Technische Universität Graz

11. Workshop on

Fast Boundary Element Methods in Industrial Applications

Söllerhaus, 26.–29.9.2013

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

Berichte aus dem Institut für Numerische Mathematik

Book of Abstracts 2013/10

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Technische Universität Graz
Institut für Numerische Mathematik
Steyrergasse 30
A 8010 Graz

WWW: http://www.numerik.math.tu-graz.ac.at

Program

Thursday, September 26, 2013	
15.30–16.50	Coffee
16.50–17.00	Opening
17.00–17.30	R. Hiptmair (Zürich) Combined field integral equations for acoustic scattering by partially impenetrable composite objects
17.30–18.00	E. Spindler (Zürich) Second–kind single trace BEM for acoustic scattering at composite objects
18.30	Dinner
Friday, September 27, 2013	
9.00–9.30	R. James (London) Recent progress on the fast boundary–element library BEM++
9.30–10.00	B. Kager (Graz) A data efficient, CQM–based BEM approach for elastodynamics
10.00–10.30	A. Bantle (Ulm) NURBS–enhanced boundary element methods
10.30–11.00	Coffee
11.00–11.30	T. Traub (Graz) A directional fast multipole method for elastodynamics
11.30–12.00	G. Mitscha–Eibl (Wien) Stability of FEM–BEM couplings for nonlinear elasticity problems
12.00–12.30	M. Peters (Basel) $\mathcal{H}$–matrix accelerated second moment analysis for elliptic problems with rough correlation
12.30	Lunch
15.00–15.30	Coffee
17.00–17.30	C. A. Urzua Torres (Santiago) Operational preconditioners for boundary integral equations on screens in $\mathbb{R}^2$
17.30–18.00	T. Führer (Wien) Efficient additive Schwarz preconditioning of the hypersingular integral equation on locally refined triangulations
18.00–18.30	S. Kurz (Tampere) Modeling and simulation of the Wilson–Wilson experiment
18.30	Dinner

Saturday, September 28, 2013	
9.00–9.30	Z. Peng (Albuquerque) Integral equation domain decomposition with discontinuous Galerkin discretization for time–harmonic Maxwell equations
9.30–10.00	G. Unger (Graz) Boundary element methods for resonance problems
10.00–10.30	O. Stein (Zürich) Maxwell equations on S^2
10.30–11.00	Coffee
11.00–11.30	H. Harbrecht (Basel) On shape optimization with parabolic state equation
11.30–12.00	A. Kimeswenger (Graz) Boundary control of exterior boundary value problems
12.30	Lunch
13.30–18.00	Hiking Tour
18.30	Dinner
Sunday, September 29, 2013	
9.00–9.30	M. Utzinger (Basel) Adaptive wavelet BEM
9.30–10.00	O. Steinbach An energy space approach for the Cauchy problem
10.00–10.30	Closing and Coffee

NURBS–enhanced boundary element methods

A. Bantle, S. Funken
Universität Ulm, Germany

When using high order Boundary Element Methods (BEM) to solve problems on domains with curved boundaries it is necessary to approximate the boundary accurately. An significant loss of accuracy is observed in p- and hp- BEM using a polygonal approximation of the boundary. There are several approaches that remedy this problem, namely isoparametric, isogeometric, and NURBS-enhanced methods. In order to preserve the convergence rates of high order methods the isoparametric approach approximates the boundary using piecewise polynomials of the same order as the polynomials in the ansatz space. However, there is still an approximation error that has to be considered in the error analysis.
Isogeometric methods use Non-Uniform Rational B-Splines (NURBS) for the approximation of the boundary, so that complicated geometries are approximated more accurately and common geometries like circles, ellipses, etc. are represented exactly. However, since NURBS are also taken as ansatz functions, the approximation theory for piecewise polynomials cannot be adapted easily.
NURBS-enhanced methods combine the ideas of both approaches. While the geometry is approximated with NURBS, a piecewise polynomial basis is used for the ansatz space. This approach has the advantages that in many cases the convergence is not affected negatively by a geometrical error. However, using different bases for the geometry and the ansatz space results in a higher computational effort compared to the other two approaches.
We present a NURBS-enhanced BEM for the Laplace and the Lamé equations, where we use NURBS to describe the geometry and Legendre polynomials as ansatz functions. The arising singular integrals are evaluated using different regularization techniques and adapted quadrature rules. Finally, we present numerical results for h-, p- and hp- NURBS-enhanced BEM.

