DFG-Sonderforschungsbereich 393

"Numerische Simulation auf massiv parallelen Rechnern"

and

Fakultät für Mathematik, Technische Universität Chemnitz

Chemnitz FEM-Symposium 2003

Programme

Collection of abstracts

and

List of participants

Chemnitz, September 22 - 24, 2003

Scientific topics:

The symposium is devoted to all aspects of finite elements and wavelet methods in partial differential equations.

The topics include (but are not limited to)

- adaptive methods,
- parallel implementation,
- high order methods.

This year we particularly encourage talks on

- fast solvers, e.g.
  - domain decomposition methods,
  - multi-level methods,
  - for hp-methods,
  - using H-matrices,
- simulation of materials with nonlinear properties, e.g.
  - deformation,
  - damage,
  - crack propagation,
- mixed formulations,
- problems with anisotropic solution.

Invited Speakers:

Manfred Dobrowolski (Würzburg): *The Ladyzhenskaja constant in the numerical analysis of the Stokes equations*

Ricardo Duran (Buenos Aires): *Error estimates for an average interpolation on anisotropic $\mathcal{Q}_1$ elements*

Ulrich Langer (Linz): *Sparse Algebraic Multigrid Preconditioners and their use in Boundary and Finite Element DD Methods*

Markus Melenk (Leipzig): *Boundary concentrated FEM*

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Chemnitz, September 22 - 24, 2003

Programme for Monday, September 22, 2003

Start at 09:00

Chairman: Arnd Meyer

09:00 – 09:05	A. Meyer (Chemnitz)	Welcome
09:05 – 09:50	U. Langer (Linz)	Sparse Algebraic Multigrid Preconditioners and their use in Boundary and Finite Element DD Methods
10:00 – 10:25	M. Jung (Dresden)	Fast solvers for the first biharmonic boundary value problem

Tea and coffee break

Chairman: Ulrich Langer

11:00 – 11:25	B. Khoromskij (Leipzig)	Hierarchical Tensor-Product Approximation to Elliptic and Parabolic Solution Operators in Higher Dimensions
11:30 – 11:55	S. Beuchler (Chemnitz)	A DD-preconditioner for p-fem
12:00 – 12:25	J. Kruis (Prague)	Combination of Domain Decomposition Methods with Sparse Direct Solver
12:30 – 12:45	M. Mair (Stuttgart)	Overlapping domain decomposition methods for domains with holes based on complementary decomposition

Lunch

Chairman: Peter Jimack

14:45 – 15:35	M. Dobrowolski (Würzburg) The Ladyzhenskaja constant in the numerical analysis of the Stokes equations
15:45 – 16:10	V. Dolejsi (Prague) The dicontinuous Galerkin method for the numerical solution of the compressible flows

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short break

Chairman: Peter Jimack

16:25 – 16:50	M. Braack (Heidelberg) Numerical parameter estimation for chemical models in multidimensional reactive flows
16:55 – 17:10	P. Skrzypacz (Magdeburg) Superconvergence of a 3d finite element method for stationary stokes and navier-stokes problems

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Tea and coffee break

Chairman: Bernd Heinrich

17:45 – 18:10	B. Nkemzi (Trieste) The Fourier-finite-element method for the Lamé equations in nonsmooth axisymmetric domains
18:15 – 18:30	J. Novak (Liberec) Influence of Piezoelectricity on Resonance Frequencies of Piezoelectric Resonators
18:35 – 18:50	S. Zaglmayr (Linz) t.b.a.

Dinner

20:00 Wine reception and poster session

Programme for Tuesday, September 23, 2003

Start at 09:00

Chairman: Thomas Apel

09:00 – 09:50 R. Duran (Buenos Aires)
Error estimates for an average interpolation on anisotropic $\mathcal{Q}_1$ elements

10:00 – 10:25 M. Picasso (Lausanne)
Anisotropic, adaptive finite elements for elliptic and parabolic problems

10:30 – 10:45 S. Grosman (Chemnitz)
The robustness of the hierarchical a posteriori error estimator for reaction-diffusion equation on anisotropic meshes

Tea and coffee break

Chairman: Ricardo Duran

11:15 – 11:40 R. Rodriguez (Concepcion)
A posteriori error estimates for the finite element approximation of eigenvalues problems.

