbf{M} - \mathbf{K} & \mathbf{V} \end{pmatrix} + \mathbf{S}\mathbf{S}^T,$$

where $\mathbf{A}$ corresponds to the FEM part, $\mathbf{V}$ resp. $\mathbf{K}$ to the discrete simple-layer resp. double-layer integral operator and $\mathbf{M}$ is the mass matrix. We consider block-diagonal preconditioners

$$\begin{pmatrix} \mathbf{P}_{\text{FEM}} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}_{\text{BEM}} \end{pmatrix},$$

where the diagonal blocks $\mathbf{P}_{\text{FEM}}$ and $\mathbf{P}_{\text{BEM}}$ are symmetric and positive definite. These are obtained from a local multilevel additive Schwarz decomposition of the energy space. While the analysis relies on this abstract frame, the resulting preconditioners are obtained from simple algebraic postprocessing of the (history of the) Galerkin matrix.
Starting from an initial mesh which is adaptively refined by bisection, we prove that the condition number of the preconditioned system remains bounded, where the bound depends only on the initial mesh.
Although we shall mainly discuss the 2D Laplace transmission problem, the principal ideas also apply to the 3D case and Lamé-type transmission problems. Moreover, the analysis transfers to other coupling methods, such as the symmetric coupling or the symmetric and non-symmetric Bielak-MacCamy coupling.

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Reliable and efficient a posteriori error estimation for adaptive IGA boundary element methods for weakly-singular integral equations

M. Feischl, G. Gantner, D. Praetorius
TU Vienna, Austria

A posteriori error estimation and adaptive mesh-refinement are well-established and important tools for standard boundary element methods (BEM) for polygonal boundaries and piecewise polynomial ansatz functions. In contrast, the mathematically reliable a posteriori error analysis for isogeometric BEM (IGABEM) has not been considered, yet. In our talk, we aim to shed some light on this gap and to transfer some known results on reliable a posteriori error estimators from standard BEM to IGABEM.

As model example serves the weakly-singular integral equation for the 2D Laplacian. For our IGABEM, we employ non-uniform rational B-splines (NURBS). With ϕ denoting the exact solution and Φ_ℓ being the discrete IGABEM solution, we prove in [2] that the (numerically computable) Faermann error estimator η_ℓ, proposed and analyzed in [1] for standard BEM, provides lower and upper bounds for the (in general, non-computable and unknown) error in the $H^{-1/2}$-energy norm, i.e.,

$$C_{\rm eff}^{-1}\,\eta_\ell \le |||\phi - \Phi_\ell||| \le C_{\rm rel}\,\eta_\ell.$$

We prove that the constants $C_{\rm eff}, C_{\rm rel} > 0$ remain bounded even if new knots are inserted resp. the multiplicity of knots is increased. In particular, η_ℓ can thus be used to monitor the error decay if the mesh is refined. Moreover, the local contributions of η_ℓ can be used for adaptive IGABEM computations to steer an adaptive algorithm of the form

$$\boxed{\texttt{Solve}} \longrightarrow \boxed{\texttt{Estimate}} \longrightarrow \boxed{\texttt{Mark}} \longrightarrow \boxed{\texttt{Refine}}$$

which automatically detects singularities of the solution and adapts the mesh accordingly. If compared to uniform mesh refinement, this dramatically reduces the storage requirements as well as the computing time needed to achieve a certain prescribed accuracy.

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The $\mathcal{H}^2$-wavelet method

Daniel Alm, Helmut Harbrecht, Ulf Krämer
Universität Basel, Switzerland

Abstract: We introduce the $\mathcal{H}^2$-wavelet method for the fast solution of nonlocal operator equations on unstructured meshes. On the given mesh, we construct a wavelet basis which provides vanishing moments with respect to the traces of polynomials in the space. With this basis at hand, the system matrix in wavelet coordinates is compressed to $(N \log N)$ relevant matrix coefficients, where N denotes the number of boundary elements. The compressed system matrix is computed with nearly linear complexity by using the $\mathcal{H}^2$-matrix approach. Numerical results in three spatial dimensions validate that we succeeded in developing a fast wavelet Galerkin scheme on unstructured triangular or quadrangular meshes.