Efficient additive Schwarz preconditioning of the hypersingular integral equation on locally refined triangulations

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

We consider the hypersingular integral equation for the 2D and 3D Laplacian. It is well-known that the condition number of the Galerkin matrix grows as the mesh is refined. The situation is even worse on locally refined meshes, where the condition number grows with the number of elements as well as the global mesh-size quotient $h_{\max}/h_{\min}$. Therefore, the developement of efficient preconditioners is a necessary and important task.
In this talk, we present the results of our recent work [1], where we consider a (local) multilevel diagonal preconditioner. The basic idea of this preconditioner is to consider only newly created nodes in $\mathcal{T}_{\ell+1}\backslash\mathcal{T}_\ell$ plus their immediate neighbours for preconditioning. For uniform refinement, it was proved in [3] that multilevel diagonal preconditioners are efficient in the sense, that the condition number of the preconditioned system is independent of the number of levels and the mesh-size. On locally refined triangulations such a result was unknown.
Basically, the proof consists of providing a stable subspace decomposition for the fractional order Sobolev space $H^{1/2}$ by means of a variant of the Scott-Zhang projection [2]. In the frame of 2D-FEM, a stable subspace decomposition of H^1 has been considered in [4], and we transfer and extend these ideas to $H^{1/2}$.
We show efficiency of the (local) multilevel diagonal preconditioner in the sense that the condition number of the resulting system is independent of the mesh-size and the number of levels. Numerical examples on closed and open boundaries underline our theoretical results.

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On shape optimization with parabolic state equation

H. Harbrecht[1], J. Tausch[2]
[1]Universität Basel, Switzerland
[2]Southern Methodist Universität, Dallas, USA

The present talk is concerned with the numerical solution of shape identification prob- lems for the heat equation. Namely, we aim at the determination of inclusions or voids from measurements of the temperature and the heat flux at the boundary. The particular shape identification problem is reformulated as a shape optimization problem. Then, the shape gradient is computed by means of the adjoint method. A gradient based nonlinear Ritz-Galerkin scheme is applied to discretize the shape optimization problem. The states and their adjoint equations are expressed as parabolic boundary integral equations and solved using a Nyström discretization and a space-time fast multipole method for the rapid evaluation of thermal potentials. Special quadrature rules are derived to handle singularities of the kernel and the solution. Numerical experiments are carried out to demonstrate the feasibility and scope of the present approach.

Combined field integral equations for acoustic scattering by partially impenetrable composite objects

X. Claeys[1], R. Hiptmair[2]

[1] Laboratoire Jacques–Louis Lions, UPMC, Paris, France

[2]ETH Zürich, Switzerland

We study the direct first-kind boundary integral equations of [4] arising from transmission problems for the Helmholtz equation with piecewise constant coefficients and Dirichlet boundary conditions imposed on a closed surface. We identify necessary and sufficient conditions for the occurrence of so-called spurious resonances, that is, the failure of the boundary integral equations to possess unique solutions. Inspired by the combined field integral equations (CFIE) of [1] we propose a modified version of the boundary integral equations that is immune to spurious resonances. Via a gap construction [3, Sect. 5.2] it will serve as the basis for a universally well-posed stabilized global multi-trace CFIE formulation that generalizes the method of [2] to situations with Dirichlet boundary conditions.

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Recent progress on the fast boundary–element library BEM++

S. Arridge, T. Betcke, N. Chaulet, R. James, M. Schweiger, W. Śmigaj
University College London, UK

BEM++ is an open-source boundary element library written in C++ and Python. It has been developed jointly by University College London (UCL), the University of Reading and the University of Durham. All standard boundary integral operators, namely the single-layer potential, double-layer potential, adjoint double-layer potential and hypersingular operators are implemented by the library for Laplace, Helmholtz and modified Helmholtz problems in three dimensions and discretised using the Galerkin method. More complex operators may be built either explicitly or more simply by superposition of the standard operators. Acceleration is achieved using the Adaptive Cross Approximation (ACA) using the well-established AHMED library [1].