11:45 – 12:10 C. Pester (Chemnitz)
A posteriori error estimation on spherical domains

12:15 – 12:40 M. Grajewski (Dortmund)
Numerical analysis and a-posteriori error control for a new nonconforming quadrilateral linear finite element

12:45 – 13:10 P. Jimack (Leeds)
Adaptive finite element solution of time-dependent PDEs based upon moving meshes

Lunch

14:45 Excursion to ”Greifensteine”

Dinner

Chairman: Markus Melenk

20:00 – 20:25 T. Hohage (Göttingen)

New methods for the construction of transparent boundary conditions

20:30 – 20:55 T. Todorov (Gabrovo)

A Study of the Constant in the Strengthened Cauchy Inequality for 3D Elasticity Problems

21:00 – 21:15 U. Risch (Magdeburg)

Superconvergence of a non-conforming low order finite element

Programme for Wednesday, September 24, 2003

Start at 09:00

Chairman: Reinhold Schneider

09:00 – 09:50	M. Melenk (Leipzig)	Boundary concentrated FEM
10:00 – 10:25	G. Matthies (Magdeburg)	A priori error estimates of higher order finite element methods for an equation of mean curvature type

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short break

Chairman: Reinhold Schneider

10:40 – 11:05	M. Maischak (Hannover)	hp-Version of BEM for Signorini problems in 2 and 3 dimensions
11:10 – 11:35	O. Steinbach (Stuttgart)	Boundary Element Tearing and Interconnecting Methods

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Tea and coffee break

Chairman: Manfred Dobrowolski

12:00 – 12:25	Z. Dostal (Ostrava)	Scalable algorithms for variational inequalities and contact problems
12:30 – 12:55	O. Sander (Berlin)	Fast Solving of Contact Problems on Complicated Geometries
13:00 – 13:15	S. Hüeber (Stuttgart)	A primal-dual active set strategy for nonlinear multibody contact problems
13:20 – 13:25	A. Meyer (Chemnitz)	Closing

Lunch

Optimal preconditioners for the p-Version of the fem

Sven Beuchler[1]

In this talk, a uniformly elliptic second order boundary value problem in 2D is discretized by the p-version of the finite element method. An inexact Dirichlet-Dirichlet domain decomposition pre-conditioner for the system of linear algebraic equations is investigated. The solver for the problem in the sub-domains and a pre-conditioner for the Schur-complement are proposed as ingredients for the inexact DD-pre-conditioner. Finally, several numerical experiments are given.

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Numerical parameter estimation for chemical models in multidimensional reactive flows

Malte Braack[1] Roland Becker[2] Boris Vexler[3]

We present an algorithm for parameter identification in combustion problems modeled by partial differential equations. The method includes local mesh refinement controlled by a posteriori error estimation with respect to the error in the parameters. The algorithm is applied to two types of combustion problems. The first one deals with the identification of Arrhenius parameters, while in the second one diffusion coefficients for an hydrogen flame are calibrated.

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The Ladyzhenskaja constant in the numerical analysis of the Stokes equations

Manfred Dobrowolski[1]

In finite element theory, the discrete LBB constant is determined by a constant factor c, which depends on the chosen element, multiplied with the continuous Ladyzhenskaja constant. Thus, a small LBB constant is mainly caused by a small Ladyzhenskaja constant. In the numerical approximation of channel flows, it is observed that the convergence of multigrid methods deteriorates for large aspect ratios. This can now be explained by the result that the Ladyzhenskaja constant behaves like a^{-1}, where a denotes the aspect ratio of the 2d- or 3d-domain. On the other hand, the dependence on the LBB constant in the regularity and convergence estimates for the Stokes equations can be weakened. It is proved that the convergence of the velocity and the local convergence of the pressure are independent of the aspect ratio. Thus, the LBB constant influences the algebraical, but not the analytical properties of the discrete system. Finally, using a discrete Crouzeix-Velte decomposition some methods for determining the Ladyzhenskaja constant numerically are discussed.

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The discontinuous Galerkin method for the numerical solution of the compressible flows

Vit Dolejsi[1]

We deal with the numerical solution of the compressible flows. The presented numerical method uses the discontinuous Galerkin finite element (DG FE) approach based on piecewise polynomial approximations without any requirement on the interelement continuity. Our goal is to develop a sufficiently accurate and robust numerical scheme for the simulation of compressible high-speed flow which produce numerical solutions not suffering from the so-called spurious oscillations in the vicinity of discontinuities and steep gradients.

We mention some theoretical results for the numerical solution of the scalar convection-diffusion equation with the aid of the antisymmetric variant of the discontinuous Galerkin method with the stabilization "jump" term. Main emphasis is put on the discretization of the Navier-Stokes equations. In order to avoid spurious oscillations, we propose a suitable limiting of the order of accuracy of the method based on a local averaging procedure. Several numerical examples demonstrating the efficiency of the proposed method are presented and compared with the results of another authors.

