Math. Forschungsinstitut
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MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

Tagungsbericht 46/1994

Finite Volume Methods

30.10. – 5.11.1994

Tagungsleiter: D. Braess (Bochum)
W. Hackbusch (Kiel)
P. Wesseling (Delft)

The conference was organized by D. Braess (Bochum), W. Hackbusch (Kiel), and P. Wesseling (Delft). It brought together researchers from the numerical treatment of partial differential equations from 8 countries. Finite volume methods are mainly used when the aspect of conservation laws is more dominating than a variational principle. For this reason most of the lectures were concerned with hyperbolic equations. The application to elliptic equations is found in problems with large convection terms since upwinding is more easily constructed with finite volumes than with finite elements.

The convergence theory for finite volumes is younger than the analogous one for finite elements. Stimulatung lectures were concerned with higher order schemes, with the analysis of the appropriate weak norms for getting convergence, with splitting methods for the treatment of nonlinearities or saddle point problems, and with box schemes for the simplification of the computation. Moreover, it turned out that the differences between finite volumes and finite elements are more significant when 3-dimensional problems are treated.

The lectures reflect the fact that the mathematical theory of finite volume methods is still young and not yet settled. It showed the need for a sound mathematical theory since the need of the computation of time dependent solutions for large scale problems has become more important during the last years.

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Vortragsauszüge

Randolph Bank

An Algorithm for Coarsening Unstructured Grids

We develop and analyse a procedure for creating a hierarchical basis of continuous piecewise linear polynomials on an arbitrary, unstructured, nonuniform triangular mesh. Using these hierarchical basis functions, we are able to define and analyse corresponding iterative methods for solving the linear systems arising from finite element discretizations of elliptic partial differential equations. We show that such iterative methods perform as well as those developed to the usual case of structured, locally refined meshes. In particular, we show that the generalized condition numbers for such iterative methods are $O(J^2)$ where J is the number of hierarchical basis levels.

Herbert Gajewski, Klaus Gärtner

On the Discretization of van Roosbroeck's Equations with Magnetic Field

Van Roosbroeck's drift-diffusion model of charge carrier transport is of fundamental significance for the mathematical description and numerical simulation of semiconductor devices. It is a system of parabolic reaction-diffusion equations for the carrier densities and Poisson's equation for the electrostatic potential - which causes the drift of carriers. The key for the analysis of this system is a convex functional, which may be interpreted as free energy. First of all, this functional turns out to be a Lyapunov function ensuring global stability of the thermal equilibrium solution.

Because of its practical relevance much effort has been spent for solving the device equations numerically. The favourable space discretization scheme is due to Scharfetter-Gummel and is actually a finite volume method.

We extend the Scharfetter-Gummel idea to situations with magnetic field. We use simplex elements and describe a quite canonical way of calculating cross products between discrete currents and the magnetic field vector. Moreover, we show that the resulting discretization scheme essentially preserves the mathematical structure of the continuous problem. Our main result ensures global stability of the thermal equilibrium of the discrete system.

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Michael Griebel

Prewavelet-Multilevel Methods for the Solution of Elliptic PDEs.

We describe tensor product type techniques to derive robust solvers for anisotropic elliptic model problems on rectangular domains in $\mathbb{R}^d$. Our analysis is based on the theory of additive subspace correction methods and applies to finite-element- and prewavelet-schemes. We present multilevel- and prewavelet-based methods that are robust for anisotropic diffusion operators with an additional Helmholtz term. Furthermore, the resulting convergence rates are independent of the discretization level. Besides their theoretical foundation, we also report on the results of various numerical experiments to compare the different methods. Partly, this is joint work with P. Oswald (Texas).

Emmanuel Guilmineau

Applications of the CPI Finite Volume Method to the Computation of the Turbulent Viscous Flow Past Airfoil

Numerical solutions of the incompressible Navier-Stokes equationsi in two-dimensional domains, with the help of the CPI discretization, are presented for an AS 240 airfoil at different incidences. The strongly conservative equations are discretized with a finite volume method. The method uses a system of numerically generated curvilinear coordinates and retains the pressure and the cartesian velocity components as dependent variables on a non-staggered grid. The flow around an AS 240 airfoil at two fixed incidences is computed and compared to experimental results.