An overview of the recent updates made to BEM++ over the past year will be given, in addition to the work in progress and future directions for the library. New features include support for mixed Dirichlet/Neumann problems, higher order basis functions and Maxwell problems. Current work is under way to incorporate the Fast Multipole Method (FMM) into the library, with preliminary support for high frequency Helmholtz, and support for more general operators under way using the black-box FMM [2]. Future directions include time-domain analysis, and improved (opposite order) pre-conditioners for Helmholtz and Maxwell are in development.

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A data efficient, CQM-based BEM approach for elastodynamics

B. Kager, M. Schanz
TU Graz, Austria

The treatment of time dependent wave propagation phenomena with the boundary element method inherently involves the computation of convolution integrals. If Lubich's Convolution Quadrature Method [1] is used to evaluate approximations of such integrals, the convolution weights are usually computed via Cauchy's Integral Formula. Contrary to this, Hackbusch et. al. [2] proposed a direct weight computation involving Hermite polynomials for the simulation of acoustic wave propagation. In this talk, we present a new algorithm for the computation of linear elastodynamic problems that is an extension of this approach. Additionally, taking into account crucial properties of the weight functions, we present a data efficient storage scheme based on geometrical clustering. Finally, we further enhance the proposed algorithm by application of low rank approximation.
The talk will be concluded by discussing the results of some numerical examples in terms of memory efficiency.

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Modeling and simulation of the Wilson–Wilson experiment

H. Heumann[1], S. Kurz[2]
[1]TU München, Germany
[2]Tampere University of Technology, Finland

The classical 1913 Wilson–Wilson experiment [1,2] has regained attention, both from the experimental [3] and conceptual point of view [4–8]. The experiment consists of a magnetic non–conducting hollow rotating cylinder which is immersed in the external magnetic field of a solenoid. According to the relativistic theory of moving media a potential difference occurs between the inner and outer surfaces of the cylinder.
A mathematical model is presented, based on Maxwell's equations and the 1910 Minkowski relations [9] for moving media. Electric and magnetic fields are coupled through motional terms in the constitutive relations. This particular kind of coupling is usually not considered in existing numerical models. Interestingly, Ohm's law does not enter the model, since there is no bulk conductivity.
Effects due to the finite axial extension of the cylinder can be conveniently assessed with the help of a numerical simulation, for instance with finite elements [10]. This should be useful for the correct interpretation of the experi–mental data.

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Boundary control of exterior boundary value problems

A. Kimeswenger, O. Steinbach
TU Graz, Austria

In this presentation we discuss boundary control problems subject to second order partial differential equations in unbounded exterior domains. Examples are given by the Laplace and the Helmholtz equations. Since the control is considered in $H^{\frac{1}{2}}(\Gamma)$ the regularisation is realised by the exterior Steklov-Poincaré operator. To be able to deal with unbounded domains, boundary integral equations are used. For the numerical approximation we consider a symmetric Galerkin boundary element method and we apply a semi-smooth Newton method in the case of box constraints. Numerical examples are given at the end of the talk.

Stability of FEM-BEM couplings for nonlinear elasticity problems

M. Feischl[1], T. Führer[1], M. Karkulik[2], G. Mitscha–Eibl[1], D. Praetorius[1]
[1]TU Wien, Austria
[2]Pontificia Universidad Católica de Chile

We consider a transmission problem in elasticity with a nonlinear material behavior in the bounded interior domain, which can be rewritten by means of the symmetric coupling as well as non–symmetric coupling methods, such as the Johnson–Nédélec coupling. Problems arise when trying to prove solvability of the Galerkin discretization, because the space of rigid body motions is contained in the kernel of the Lamé operator.