References:

[1] Dolejsi, V.: On the Discontinuous Galerkin Method for the Numerical Solution of the Euler and the Navier–Stokes Equations, Int. J. Numer. Methods Fluids, submitted

[2] Dolejsi, V.: A higher order scheme based on the finite volume approach, In R. Herbin and D. Kröner (eds): Finite Volumes for Complex Applications III (Problems and Perspectives), 2002, Hermes, 333-340

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Scalable algorithms for variational inequalities and contact problems

Zdenek Dostal[1] David Horak[2]

We shall first briefly review the FETI methodology proposed by C. Farhat and F.-X. Roux adapted for solution of variational inequalities. Using the classical results by Mandel and Tezaur related to the scalability of FETI for solution of linear elliptic boundary value problems, we shall show how to exploit their results to reduce the discretized variational inequality to the bound and equality constrained quadratic problem with the condition number of the Hessian independent on the discretization parameter h. Then we shall show that such problems may be solved efficiently by recently proposed algorithms for solution of quadratic programming problems with the rate of convergence in terms of the spectral condition of the Hessian of the cost function. In particular, it follows that if we impose the equality constraints by the penalty method, we can solve our penalized problem to the prescribed relative precision in a number of iterations that does not depend on h. Since we managed to prove that a prescribed bound on the relative feasibility error of the solution may be achieved with the value of the penalty parameter that does not depend on the discretization parameter h, we conclude that these results may be used to develop scalable algorithms for numerical solution of elliptic variational inequalities. We give results of numerical experiments with parallel solution of both coercive and semicoercive model problems discretized by up to more than eight million of nodal variables to demonstrate numerically optimality of the penalty and scalability of the algorithm presented.

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Error estimates for an average interpolation on anisotropic $\mathcal{Q}_1$ elements.

Ricardo G. Durán[1] Ariel L. Lombardi[2]

In this talk we present new results on error estimates for mean average interpolation on anisotropic $\mathcal{Q}_1$ rectangular elements in two and three dimensions.

We begin by recalling some previously known results showing in particular the advantages of average interpolations over the Lagrange interpolation in the anisotropic case, even for functions for which the Lagrange interpolation is well defined.

Then, we introduce our average interpolation operator and explain the ideas used to obtain the error estimates. In particular, we show how the well known Hardy inequality can be used to prove error estimates for functions in weighted Sobolev spaces.

Our results improve previously known ones in several aspects. In particular, our estimates are valid under a very mild assumption that includes more general meshes than those allowed in previous works.

We end the talk by showing some applications of our results in the approximation of singularly perturbed problems.

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Numerical analysis and a-posteriori error control for a new nonconforming quadrilateral linear finite element

Matthias Grajewski[1] Stefan Turek[2] Jaroslav Hron[3]

Starting with a short introduction of the investigated nonconforming linear quadrilateral $\tilde{P}_1$-finite element which has been recently developed by Park, we examine in detail the numerical behaviour of this element with special emphasis on the treatment of Dirichlet boundary conditions, efficient matrix assembly, solver aspects and the use as Stokes element in CFD. Furthermore, we compare the numerical characteristics of $\tilde{P}_1$ with other low order finite elements. Moreover, we derive a dual weighted residual based a-posteriori error estimation procedure in the sense of Becker and Rannacher for $\tilde{P}_1$. Several test examples show the efficiency and reliability of the proposed method for elliptic 2nd order problems.

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The robustness of the hierarchical a posteriori error estimator for reaction-diffusion equation on anisotropic meshes

Serguei Grosman[1]

Singularly perturbed reaction-diffusion problems exhibit in general solutions with anisotropic features, e.g. strong boundary and/or interior layers. This anisotropy is reflected in the discretization by using meshes with anisotropic elements. The quality of the numerical solution rests on the robustness of the a posteriori error estimator with respect to both the perturbation parameters of the problem and the anisotropy of the mesh. The simpliest local error estimator from the implementation point of view is the so-called hierarchical error estimator. The robustness proof is mainly based on two facts: the saturation assumption and the strengthened Cauchy-Schwarz inequality. The proofs of both these facts are given in the present work as well as the concluding proof of the robustness of the estimator. A numerical example confirms the theory.

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New methods for the construction of transparent boundary conditions

Thorsten Hohage[1]

A complete formulation of time-harmonic wave propagation problems in unbounded domains always involves a radiation condition at infinity. For finite element computations the infinite domain is truncated, and the radiation condition is replaced by a so-called transparent boundary condition at the artificial boundary of the computational domain.

For scattering problems with bounded obstacles, there are a number of equivalent radiation conditions, the most well-known being Sommerfeld's radiation condition. All of these conditions lead to different approaches for the construction of transparent boundary conditions such as FEM/FEM coupling methods, approximation of the Dirichlet-to-Neumann map by local operators, infinite elements, or the PML method. We briefly review each of these methods.

For more complicated exterior domains such as half-planes or exterior domains involving wave-guides, some or all of the usual formulations of the radiation condition are not valid. Recently, a more general radiation condition called pole condition, which is based on a Laplace transform in radial direction, has been suggested by Frank Schmidt. This condition can be shown to be equivalent to standard radiation conditions in many situations. The pole condition also leads to transparent boundary conditions which are fairly straightforward to implement. Although they seem to require a bit more storage and computation time then for example the PML method, the total computational cost is typically dominated by the solution of the finite element problem in the interior domain. An attractive feature of this approach is a new representation formula which allows a very cheap evaluation of the exterior solution. Our results are illustrated by numerical examples.