Structure Preserving Mesh Coupling for Maxwell's Equations

Ossi Niemimäki, Stefan Kurz, Lauri Kettunen
Tampere University of Technology, Finland

The state of the art for mesh coupling at nonconforming interfaces is presented and reviewed. Mesh coupling is fre-quently applied to the modeling and simulation of motion in electromagnetic actuators. The focus of the contribution is on lowest order Whitney elements. Both interpolation- and projection-based methods are considered. In addition to accuracy and efficiency, we emphasize the question whether the schemes preserve the structure of de Rham com-plex, which underlies Maxwell's equations. As a new contribution, a structure preserving projection method is pre-sented, in which mortar spaces are chosen from the Buffa-Christiansen complex. This approach is structure preserv-ing. Its performance is compared with a straightforward interpolation based on Whitney and de Rham maps.

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A Boundary Element Method for Homogenization

D. Lukáš, J. Bouchala, and M. Theuer
TU VSB Ostrava, Czech Republic

Homogenized coefficients of periodic structures are calculated via an auxiliary partial differential equation in the periodic cell. Typically a volume finite element discretization is employed for the numerical solution. In this talk we reformulate the problem as a boundary integral equation using Steklov-Poincaré operators. The resulting boundary element method discretizes boundary of the periodic cell and the interface between materials within the cell. Under smoothness assumptions we prove that the homogenized coefficients converge quadratically with the mesh size. We support the theory with examples.

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New analytical results on the convergence of a Convolution Quadrature method

Timo Betcke, Nicolas Salles
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We present new analytical results on the convergence of the numerical solution of wave problems computed using a Convolution Quadrature method with a multistep scheme. Instead of applying the Laplace transform at the beginning, we discretize using a multistep scheme, and then we perform a Z-Transform of the discrete time-steps. It results a range of modified Helmholtz problems in the Laplace domain. We prove that the numerical solution obtained with this method can converge exponentially to the exact solution of the underlying time-stepping solution.
The rate of convergence relies upon the analyticity of the frequency solutions which depends on the location of the scattering poles of the related modified Helmholtz problem, so on the integral formulation involved, and on the contour used to apply the inverse Z-Transform. Numerical results obtained using BEM++ and a time-domain toolbox are presented.

Space–time finite and boundary element methods for parabolic initial boundary value problems

O. Steinbach
TU Graz, Austria

In most cases, finite and boundary element methods for time–dependent partial differential equations rely on time–stepping schemes. Although such an approach allows for a subsequent solution of the discrete system, it may not reflect the behavior of the solution properly, at least from an approximation point of view. For the model problem of the heat equation we will consider finite and boundary element methods with respect to general decompositions of the space–time domain and its boundary into finite and boundary elements, respectively. In particular, such an approach allows for an adaptive refinement simultaneously in space and time. Moreover, the global solution of the overall space–time system can be done in parallel, in contrast to more standard time discretization schemes. Here we will present a stability and error analysis of space–time finite and boundary element methods, and we present some numerical results which indicate the potential of the proposed approach.

Boundary element methods for Maxwell's eigenvalue problem

Gerhard Unger
TU Graz, Austria

In [1,2] boundary element approaches for Maxwell's eigenvalue problem for bounded domains were suggested. Numerical examples in these papers indicate a spectrally correct approximation of Maxwell's eigenvalue problem by the boundary element method when Raviart-Thomas elements are used. An analysis of the boundary integral formulations and their numerical approximations was not given there. In this talk we address these issues and consider Maxwell's eigenvalue problem also in unbounded domains. We analyze boundary integral formulations of Maxwell's eigenvalue problem in the framework of eigenvalue problems for holomorphic Fredholm operator-valued functions. General numerical results of this theory are applied to the Galerkin discretization of boundary integral formulations of Maxwell's eigenvalue problem.

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Dual-preconditioning for boundary integral equations on screens

Ralf Hiptmair, Carlos Jerez-Hanckes, Carolina Urzúa-Torres
Seminar for Applied Mathematics, ETH Zurich, Switzerland

Operator preconditioning [2,3] based on Calderón identitites breaks down when considering open boundaries as when modeling screens. On the one hand, the double layer operator and its adjoint disappear. On the other hand, the associated weakly singular and hypersingular operators no longer map fractional Sobolev spaces in a dual fashion but degenerate into different subspaces depending on their extensibility by zero.
In this presentation, we review our dual-preconditioning technique for the Laplacian in 2D [4] and its extensions. Moreover, we discuss some first results for dual-preconditioning over three-dimensional screens using Buffa and Christiansen's approach [1].