In this talk, which is based on the recent preprint [3], we present how to extend the ideas of *implicit stabilization*, developed for Laplace–type transmission problems in [1], to elasticity problems. We introduce modified equations which are fully equivalent (at the continuous as well as at the discrete level) to the original formulations. Our analysis extends the works [2,4,5,6]. Unlike [2], we avoid any assumption on the mesh-size. Unlike [4], we avoid the use of an interior Dirichlet boundary. Unlike [6], we avoid any pre– and postprocessing steps as well as the numerical solution of additional boundary value problems.

Numerical experiments for the Johnson–Nédélec coupling on adaptively generated meshes conclude the talk.

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Integral equation domain decomposition with discontinuous Galerkin discretization for time-harmonic Maxwell equations

J. F. Lee, R. Hiptmair[2], Z. Peng[3]

[1]Ohio State University, Columbus, USA

[2]ETH Zürich, Switzerland

[3]University of New Mexico, Albuquerque, USA

Surface integral equation (SIE) methods have shown to be effective in solving electromagnetic wave scattering and radiation problems. It is mainly due to the fact both the analysis and unknowns reside only on the boundary surfaces of the targets. However, applications of the SIE methods often lead to dense and ill-conditioned matrix equations. The efficient and robust solution of the SIE matrix equation poses an immense challenge. This talk will discuss some recent progress in SIE methods for solving time-harmonic Maxwell equations.

The first topic is domain decomposition for surface integral equations via multi-trace formulation. The entire computational domain is decomposed into a number of non-overlapping sub-regions. Each local sub-region is homogeneous with constant material properties and described by a closed surface. Through this decomposition, we have introduced at least two pairs of trace data as unknowns on interfaces between sub-regions (multi-trace formulation). This multi-trace feature admits two major benefits: the localized surface integral equation for the homogeneous sub-region problem is amenable to operator preconditioning; the resulting linear systems of equations readily lend themselves to optimized Schwarz methods.

A discontinuous Galerkin surface integral equation method is proposed for the numerical solution of sub-regions. The main objective of this work is to allow the implementation of the combined field integral equation (CFIE) using square-integrable, L2, trial and test functions without any considerations of continuity requirements across element boundaries. Due to the local characteristics of L2 vector functions, it is possible to employ non-conformal surface discretizations of the targets. Furthermore, it enables the possibility to mix different types of elements and employ different order of basis functions within the same discretization. Therefore, the proposed method is highly flexible to apply adaptation techniques.

The capability of these methods is illustrated through several real-world applications, including EMI/EMC analysis of multiple antennas installed on a high-definition mock-up aircraft, and electromagnetic scattering from a complex composite unmanned aerial vehicle.

$\mathcal{H}$–matrix accelerated second moment analysis for elliptic problems with rough correlation

J. Dölz, H. Harbrecht, M. Peters
Universität Basel, Switzerland

In this talk, we consider the efficient solution of the Laplace equation with stochastic Dirichlet data by the boundary integral equation method. It is well understood how to compute the two-point correlation of the solution 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 here that the concept of the $\mathcal{H}$-matrix arithmetic provides a powerful tool to cope with this problem. By employing a parametric surface representation, we end up with an $\mathcal{H}$-matrix arithmetic based on balanced cluster trees. This considerably simplifies the implementation and improves the performance of the $\mathcal{H}$-matrix arithmetic. Numerical experiments are provided to validate and quantify the presented methods and algorithms.

Second–kind single trace BEM for acoustic scattering at composite objects

X. Claeys[1], R. Hiptmair[2], E. Spindler[2]

[1] Laboratoire Jacques–Louis Lions, Paris, France
[2] ETH Zürich, Switzerland

We consider acoustic scattering at composite objects with Lipschitz boundary. The widely used classical first-kind approach leads to ill-conditioned linear systems on fine meshes and no suitable preconditioner is available. Consequently, one observes slow convergence of iterative solvers, which are inevitable when solving compressed large linear systems.
To tackle this problem, a new intrinsically well-conditioned second–kind boundary element formulation has been discovered by one of the authors [1]. We adopt this idea and extend it by lifting the formulation from the trace spaces $H^{\frac{1}{2}}(\Gamma) \times H^{-\frac{1}{2}}(\Gamma)$ into the space $L^2(\Gamma) \times L^2(\Gamma)$. This enables us to solely work with discontinuous ansatz functions in order to approximate the unknown boundary data.
In the talk we are going to focus on recent computational results obtained for 3D acoustic scattering. These results were obtained by an implementation of the two approaches using the C++ Boundary Element Template Library (BETL) by Lars Kielhorn (SAM, ETH Zürich). They show competitive accuracy of the new second-kind approach compared to the classical first–kind approach, and confirm the excellent conditioning of the Galerkin matrices and superior convergence of GMRES.