References:

[1] T. Hohage, F. Schmidt, and L. Zschiedrich. Solving time-harmonic scattering problems based on the pole condition: Theory. SIAM J. Math. Anal., 35:183–120, 2003.
[2] T. Hohage, F. Schmidt, and L. Zschiedrich. Solving time-harmonic scattering problems based on the pole condition: Convergence of the PML method. SIAM J. Math. Anal., to appear.
[3] T. Hohage, F. Schmidt, and L. Zschiedrich. A new method for the solution of scattering problems. In B. Michielsen and F. Decavèle, editors, Proceedings of the JEE'02 Symposium, pages 251–256, Toulouse, 2002. ONERA.

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Finite Element of elasticity with couple-stress using the analogy between plane couple-stress and Reissner/Mindlin plate

Ruoyu Huang[1] C C WU[2]

Classical theory of elasticity is thought to be not adequate for modeling some of the newer materials such as materials with a granular, fibrous or lattice structure. These materials have an internal structure that influences their behavior when viewed as continuous medium. For these materials it is useful to generalize the notation of a simple elastic body to take into account this structure. The theory of elasticity with couple-stress is one of the generalized theories that take into account the effect of micro-rotation of internal structure. The requirement of C1 continuity is one of the essential difficulties of finite element formulation for plane elasticity with couple-stress. The analogy between plane couple-stress and Reissner/Mindlin plate bending provides a new way to overcome this difficulty. The present work researches a general method to construct finite element of plane couple-stress based on the analogy theory. Using this method, the well-known 8-nodes 24 D.O.F Serendipity R/M plate element Q8S is transformed to a 4-nodes 12 D.O.F plane couple-stress element with convenient degree of freedom. Numerical results about the problem of stress concentration show the element have satisfactory precision and convergence behavior. The present element is useful for further analysis of crack problems considering the effect of couple-stress.

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A primal-dual active set strategy for nonlinear multibody contact problems

Stefan Hüeber[1] Barbara Wohlmuth[2]

The simulation of nonlinear multibody contact problems in linear elasticity plays an important role for a wide range of technical applications. For solving such problems, domain decomposition using mortar techniques provide a powerful tool. We use a primal-dual active set strategy to find the actual contact zone, which can be interpreted as a semi-smooth Newton method. In the case of multibody systems, a basis transformation enables us to apply the active set strategy as in the case of only one body. Various numerical examples will show the flexibility of our method.

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Adaptive finite element solution of time-dependent PDEs based upon moving meshes

Peter Jimack[1] Michael J Baines[2] Matthew E Hubbard[3]

We consider a Lagrangian Moving Finite Element Method for which the mesh velocity is determined by the invariance of a monitor function, such as the local mass. The method will be described and its application to both second and fourth order nonlinear diffusion equations with moving boundaries will be demonstrated in two dimensions.

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Fast parallel solvers for the first biharmonic problem

Michael Jung[1]

We consider the first biharmonic problem in the mixed variational formulation. The finite element discretization leads to a system of linear algebraic equations

$$\begin{pmatrix} M & B^\top \\ B & 0 \end{pmatrix} \begin{pmatrix} \underline{w} \\ \underline{u} \end{pmatrix} = \begin{pmatrix} 0 \\ -\underline{f} \end{pmatrix} . \tag{1}$$

The system matrix of (1) is symmetric but indefinite. Therefore, special effort must be spent for the construction of efficient solution methods. In the talk, we discuss the following three possibilities for getting efficient solvers:

1. By eliminating $\underline{w}$ we get the Schur complement system $BM^{-1}B^\top\underline{u} = \underline{f}$. The condition number of the matrix $BM^{-1}B^\top$ is of the order $\mathcal{O}(h^{-4})$, where h is the discretization parameter. For getting an efficient iterative solver for this Schur complement system one needs an appropriate preconditioner. We use a preconditioner which involves the solution of two discrete Poisson's equations by means of multigrid methods. Using this preconditioner the number of iterations of the preconditioned conjugate gradient (pcg) method is of the order $\mathcal{O}(h^{-0.5}\ln\varepsilon^{-1})$ (ε a prescribed accuracy), whereas the number of iterations of the cg method without preconditioning is of the order $\mathcal{O}(h^{-2}\ln\varepsilon^{-1})$.

2. We use the conjugate gradient method of Bramble-Pasciak type for solving the system of equations (1). The system of equations will be transformed into a system $\mathcal{A}\underline{v} = \underline{g}$, where the matrix $\mathcal{A}$ is symmetric and positive definite with respect to a special inner product. We solve this system of equations by means of the pcg method in the special inner product. As preconditioner C_{M} for the matrix M we use diag(M), the diagonal part of M, and for the matrix $BC_{\mathrm{M}}^{-1}B^\top$ a preconditioner as described above for the first solution method. The pcg method applied to the transformed system of equations has the same convergence properties as the first variant of the solvers.