Wolfgang Hackbusch

On Stability of Finite Volume Methods

In contrast to finite element (FE) methods, the stability of finite volume (FV) methods is not obvious, when applied to elliptic problems. In the case of linear ansatz functions in a general triangulation, one can show that the FE and FV stiffness matrices coincide. The right-hand sides differ only by $O(h)$ or $O(h^2)$, depending on the construction of the control volume. This ensures stability and convergence of the corresponding FV method. Due to results of T. Schmidt (Thesis Kiel, 1992), the situation is different for general quadrilaterals. If these are not parallelograms, the matrix is non symmetric even if the underlying problem is symmetric. Using local energy inequalities, under certain conditions one can prove stability. However, numerical experiments confirm that there are situations, where stability is in doubt.

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Bernd Heinrich

Finite Volume Methods for Elliptic Problems with Singularities

The solutions of elliptic problems in domains with corners on the boundary or on interfaces contain singularities, in general. For such problems, appropriate finite volume schemes on locally refined meshes of triangles are derived and studied from the point of view of numerical analysis. A priori estimates proving the stability of the approximation scheme and the rate of convergence in discrete analogues of the spaces H^1 and C are given.

Rolf Jeltsch

Multidimensional Finite Volume Methods for Systems of Conservation Laws (e.g. Euler eq., shallow water eq.)

In his thesis N. Botta derived a finite volume method based on dimensional splitting for the inviscid Euler flow of gas dynamics. The fluxes occur cell sides are approximated using Pandolfi's Riemann solver. This solver is reformulated in a form which allows to show that the physical entropy satisfies a numerical entropy condition for a large range of flow situations. This scheme is then extended to a "second order" scheme following wave propagation ideas of LeVeque. Numerical results are shown. (This is part of the thesis of N. Botta)

Hartmut Kapitza

3-D Atmospheric Flow Simulation with McCormick's Method on a Staggered Terrain-Following Coordinate System

The conservation laws for momentum, mass and energy are used to derive model equations for volume integrals of the relevant variables on a non-orthogonal terrain-following coordinate system. The equations are solved with McCormick's method. Sound waves are eliminated by using the anelastic approximation. The resulting Poisson equation for the non-hydrostatic pressure is solved with a preconditioned conjugate gradient method. The system is tested for a case of mountain lee-waves for which analytical solutions are available.

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Thomas Kerkhoven

Element-Geometry Dependent Error Estimates for the Box-Method

The perpendicular bisector box-method (PBM) discretization of the Laplacean on a simplicial element is equivalent with a piecewise linear Petrov-Galerkin method with piecewise constant test-functions. This PBM element matrix is expressed in terms of Galerkin's piecewise linear (PLG) element matrix and the average values assumed by test-functions over element-faces only. Subject to smoothness conditions on coefficients, these results are shown to be applicable to the accuracy analysis of PBM discretizations of extremum stable elliptic gradient equations. The latter are shown to satisfy sufficient conditions for a discrete maximum principle on N-dimensional Delaunay triangulations. This need not be the case in the PLG equations.

The dependence of the discretized Laplacean on only the element-face averages of test-functions enables the substitution of piecewise polynomial test-functions for the piecewise constants. The latter are used to establish piecewise linear accuracy for the PBM by an adaptation of an error estimate for Petrov-Galerkin methods by Strang.

Barry Koren

1) A Monotone, Central Finite-Volume Scheme for Advection
2) An Advection-based Finite-Volume Scheme for Source Terms

1) A new, second-order accurate, monotone finite-volume scheme is presented. The scheme has maximal compactness; it uses 3 points in 1-D and 7 points in 3-D. (Comparable cell-centered finite-volume schemes use 4 points in 1-D and 13 points in 3-D.) Because of its compactness, the new finite-volume scheme requires a lower amount of message passing at internal grid boundaries. This implies better parallelization properties. Numerical results are presented.

2) The discretization of source terms is made compatible to that of advection terms. Besides an improved numerical accuracy (due to cancelling of discretization errors), for steady problems the benefit may also be improved convergence rates. Numerical results are presented.

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Seiichi Koshizuka

Computational Fluid Dynamics (BFC, Particle Methods) Thermal-Hydralics of Nuclear power plants

A particle method for simulating liquid fragmentation of incompressible viscous fluid is presented. Pressure gradient, diffusion, incompressibility and free surfaces are modeled by particle interactions. Since the present method never uses a grid system, fragmentation of fluids can be analyzed. In addition, the method is free from the numerical diffusion because of fully Lagrangian treatment of particles. Accuracy of each interaction model is assessed with a simple test problem. All models are based on deterministic processes in order to reduce the computational cost. Calculation results of collapse of a water column show that fluid splashing and fragmentation from a free surface can be simulated by the present method.