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Maxwell Equations on S^2

S. Kurz[1], R. Hiptmair[2], O. Stein[2]
[1]Tampere University of Technology, Finland
[2]ETH Zürich, Switzerland

We refer to the Söllerhaus workshop 2012 [1] where a case study concerning Maxwell-type problems on S^2 was presented. This is further elaborated in two directions: We extend the case study from static problems to problems involving waves and we look at numerical results.
We are interested in solving the following problem on the sphere S^2:

$$(\delta d - k^2)\omega = 0, \qquad k > 0, \tag{1}$$

where ω is a one form, with given boundary conditions on the boundary of a simply connected domain $\Omega \subset S^2$. This is a generalization of **curl curl**-type problems from flat space to a two-dimensional Riemannian manifold with constant curvature.
In this work, this problem is approached by first finding an explicit expression of the Green's double form for the Helmholtz problem with the Hodge Laplacian:

$$(\triangle - k^2)\omega = 0, \tag{2}$$

$\triangle = \delta d + d\delta$. This is accomplished for both zero and one forms. The case $k = 0$ for zero forms has already been analyzed in [2]. In the general case $k > 0$ the Green's double forms involve hypergeometric functions, while in the case $k = 0$ they can be reduced to simpler trigonometric functions.
The two Helmholtz Green's double forms are then used to construct a Green's double form for (1). The treatment in [3] guides the transition of Green's double forms for (2) to Green's double forms for (1). This Green's double form can then further be leveraged to set up boundary integral equations.

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An energy space approach for the Cauchy problem

T. X. Phan[1], O. Steinbach[2]
[1]TU Hanoi, Vietnam, [2]TU Graz, Austria

In this talk we discuss the Cauchy problem of the Laplace equation where the complete Cauchy data are given on some part of the boundary, but are unknown on the remainder. For the solution of this inverse problem we consider a tracking type functional for the given Neumann datum while the unknown Dirichlet datum enters as a regularisation. For both we consider the related energy norms which can be realised by using Steklov–Poincaré or boundary integral operators. We present a detailed numerical analysis of our approach, and we give some numerical results also in comparison to more standard approaches when using more convenient norms.

A Directional Fast Multipole Method for Elastodynamics

P. Blanchard[1], M. Schanz[2], T. Traub[2]
[1]École Normale Supérieure de Cachan, France
[2]TU Graz, Austria

Boundary elements methods are very well suited for the study of wave propagation phenomena due to it's reduction in dimensionality of the problem. However we need to deal with a convolution in time and densely populated system matrices.
To efficiently treat the arising convolution integral we implement the Convolution Quadrature Method as proposed by Banjai and Sauter [1] which leads to a decoupled system of problems in Laplace domain. Thus, each problem can be solved separately and only the results needs to be stored. This leads to a drastic reduction in memory consumption.
To further reduce storage requirements and solution time, fast methods can be applied. While the efficiency of $\mathcal{H}$-matrix techniques decreases as the integral kernel becomes more and more oscillatory, Fast Multipole Methods overcome this bottleneck by introducing suitable kernel expansions. A directional approach for oscillatory kernel functions was developed by Engquist et al. [2]. Based thereupon a directional Fast Multipole Method (DFMM) was introduced by Messner et al [3], which we extend to the Lamé kernel.
To do this we need to separate the far field into two oscillating parts, which will be approximated individually. This can be done either directly by computing the tensorial fundamental solution or by utilizing a representation of the fundamental solution using derivatives of the Helmholtz kernel [4]. We will present both methods and discuss their advantages and disadvantages.
The talk will be concluded by discussing the results of some numerical examples in terms of memory efficiency and computational costs.