3. We apply multigrid methods to solve the system of equations (1). Especially, we discuss the choice of appropriate smoothing procedures.

Finally, we present numerical experiments which were performed on a CRAY T3E.

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Hierarchical Tensor-Product Approximation to Elliptic and Parabolic Solution Operators in Higher Dimensions

Boris N. Khoromskij[1] I. Gavrilyuk[2] W. Hackbusch[3]

A class of $\mathcal{H}$-matrices allows an approximate matrix arithmetic with almost linear complexity. In the present talk, we discuss the $\mathcal{H}$-matrix techniques combined with the Kronecker tensor-product approximation to represent the inverse of an elliptic operator on a hypercube $(0,1)^d$ in the case of a high dimension d. We also represent (in this data-sparse format) the operator exponential, the fractional power of an elliptic operator as well as the solution operator of the matrix Lyapunov equation. The complexity of these representations can be estimated by $O(N^{1/d} \log^q N)$, where N is the discrete problem size. We give numerical examples that confirm the theory.

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Combination of Domain Decomposition Methods with Sparse Direct Solver

Jaroslav Kruis[1] Richard Vondracek[2] Zdenek Bittnar[3]

Article deals with solution of large sparse systems of linear algebraic equations arising from finite element method. Domain decomposition methods (Schur complement method and DP-FETI method) with sparse direct solver are used. Both DD methods lead to factorization of matrices of subdomains. It is the most computationally intensive part of the algorithms. The main idea is application of sparse direct strategy for the factorization instead of usual LDL method based on skyline storage scheme. It leads to less memory requirements and the factorization is done faster. Sparse direct solver is based on block structure of solved matrix and uses approximate minimum degree algorithm. Symbolic factorization precedes memory allocation and the final numerical factorization. Numerical examples obtained on structured and also on unstructured meshes of regular and general domains are used for comparison with standard implementation (based on skyline). Applied strategy is approximately 3-10 times faster. Bigger problems (with more degrees of freedom) are solvable thanks to smaller memory requirements.

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Sparse Algebraic Multigrid Preconditioners and their use in Boundary and Finite Element DD Methods

Langer, Ulrich[1] Pusch, David[2]

Efficient preconditioners for boundary element (BE) matrices are needed in many application. In the primal as well in the dual boundary element domain decomposition (DD) methods preconditioners for the discrete single layer potential integral operator, arising from the BE approximation of interior or exterior Dirichlet boundary value problems, are required. In the primal boundary and finite element DD method, preconditioners for the assembled discrete hypersingular integral operator are needed. Geometric and algebraic multigrid techniques based on sparse approximations of the corresponding boundary element matrices are a powerful technique for the construction of robust and at least almost optimal preconditioners for these BE matrices. In this talk we present new algebraic multigrid (AMG) preconditioners for sparse boundary element matrices arising from the Adaptive-Cross-Approximation (ACA) of dense boundary element matrices. As model problem we consider the single layer potential integral equation resulting from the interior Dirichlet boundary value problem for the Laplace equation. The standard Galerkin boundary element discretization leads to fully populated system matrices which require $O(N^2)$ complexity for the memory and the matrix-by-vector multiplication, where N denotes the number of boundary unknowns. Sparse approximations such as ACA reduce this complexity to almost $O(N)$. Since the single layer potential operator is a pseudodifferential operator of the order -1, the resulting boundary element matrices are ill-conditioned. Iterative solvers dramatically suffers from this property for growing N. Our AMG preconditioners avoid this dramatical grow in the number of iterations and lead to almost optimal solvers with respect to the total complexity. This behaviour is confirmed by our numerical experiments. We mention that our AMG preconditioners use only single grid information provided by the usual mesh data and by the ACA anyway. Analogous results hold for the hypersingular operator and for the assembled hypersingular operator living on the skeleton of a domain decomposition.

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Overlapping domain decomposition methods for domains with holes based on complementary decomposition

Michael Mair[1] Barbara Wohlmuth[2]

In some optimization problems, size, shape, and placement of holes play a certain role. Domain decomposition approaches for either natural or Dirichlet boundary conditions are proposed. These approaches lead to saddle point problems. We present some theoretical results concerning existence and uniqueness of the solutions and give an a priori estimate for the discretization error. A solution by iterative solvers using a SOR scheme as a preconditioner is considered and some numerical results showing the efficiency of the preconditioner are given. In addition, we address implementation issues and suggest possible applications of the method.