Dietmar Kröner

Convergence and Error Estimates for Finite Volume Methods for Conservation Laws

There are some recent results concerning convergence and error estimates for finite volume methods on unstructured grids for conservation laws. But unfortunately there are no error estimates for higher order schemes which indicate better convergence rates than for first order schemes. Therefore we have applied these schemes to linear convection dominated diffusion problems. In this case we could prove better convergence rates for the higher order schemes than for the first order ones. Up to now these estimates are not sharp. Numerical experiments show that the results can be improved. In this lecture we shall also present some numerical experiments in multidimensions using these schemes in the context of local adaption and coarsening.

R.D. Lazarov

H^1- and L^2-Error Estimates of the Finite Volume Approximations of Convection-Diffusion Problems

The upwinding has been used to avoid the conditional stability that is characteristic for the central finite difference approximations of the convection terms in convection-diffusion problems. However, these approximations are of first order and add substantial numerical diffusion to the physical problem. Various modifications of the upwind schemes have been proposed aiming second order of accuracy and unconditional stability.

Cell-centered finite difference approximations on triangular and rectangular meshes of second order convection-diffusion equations of divergence type are discussed and studied. A number of upwind finite difference methods of second order of approximation on uniform and almost uniform meshes that satisfy the discrete

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maximum principle are constructed. The error estimates are in both discrete H^1 and L^2 norms. Namely, it is proved that the error in discrete H^1-norms is of order $O(h^{m-1})$, $\frac{3}{2} < m \leq 3$ for solutions $u \in H^m(\Omega)$. These results can be viewed as a natural extension of some previous results to non-selfadjoint equations. In addition, error estimate in L^2-norm elaborating the discrete "Aubin-Nitsche trick" of duality argument proposed by Samarskii, Lazarov, and Makarov for finite difference schemes for general self-adjoint elliptic equations is derived.

Randell J. LeVeque

Multi-Dimensional Wave Propagation Methods

A class of multi-dimensional finite volume methods for hyperbolic equations can be defined by solving Riemann problems at each interface between grid cells in the normal direction, and then solving Riemann problems in the tangential direction to decompose the flux differences into waves moving in a multi-dimensional manner. These waves are used to update fluxes at all the nearby cell interfaces. Second order corrections are defined based on the waves, with limiters to maintain high resolution of discontinuities. A software package, CLAWPACK, has been developed based on these ideas which solves general systems of conservation laws in 1D and 2D. This package is available from netlib by anonymous ftp from netlib.att.com in netlib/pdes/claw, or through
ftp://amath.washington.edu/pub/leveque/programs/clawpack.html.

Frank Liebau

Finite Volume Element Method with quadratic Basisfunction

The box method for discretizing Poisson's equation with piecewise quadratic basis functions are presented. For general 2-D triangulations the control volumes (cell, box) are chosen as polygons defined by the medians of the (refined) triangles. The matrix of the box method is nonsymmetric and not an M-matrix. The stability analysis is based on elementwise estimates of "local" inner products. Assumptions of the shape of the triangles leads to sufficient conditions for discrete ellipticity and to a second order error of the method in the discrete H^1 semi-norm.

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John Mackenzie

A Posteriori Error Estimates and Adaptivity of Finite Volume Methods

We consider the problem of developing adaptive finite volume methods. By writting the cell vertex finite volume method as a Petrov-Galerkin finite element method, a posteriori error estimates have been obtained for scalar linear advection problems and also for Friedrich's systems. All of the error estimates are based on taking appropriate norms of the residual of the finite volume approximation. Local estimates are obtained by splitting the error into a component which is generated locally on each cell and a component which is transported through the cell. Each error component satisfies a local boundary value problem and it is shown that only the cell error contributes to the cell residual. Strong and weak norm estimates are then given for the cell error. A series of numerical experiments confirm that the error estimates are sharp. A moving mesh algorithm based on an equidistribution principle is used with the a posteriori error estimates and numerical experiments show that this is an effective adaptive strategy.

T.F. Maitre

1. Obtaining and Studying (Error Bounds) Certain Classes of F.V. Schemes from Mixed Finite Element Technique.
2. Studying of so-called Finite Volume Element Methods.

For simplicity, we consider model problem (1) $\Delta u + f = 0\ (\Omega), u = 0\ (\partial\Omega)$. We can show that certain finite volume – finite differences schemes for (1) can be deduced from the mixed dual formulation: (2) $(p,u) \in X, \int_\Omega (p, q + u\, div\, q + v\, div\, p + fv) = 0, \quad \forall (q,v) \in X$ with $X = H(div;\Omega) \times L^2(\Omega)$, after discretization by the Raviart-Thomas element of lowest order and explicit elimination of the vector field p_h. For some particular situations, the elimination can be done on the "exact" discrete problem. For general situations, we have used special numerical integration formulas diagonalizing the matrix corresponding to $\int_\Omega p_h, q_h$, and thus allowing explicit elimination.
This relation of finite volume schemes to mixed finite element allows to deduce error estimates in L^2-norm for the finite-volume directly from the theory of mixed f.e.m.
Our methadology can be applied to more general problems than the model one....