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Boundary element methods for resonance problems

O. Steinbach, G. Unger
TU Graz, Austria

We characterize resonances as eigenvalues of boundary integral operator eigenvalue problems and use boundary element methods for their numerical approximation. Eigenvalue problem formulations for resonance problems which are based on standard boundary integral equations exhibit additional eigenvalues which are not resonances but eigenvalues of a related ïnterioreëigenvalue problem. In practical computations it is for some typical applications hard to extract the resonances when using standard boundary integral formulations. In this talk we present regularized combined boundary integral formulations which only exhibit resonances as eigenvalues. We provide a comprehensive numerical analysis of the boundary element approximations of these eigenvalue problem formulations where general results of the discretization of eigenvalue problems for holomorphic Fredholm operator–valued functions are used. Finally we present some numerical examples.

Operational preconditioners for boundary integral equations on screens in $\mathbb{R}^2$

R. Hiptmair[1], C. Jerez–Hanckes[2], C. A. Urzúa Torres[2]
[1]ETH Zürich, Switzerland
[2]Pontificia Universidad Católica de Chile, Santiago, Chile

Operator preconditioning [1,2] based on Calderón identitites breaks down when considering open boundaries as when modeling screens or cracks. 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.
Based on Calderón-type identities deduced from Jerez-Hanckes and Nédélec [3,4] for an open interval, we build preconditioners for associated integral operators for uniform and locally quasi-uniform meshes [5,6,7]. In this presentation, we show the numerical implementation of these preconditioners for the Laplacian, as well as an extension to the Helmholtz operator.

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Adaptive wavelet BEM

M. Utzinger
Universität Basel, Switzerland

In this talk, we present an algorithm for the adaptive solution of boundary integral equations. This algorithm is based on adaptively chosen wavelet bases for the Galerkin discretization of the equation under consideration. In particular, we will elaborate on the efficient numerical implementation of this algorithm. The major advantage of wavelet bases for the discretization of boundary integral equations lies in the sparsity of the resulting stiffness matrix and the fact that they directly provide a provable error estimator for the refinement. Numerical examples will be provided to illustrate and quantify the presented algorithm.

Participants

1. Andreas Bantle, M. Sc.
   Institut für Numerische Mathematik, Universität Ulm,
   Helmholtzstrasse 18, 89069 Ulm, Germany
   `andreas.bantle@uni-ulm.de`

2. Dipl.–Ing. Michael Feischl
   Institut für Analysis und Wissenschaftliches Rechnen, TU Wien,
   Wiedner Hauptstrasse 8–10, 1040 Wien, Austria
   `michael.feischl@tuwien.ac.at`

3. Dipl.–Ing. Thomas Führer
   Institut für Analysis und Wissenschaftliches Rechnen, TU Wien,
   Wiedner Hauptstrasse 8–10, 1040 Wien, Austria
   `thomas.fuehrer@tuwien.ac.at`

4. Dipl.–Ing. Anita Haider
   Institut für Baumechanik, TU Graz,
   Technikerstrasse 4, 8010 Graz, Austria
   `anita.haider@tugraz.at`

5. Prof. Dr. Helmut Harbrecht
   Mathematisches Institut, Universität Basel,
   Rheinsprung 21, 4051 Basel, Switzerland
   `helmut.harbrecht@unibas.ch`

6. Prof. Dr. Ralf Hiptmair
   Seminar für Angewandte Mathematik, ETH Zürich, Rämistrasse 101,
   8092 Zürich, Switzerland
   `hiptmair@sam.math.ethz.ch`

7. Richard James, PhD
   Department of Mathematics, University College London,
   Gower Street, London WC1E 6BT, United Kingdom
   `r.w.james@ucl.ac.uk`

8. Dipl.–Ing. Bernhard Kager
   Institut für Baumechanik, TU Graz,
   Technikerstrasse 4, 8010 Graz, Austria
   `bernhard.kager@tugraz.at`

9. Dr.–Ing. Lars Kielhorn
   Seminar für Angewandte Mathematik, ETH Zürich, Rämistrasse 101,
   8092 Zürich, Switzerland
   `lars.kielhorn@sam.math.ethz.ch`