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hp-Version of BEM for Signorini problems in 2 and 3 dimensions

Matthias Maischak[1]

The variational formulation of Signorini-problems leads to a variational inequality on a convex subset. Applying the symmetric formulation of the boundary element method to this variational inequality introduces the Poincare-Steklov operator, which can be represented in its discretized form by the Schur-complement of the dense Galerkin-matrices for the single layer potential, the double layer potential and the hypersingular integral operator. Considering the difficulties in discretizing the convex subset involved, traditionally only the h-version is used for the discretization. Only recently, the investigation of p- and hp-versions for Signorini problems started. Here, convergence results for the quasi-uniform hp-version of BEM, FEM and FEM-BEM coupling Signorini problems are shown, as well as a-posteriori error estimates for the hp-version, which can be used as error indicators for adaptive hp-algorithms. Numerical experiments are presented which underline the theoretical results.

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A priori error estimates of higher order finite element methods for an equation of mean curvature type

Gunar Matthies[1]

We consider error estimates for higher order finite element discretisations of the problem

$$-\text{div}\,\frac{\nabla u}{\sqrt{1+|\nabla u|^2}} + \lambda u = f \quad \text{in } \Omega, \qquad \frac{\partial u}{\partial n} = 0 \quad \text{on } \partial\Omega,$$

where Ω is a convex polygonal domain in $\mathbf{R}^2$. This equation occurs for instance in the description of the hexagonal surface deformations of ferrofluids, see the book by Rosensweig (1998).

For solving the above given problem, we consider conforming finite element methods which are based on triangulations of Ω into triangles and/or convex quadrilaterals. We prove optimal H^1 and L^2 error estimates for finite elements of order $k \geq 2$. A main part is the proof of a uniform bound of the $W^{1,\infty}$ norm of discrete solutions u_h. Such a bound for linear elements on triangles was established by Johnson and Thomée (1975). In that paper also optimal L^p estimates for $p < 2$ were shown by duality arguments. The more detailed analysis for linear elements given by Rannacher (1977) leads to an optimal L^2 error bound.

Our technique to get a $W^{1,\infty}$ bound is different from that of Johnson and Thomée (1975) and can be applied to elements of any order $k \geq 1$. In contrast to Rannacher (1977) we obtain the optimal L^2 error estimate directly by duality arguments.

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Boundary concentrated FEM

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It is known for elliptic problems with smooth coefficients that the solution is smooth in the interior of the domain; low regularity is only possible near the boundary. The *hp*-version of the FEM allows us to exploit this property if we use meshes where the element size grows porportionally to the element's distance to the boundary and the approximation order is suitably linked to the element size. In this way most degrees of freedom are concentrated near the boundary.

In this talk, we will discuss convergence and complexity issues of the boundary concentrated FEM. We will show that it is comparable to the classical boundary element method (BEM) in that it leads to the same convergence rate (error versus degrees of freedom). Additionally, it generalizes the classical FEM since it does not require explicit knowledge of the fundamental solution so that it is also applicable to problems with (smooth) variable coefficients.

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The Fourier-finite-element method for the Lamé equations in nonsmooth axisymmetric domains

Boniface Nkemzi[1]

Partial Fourier series expansion is applied to the Dirichlet problem for the Lamé equations in axisymmetric domains $\hat{\Omega} \subset \mathbf{R}^3$ with conical points and re-entrant edges on the boundary. This leads to dimension reduction of the three-dimensional boundary value problem resulting to an infinite sequence of decoupled two-dimensional boundary value problems on the plane meridian domain $\Omega_a \subset \mathbf{R}^2_+$ of $\hat{\Omega}$with solutions $\mathbf{u}_n$ $(n = 0, 1, 2, \cdots)$ being the Fourier coefficients of the solution $\hat{\mathbf{u}}$ of the three-dimensional boundary value problem. The asymptotic behavior of the Fourier coefficients $\mathbf{u}_n$ $(n = 0, 1, 2, \cdots)$ near the angular points of the domain Ω_a is fully described by singular vector-functions and treated numerically by the finite element method on graded mesh refinements of the domain $\hat{\Omega}$. An approximation for the solution of the three-dimensional problem is obtained by means of Fourier synthesis. It is proved that for $\hat{f} \in L_2(\hat{\Omega})$, the rate of convergence of the combined approximations in the Sobolev space $W^1_2(\hat{\Omega})$ is of the order $\mathcal{O}(h + N^{-1})$, where h and N represent, respectively, the parameters of the finite-element- and the Fourier-approximation, with $h \to 0$ and $n \to \infty$.