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J. Molenarr

A Cell-Centered Multigrid Method for 3D Interface Problems

A multigrid method is presented for the cell-centered finite volume discretization of symmetric, second order, elliptic boundary value problems. These problems typically involve strong anisotropies and inhomogenities. We focus on the construction of the coarse grid operators needed in the multigrid algorithm. The usual approach is to construct these coarse grid operators as the Galerkin approximation of the finest grid operator, given the grid transfer operators. The disadvantage of this approach is that the coarse grid stencil are often denser then the finest grid stencil. Moreover, the coarse grid matrices may loose the M-matrix property.

These problems are avoided if the coarse grid operators are constructed by finite volume discretizations on the coarse grids. We discuss the definition of the coarse grid coefficients, and show results for several hard test problems.

K.W. Morton

Cell Vertex Finite Volume Algorithms

We first review the types of problem for which finite volume methods might be expected to show to advantage: steady problems, governed by conservation laws, with rapid solution variation in complicated geometries. Then we review the attractive features of the cell vertex scheme through 1D first order systems, 1D & 2D convection-diffusion, 2D & 3D Euler and Navier-Stokes equations; this shows the key algorithmic elements in the scheme - construction of the cell residuals using gradient recovery, distribution matrices and artificial dissipation to obtain the nodal residuals, and the subsequent iteration. Recently achieved improvements and further required improvements in these elements are described.

Rolf Rannacher

Finite Volume and Finite Element Discretizations on Anisotropic Meshes

In many applications of finite volume or finite element methods the use of anisotropically refined meshes is dictated by the structure of the solution to be computed (e.g., boundary or interior layers). Traditionally the convergence and error analysis of these methods is given only for quasi-uniform meshes which may allow for local mesh refinement but normally excludes anisotropies. In the presence of mesh deteriorations important properties of the discretization like consistency or stability may get lost depending on the particular characteristics of the method. In this lecture some questions concerning the behavior of standard finite element schemes for elliptic problems including the Stokes problem are discussed. Some of these schemes need special treatment to make them suitable for use on anisotropic

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meshes. Through the consideration of numerical integration many of the obtained results carry over to certain finite volume methods.

Uwe Risch

Cell Centre FVM for Elliptic Equations on General Quadrilateral Grids

A set of cell centre F.V. schemes for discretizing diffusion terms is constructed in a unified manner as nonconforming F.E. schemes. This framework includes box methods for F.E. spaces as well as staggered grid methods on tensor product meshes.

As a conclusion, elliptic error analysis (reproducing the known results for standard schemes) can be done as straightforward as for FEM.

As a further example, a non-standard, convergent (O(h)), 5-point scheme is proposed living on quadrilateral (not necessarily smooth deformations of tensor product) meshes of control volumes.

H.-G. Roos

Uniformly Convergent Methods for Singular Perturbation Problems via Finite Volume Approaches

We are interested in numerical methods for singularly perturbed boundary value problems of the form

$$-\epsilon\Delta u + b\nabla u + cu = f.$$

It is desirable that a method used should approximately solve the given problem with an accuracy independent of the value of the parameter ϵ.
In the one-dimensional case some finite volume approaches lead to the Il'in and related scheme, which are known to be uniformly convergent.
In two dimensions, however, the situation is different. For a special box scheme L. Angermann proved that the Il'in weight does not lead to uniform convergence. However, there exists a finite volume element method based on an exponential trial space which seems to lead to nodal first order uniform convergence.

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Endre Süli

Analysis of Cell-Vertex Finite Volume Methods

We present an analysis of the cell-vertex finite volume method for symmetric positive systems in the sense of Friedrichs of elliptic and hyperbolic type with variable coefficients. For symmetric hyperbolic systems the scheme is shown to be second-order convergent in the L_2-norm provided the characteristic curves of the differential operator are transversal to mesh lines. When characteristics are parallel to mesh lines on a set of positive measure the scheme is only first-order convergent. However if transversality fails on part of the outflow boundary only then the cell vertex scheme is second-order convergent in a weighted L_2-norm. For elliptic Friedrichs systems, such as the Cauchy-Riemann equations, we derive optimal error bounds in a mesh-dependent H^1-norm by exploiting the Babuška-Brezzi condition.