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On the coupled Darcy-Stokes flow

W. L. Wendland
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In this lecture we consider existence, uniqueness and the construction of the viscous flow in $\mathbb{R}^3$ around and through a bounded region consisting of different porous materials. The flow is modeled by Darcy flow in a given bounded domain and Stokes flow in the exterior c coupled on the boundary surface by continuous transmission of normal velocities whereas the pressure and the tangential velocities of the exterior Stokes flow satisfy the Beavers–Joseph conditions. The problem can be formulated in terms of potential theory based on surface potentials with charges on the boundary surface and a corresponding system of boundary potential operators of various types which defines a system of singular Fredholm integral equations for the charges?. This system of equations can be solved in appropriate Sobolev spaces which provides the construction of the solution to the flow problem.
This is joint work with Mirela Kohr (Babe¸s–Bolyai Univ., Cluj–Napoca, Romania) and Raja Sekhar (IIT Kharagpur, India).

Simulation of high intensity focused ultrasound with BEM++ and the Laplace-Beltrami preconditioner

E. van 't Wout, S. Arridge, T. Betcke, P. Gelat
University College London, UK

The use of High-Intensity Focused Ultrasound (HIFU) is an important medical procedure to treat diseased tissue. An array of ultrasound beams can be designed such that it focuses on a small region. The high intensity concentrated in this area heats the tissue until a level is reached in which the disease will be destroyed. The accurate focusing becomes complicated when the diseased tissue is located near a rib cage due to reflections of the ultrasound beams. In this paper we will simulate the scattering of ultrasound on a rib cage with the open-source boundary element method package BEM++ [1].
The simulation of acoustic scattering with the combined field integral equation (CFIE) for the exterior Helmholtz equation becomes increasingly expensive for large wave numbers. To improve the efficiency of the iterative linear solver for high frequency scattering, the Laplace-Beltrami preconditioner will be used to reduce the condition number of the CFIE. This operator preconditioner is based on On-Surface Radiation Condition (OSRC) techniques and approximates the Neumann-to-Dirichlet map in the high-frequency range [2].
The Laplace-Beltrami preconditioner is a local operator and therefore results in a sparse system of linear equations that is efficient to solve with a direct method. Computational experiments show that the number of iterations to solve the preconditioned CFIE hardly grows for increasing wave number. The application of the Laplace-Beltrami preconditioner to the simulation of acoustic scattering on a rib cage confirms the feasibility for geometries of industrial interest.

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Shape optimization based on BEM and subdivision surfaces

Jan Zapletal, Michal Merta
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The presented talk is concerned with numerical solution of shape optimization problems with constraints given by an elliptic partial differential equation. Our approach is based on the first-optimize-then-discretize approach, which results in the Hadamard-Zolésio form of the shape derivative given by a surface integral. This makes the boundary element method an efficient tool both for the solution of state and adjoint problems and the evaluation of the shape gradient.
To describe shape perturbations we use subdivision surfaces known, e.g., from computer graphics. While a fine-enough mesh is necessary for the boundary element analysis, the shape optimization is performed on a lower-resolution mesh representing the same limit surface. When an optimum is found on the current resolution, the control mesh is refined to describe finer details of the optimal surface.
To validate the method we present numerical experiments inspired by the Bernoulli free surface problem.

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Erschienene Preprints ab Nummer 2014/1

2014/1 K. Bandara, F. Cirak, G. Of, O. Steinbach, J. Zapletal: Boundary element based multiresolution shape optimisation in electrostatics.

2014/2 T. X. Phan, O. Steinbach: Boundary integral equations for optimal control problems with partial Dirichlet control.

2014/3 M. Neumüller, O. Steinbach: An energy space finite element approach for distributed control problems.

2014/4 L. John, O. Steinbach: Schur complement preconditioners for boundary control problems.

2014/5 O. Steinbach: Partielle Differentialgleichungen und Numerik.

2014/6 T. Apel, O. Steinbach, M. Winkler: Error estimates for Neumann boundary control problems with energy regularization.

2014/7 G. Haase, G. Plank, O. Steinbach (eds.): Modelling and Simulation in Biomechanics. Book of Abstracts.