10. Dipl.–Ing. Arno Kimeswenger
    Institut für Numerische Mathematik, TU Graz,
    Steyrergasse 30, 8010 Graz, Austria
    `arno.kimeswenger@tugraz.at`

11. Mag. Barbara Knöbl
Institut für Baumechanik, TU Graz,
Technikerstrasse 4, 8010 Graz, Austria
barbara.knoebl@tugraz.at

12. Prof. Dr. Stefan Kurz
Department of Electronics, Electromagnetics,
Tampere University of Technology, 33101 Tampere, Finland
stefan.kurz@tut.fi

13. Ing. Michal Merta
Department of Applied Mathematics, TU VSB Ostrava, Czech Republic
michal.merta@vsb.cz

14. Gregor Mitscha–Eibl, BSc
Institut für Analysis und Wissenschaftliches Rechnen, TU Wien,
Wiedner Hauptstrasse 8–10, 1040 Wien, Austria

15. Dr. Günther Of
Institut für Numerische Mathematik, TU Graz,
Steyrergasse 30, 8010 Graz, Austria
of@tugraz.at

16. Zhen Peng, PhD
University of New Mexico, Albuquerque, USA
zpeng@ece.unm.edu

17. Dipl.–Math. Michael Peters
Mathematisches Institut, Universität Basel,
Rheinsprung 21, 4051 Basel, Switzerland
michael.peters@unibas.ch

18. Prof. Dr. Dirk Praetorius
Institut für Analysis und Wissenschaftliches Rechnen, TU Wien,
Wiedner Hauptstrasse 8–10, 1040 Wien, Austria
dirk.praetorius@tuwien.ac.at

19. Prof. Dr. Sergej Rjasanow
Fachrichtung Mathematik, Universität des Saarlandes,
Postfach 151150, 66041 Saarbrücken, Germany
rjasanow@num.uni-sb.de

20. Prof. Dr.–Ing. Martin Schanz
Institut für Baumechanik, TU Graz,
Technikerstrasse 4, 8010 Graz, Austria
m.schanz@tugraz.at

21. Dr. Martin Schweiger
Department of Computer Science, University College London,
Gower Street, London, WC1E 6BT, United Kingdom
m.schweiger@cs.ucl.ac.uk

22. Elke Spindler
Seminar für Angewandte Mathematik, ETH Zürich, Rämistrasse 101,
8092 Zürich, Switzerland
elke.spindler@sam.math.ethz.ch

23. Oded Stein
Seminar für Angewandte Mathematik, ETH Zürich, Rämistrasse 101,
8092 Zürich, Switzerland
steino@student.ethz.ch

24. Prof. Dr. Olaf Steinbach
Institut für Numerische Mathematik, TU Graz,
Steyrergasse 30, 8010 Graz, Austria
o.steinbach@tugraz.at

25. Dipl.–Ing. Thomas Traub
Institut für Baumechanik, TU Graz,
Technikerstrasse 4, 8010 Graz, Austria
thomas.traub@tugraz.at

26. Dr. Gerhard Unger
Institut für Numerische Mathematik, TU Graz,
Steyrergasse 30, 8010 Graz, Austria
gerhard.unger@tugraz.at

27. Carolina A. Urzúa Torres
Escuela de Ingeniería, Pontificia Universidad Católica de Chile, Santiago, Chile
curzuat@uc.cl

28. Manuela Utzinger, M. Sc.
Mathematisches Institut, Universität Basel,
Rheinsprung 21, 4051 Basel, Switzerland
manuela.utzinger@unibas.ch

29. Prof. Dr.–Ing. Dr. h.c. Wolfgang L. Wendland
Institut für Angewandte Analysis und Numerische Simulation,
Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany
wolfgang.wendland@mathematik.uni-stuttgart.de

30. Marco Zank, BSc.
Institut für Numerische Mathematik, TU Graz,
Steyrergasse 30, 8010 Graz, Austria
zank@tugraz.at

31. Jan Zapletal, M. Sc.
Department of Applied Mathematics, TU VSB Ostrava, Czech Republic
honza.zapletal@gmail.com

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