Lutz Tobiska

Finite Volume Techniques for Constructing Stabilized Finite Elements

We consider numerical methods for solving the Boussinesq approximation of the incompressible Navier-Stokes equations. A stabilized numerical method is developed by using finite volume techniques for the convective term and mixed finite element methods for the remaining parts of the equations. The approximation by nonconforming $P1/P0$ elements satisfies the discrete Babuška-Brezzi condition with a constant that is independent of the meshsize and the shapes of the triangles. In order to handle the effect of dominated convection an upwind technique has been applied. A careful study of the error constants for the "no flow" problem still shows a linear dependence on the Reynolds number Re. Adding a term of the form $\sum_E \int_E [u_h]_E [v_h]_E dx$ to the momentum equation, the dependence of the error constant is reduced to $\sqrt{Re}$.

Panayot S. Vassilevski

Mixed Finite Element Approximation of Elliptic Problems and the Interior Penalty Method

The mixed finite element discretization method (m.f.e.) for solving second order elliptic problems is studied in connection with the cell-centered finite volume discretization method. An equivalence between a non-local, in general, bilinear form corresponding to the pressure unknown in the m.f.e. method with a bilinear form coming from the so-called interior penalty method is a key relation that allows us to approximately localize the operator (a discrete analog of the, e.g., Laplace operator) for the pressure unknown. On the basis of the interior penalty bilinear form one is then able to construct various powerful solution techniques for the original saddle-point problem. We consider two efficient ways of constructing

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preconditioners for the cell-centered bilinear form; namely a multigrid method and an additive Schwarz method. The difficulty here is that the corresponding discretization spaces consist of discontinuous piecewise polynomials, i.e., those are only L^2 subspaces and not H^1. Some numerical illustration of the presented methods is given.

Gerald Warnecke

Adaptive Finite Volume Methods

The work presented has the aim to efficiently calculate steady transonic flows. In the inviscid case the equations are of composite type, i.e. partially elliptic and hyperbolic. The flows contain shocks that are modeled by discontinuities in the solution. In order to gain insight into possible error estimation techniques some model problems were studied together with E. Süli, J. Mackenzie and Th. Sonar.

One of them are the linear positive symmetric systems of Friedrichs, as these provide a unified treatment of elliptic, hyperbolic, parabolic and mixed type (e.g. Tricomi's equation). In the talk some a posteriori error estimates were presented. These were backed up by numerical experiments in J. Mackenzie's talk. The important feature is to estimate the error by appropriate norms of the residual and to localize the results.

Pieter Wesseling

Finite Volume Discretization of Singular Perturbation Problems

Cell-centered discretization of the convection-diffusion equation on arbitrary Cartesian grids is inconsistent in the maximum norm. By means of an expansion for the global error and application of the maximum principle it is shown that nevertheless the global error is second order accurate. Next, the dependence of the error on the Péclet number Pe as $Pe \to \infty$ is studied in the presence of a parabolic boundary layer. It is shown theoretically that by suitable mesh refinement in the boundary layer and by using upwind discretization the error is first order uniformly in Pe. The number of grid cells increases as $lnPe$. Numerical experiments show that this is also true for a Pe-independent number of cells, and that with central discretization the error is second order uniformly in Pe.

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Monika Wierse

Higher Order Upwind Schemes for the Compressible Euler Equations in 3D

I shall present a numerical algorithm to solve the non-stationary three-dimensional compressible Euler equations in complex time-dependent geometries. This algorithm is an upwind finite volume method working on a grid of tetrahedra. I shall present a new cell-centered finite volume scheme of second order in space working on a grid of simplices. This approach is motivated by a theoretical result of convergence in the case of scalar conservation laws in two space dimensions. For the local adaption of the grid a criterion is necessary which controls the fineness of the grid according to the numerical error of the numerical scheme. An approach based on the residuum is well motivated for scalar conservation laws in 1D with a result of Tadmor. Therefore an interpretation of the residuum approach for the system of the Euler equations will be discussed. A new approach to model the moving boundary in a conservative manner will be presented and applied to an automotive application.

Walter Zulehner

Industrial Flow Problems in Steel Production

Three typical flow problems in steel production are presented:

- the flow and erosion process of liquid iron in the hearth of a blast furnace,
- the gas-stirred flow in an steel ladle and
- the flow of liquid steel in the continuous casting mould.

In cooperation with industry a code based on a finite volume method has been developed for solving such problems.

First preliminary results for the problems mentioned above are shown.

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