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Influence of Piezoelectricity on Resonance Frequencies of Piezoelectric Resonators

Josef Novak[1] Jiri Maryska[2]

The main goal of this work is FEM analysis of piezoelectricity influence on resonance frequencies of piezoelectric resonnators. Physical description includes elastic equations (2), electric equations (3) and piezoelectric equations of state (4, 5).

$$\varrho \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial \mathrm{T_{ij}}}{\partial x_j} \quad i = 1, 2, 3 \quad x \in \Omega, \quad \mathrm{t} \in (0, \mathrm{T}) \tag{2}$$

$$\nabla \cdot \mathbf{D} = \frac{\partial \mathrm{D_j}}{\partial x_j} = 0 \tag{3}$$

$$\mathrm{T_{ij}} = c_{ijkl} \cdot \mathrm{S_{kl}} - e_{ijk} \cdot \mathrm{E_k}, \qquad i, j = 1, 2, 3. \tag{4}$$

$$\mathrm{D}_k = e_{kij} \cdot \mathrm{S_{ij}} + \varepsilon_{ij} \cdot \mathrm{E_j}, \qquad k = 1, 2, 3, \tag{5}$$

where $\mathbf{T}$, ρ, $\mathbf{u}$, $\mathbf{D}$, $\mathbf{S}$, $\mathbf{E}$, $\mathbf{c}$, $\mathbf{e}$ and ε are are stress, density, particle displacement, electric flux density, strain, electric field and the stiffness, piezoelectric and permitivity tensors of the material.

Algebraic system after using FEM we can write as:

$$\mathbf{K} \cdot \mathbf{u} - \omega^{\mathbf{2}} \mathbf{M} \cdot \mathbf{u} + \mathbf{P}^{\mathbf{T}} \phi = \mathbf{0} \tag{6}$$

$$\mathbf{P} \cdot \mathbf{u} - \mathbf{E} \cdot \phi = \mathbf{0} \tag{7}$$

For computing resonance frequencies we can use equation 6, where $\phi = \mathbf{0}$ or equation 6, where $\phi = \mathbf{E}^{-\mathbf{1}}\mathbf{P}$. The difference between results depends on permitivity, piezoelectric cofficients. These quantities are very closely related to anizotropy of material. Important is difference between quartz resonators and piezoceramics resonators (e.g. $GAPO_4$). There is also large influence of FE mesh. All these phenomenons are discused.

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A posteriori error estimation on spherical domains

Cornelia Pester[1]

The investigation of three-dimensional corner singularities for elliptic operators like the Laplace or the Lamé operator leads to the consideration of spherical domains. The quantitative knowledge of these singularities is important for analysts and engineers, for example to study the onset of cracks. The singularities can be computed by solving operator eigenvalue problems which are defined over spherical domains Ω which are a subset of the unit sphere $\mathcal{S}^2$.

For the calculations, it is useful to choose a proper parametrization of the domain Ω. Although possessing a singularity at the poles of the sphere, spherical coordinates (φ, θ) are a common parametrization. The problem given over Ω can then be transformed to a problem over a plane parameter domain, which simplifies the implementation. In this talk, all functions defined over the unit sphere are considered in spherical coordinates. In order to apply the finite element method, a proper triangulation of Ω is needed. We focus on an isotropic finite element mesh over Ω which is the image of a mesh over the corresponding parameter domain (with straight edges).

The use of an interpolation operator which acts on functions from the Sobolev space H^1 is a typical means to investigate a posteriori error estimators. We concentrate on an interpolation operator introduced by Clément and modify it such that it is adapted to the use on spherical domains. Estimates for the interpolation error can be proved by analogy to plane domains. These results are applied to the deduction of a reliable and efficient residual error estimator for the Laplace-Beltrami operator. This operator finds application, for example, in conductivity or heat transfer problems in curved domains.

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Anisotropic, adaptive finite elements for elliptic and parabolic problems

Marco Picasso[1]

An anisotropic error indicator is derived for the Laplace problem in the energy norm, using the anisotropic interpolation results of Formaggia and Perotto. The matrix containing the error gradient is approached using a Zienkiewicz-Zhu error estimator. A numerical study of the effectivity index is proposed for anisotropic unstructured meshes, showing that the indicator is sharp. An adaptive algorithm is implemented, aiming at controlling the relative estimated error.

The methodology is then applied to other elliptic problems, namely diffusion-convection and Stokes problems with stabilized finite elements. Firstly, the stabilization coefficient is re-designed in the frame of strongly anisotropic meshes. Then, anisotropic adaptive finite elements are proposed.

Parabolic problems are also considered. A numerical study of the effectivity index is performed for the heat equation. Finally, the methodology is applied to dendritic growth of binary alloys.

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Superconvergence of a non-conforming low order finite element

Uwe Risch[1]

We investigate a non-conforming finite element on rectangular meshes applied to convection-diffusion equations with dominating convection.

This (incomplete non-conforming P_2) element can be considered as an enriched Q_1^{rot} element (Rannacher-Turek element).

Compared with the Q_1^{rot} element, one obtains a superconvergence property in the H^1 seminorm and, additionally, a stabilization in streamline direction similar to SDFEM.

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A posteriori error estimates for the finite element approximation of eigenvalue problems

Rodolfo Rodriguez[1] Ricardo G. Duran[2] Claudio Padra[3]

We deal with a posteriori error estimators for the finite element approximation of some second order eigenvalue problems. First, we consider the approximation by piecewise linear finite elements of the Laplace operator. We give a simple proof of the equivalence, up to higher order terms, between the error and a residual type error estimator. In this case, we also prove that the volumetric part of the residual is dominated by a constant times the edge or face residuals, again up to higher order terms.

Then we consider the approximation by lowest-order Raviart-Thomas elements of the mixed formulation of this problem. We present a residual type error estimator which is shown to be equivalent to the energy norm of the error, up to higher order terms.

Finally, we consider the approximation of the pure displacement formulation of a structural acoustics vibration problem. We define an error estimator by combining the two previous ones with some additional terms to take care of the variational crimes arising in the fluid-structure interface. We prove that the estimator is equivalent to the energy norm of the error, up to higher order terms, for general meshes satisfying the usual regularity assumption. The analysis also shows that the estimator yields global upper and local lower bounds for the error, and so it can be used to design an efficient adaptive scheme. We report numerical experiments which exhibits the efficiency of the method, too.

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Fast Solving of Contact Problems on Complicated Geometries

Oliver Sander[1] Rolf Krause[2]

The efficient solution of contact problems involving friction in three space dimension is a non-trivial task. The mathematical modeling of the non-penetration condition and of the frictional effects at the interface gives rise to a non-linear and non-differentiable energy functional which has to be minimized. In our talk, we present a non-linear monotone multigrid method, by means of which one-sided frictional contact problems can be solved with optimal complexity. For the case of two sided contact problems, the information transfer at the interface is realized in terms of Mortar methods. Our method uses a combination of dual Basis functions for the Lagrange Multiplier space and a suitable transformation of the arising discrete system based on work by Wohlmuth and Krause. Thus the proposed method is also applicable in case of non-matching triangulations at the interface.

We also apply our monotone method to problems on complicated geometries. To this end, we combine the multigrid method with boundary parametrizations, by means of which the possibly complex geometry of the computational domain can be successively regained starting from a simple and coarse initial mesh. We also show how these parametrization techniques can be applied in order to realize the information transfer between two bodies coming into contact by means of Mortar methods in the case of curvilinear boundaries. Numerical results in three space dimensions illustrate the efficiency and accuracy of our method. In particular, we consider the case of curvilinear contact boundaries in three space dimensions.

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Superconvergence of a 3d finite element method for stationary stokes and navier-stokes problems

Piotr Skrzypacz[1] Lutz Tobiska[2] Gunar Matthies[3]

The phenomena of the superconvergence in the finite element methods have been studied in the last two decades. For the Poisson equation it is well known that the piecewise linear conforming finite element solution approximates the interpolant to a higher order than the solution itself. This type of superconvergence is established for a nonstandard interpolant of the $Q_2 - P_1^{\text{disc}}$ element applied to the stationary Stokes and Navier-Stokes problem, respectively. The supercloseness proof is based on the Bramble-Hilbert lemma instead of the integral expansions, which are very complicated to derive in more than two space dimensions. Applying $Q_3 - P_2^{\text{disc}}$ post-processing technique we can state a supercovergence property for the discretisation error of the post-processed discrete solution to the solution itself. Finally, we show that inhomogeneous boundary values can be approximated by the standard Lagrange Q_2-interpolation without influencing the superconvergence property. Numerical experiments verify the predicted convergence rates.

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Boundary Element Tearing and Interconnecting Methods

Olaf Steinbach[1] U. Langer[2]

We introduce the Boundary Element Tearing and Interconnecting (BETI) methods as counterparts of the well-established Finite Element Tearing and Interconnecting (FETI) methods. In some practical important applications such as far field computations, handling of singularities and moving boundaries, BETI methods have certainly some advantages over their finite element counterparts. This claim is especially true for sparse BETI preconditioners. Moreover, there is a unified framework for coupling, handling, and analyzing both methods. In particular, the FETI methods can benefit from preconditioning components constructed by boundary element techniques. Numerical results confirm the efficiency and the robustness predicted by our analysis.

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A Study of the Constant in the Strengthened Cauchy Inequality for 3D Elasticity Problems

Todor D. Todorov[1] Michael Jung[2]

The constant γ in the strengthened Cauchy-Bunyakowskii-Schwarz inequality is a basic tool for constructing of two-level and multilevel preconditioning matrices. Therefore many authors consider estimates or computations of this quantity. In this paper the bilinear form arising from 3D linear elasticity problem is considered on a polyhedron. The cosine of the abstract angle between multilevel finite element subspaces is computed by a spectral analysis of a general eigenvalue problem. New theoretical results over tetrahedron meshes are obtained. Octasection and bisection approaches are used for refining of the triangulations. Tetrahedron, pentahedron and hexahedron meshes are considered. The dependence of the constant γ on the Poisson ratio is presented graphically.

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