Tagungsbericht 17/1995

Multilevel Methods and Applications

30.04.-06.05.1995

The meeting was organised by W. Hackbusch (Kiel), P. Hemker (CWI Amsterdam), and G. Wittum (Stuttgart). During the 5 days of the conference, 28 talks were given, 42 scientists from Germany (#25), USA (#8), Netherlands (#5), Austria (#1), Belgium (#1), Czech(#1), and France (#1) participated. The centre of interest were new developments in multigrid methods and related subjects. To sketch the fields of subjects, the following keywords are given:

a posteriori error estimates,
algebraic multi-grid,
cascadic multi-grid,
coarsening,
convection-diffusion equation,
domain decomposition - Schwarz method,
frequency decomposition multi-grid,
frequency filtering,
Navier-Stokes equation,
parallelisation,
plane smoother,
mg for integral equations,
multilevel extrapolation,
nonconforming / nonnested multi-grid.

The organisers and participants thank the 'Mathematischem Forschungsinstitut Oberwolfach' to make the conference possible in the usual comfortable and inspiring setting. The abstracts follow in the order as the lectures are given.

Monday, May 1, Morning Session

P. Wesseling, C. Vuik, S. Zeng:

MULTIGRID SOLUTION OF THE INCOMPRESSIBLE NAVIER-STOKES EQUATIONS IN GENERAL COORDINATES

Implicit time discretization of the incompressible Navier-Stokes equations on staggered grids in general coordinates with central discretization of the convection terms leads, with the pressure correction method, to large algebraic systems for the velocity and pressure unknowns. We apply (combinations of) multigrid and Krylov subspace methods with ILU and line-Jacobi preconditioning. The aim is to have efficiency and robustness on highly distorted computational grids, and concurrent processing potential. It is found that for the momentum equations GMRES/ILU is most suitable, whereas for the pressure multigrid with ILU smoothing, accelerated by GCR (generalized conjugate residuals) is best. GCR acceleration of a given method is found to be never detrimental, and often beneficial.

K. Oosterlee:

A GMRES-BASED PLANE SMOOTHER IN MULTIGRID TO SOLVE THREE-DIMENSIONAL ANISOTROPIC FLUID FLOW PROBLEMS

For a discretization of the three-dimensional steady incompressible Navier-Stokes equations a solution method is presented for solving flow problems on stretched grids. The discretization is a vertex-centered finite volume discretization with a flux splitting approach for the convective terms. Second order accuracy is obtained with defect correction. The solution method used is multigrid, for which a plane smoother is presented for obtaining good convergence in flow domains with severely stretched grids. A matrix is set up in a plane, which is solved iteratively with a preconditioned GMRES method. A stop criterion for GMRES is investigated which reduces the number of inner iterations compared to an 'exact' plane solver without affecting the multigrid convergence rates. It is found that the algorithm is very efficient for stretched Poisson problems. The algorithm produced good results, when the GMRES plane solver was stopped after the initial residuals are diminished by a factor of 10. For the method with the plane smoother similar wall-clock times are obtained as for an alternating line smoother, while the convergence with the line smoother was not satisfactory for the Poisson problem considered. For grid stretching in one direction for incompressible model flow problems the plane smoother was beneficial for cell aspect ratios of more than factor 50 for several flow problems at different Reynolds numbers. Here, the defect correction algorithm with the GMRES plane solver produced identical results as an 'exact' plane solver, when the GMRES iterations were stopped after the initial residuals were diminished by a factor of 100.

E. Dick:

MULTIGRID METHODS FOR NAVIER-STOKES EQUATIONS COUPLED TO k-ϵ TURBULENCE EQUATIONS IN COMPRESSIBLE TRANSITIONAL FLOWS

The equations describing compressible transitional flow are first discussed. These consist of a laminar set of Navier-Stokes equations coupled by source terms to a turbulent set of Navier-Stokes equations. The turbulent set includes two turbulence equations (k-ϵ). The coupling source terms express the interaction between turbulent and laminar parts in the flow field. These terms depend on gradients of the intermittency factor. The factor itself is described by a convection-diffusion-source equation. In two dimensions, a set of 11 coupled equations (4 laminar + 6 turbulent + 1 intermittency) is obtained. The dynamics of the set are very much governed by the source terms. The set is solved in a partially decoupled way in the sense that a multigrid method is applied to the laminar and the turbulent set separately while the interactive source terms are updated in an outer cycle. In the turbulent part of the flow equations, the source terms in the k-e equations are included in the multigrid procedure.

Several effects cause bad multigrid performance: the destruction of the smoothing by the action of the source terms in the k-e equations, the convective stiffness of the equations due to very low convective velocities compared to the acoustic velocity near walls and the diffusive stiffness due to the practical impossibility to use a sufficiently refined grid near walls causing the diffusive terms to be almost negligible with respect to the acoustic terms.

D. Hänel:

COMPUTATIONS OF COMPRESSIBLE, STRONGLY UNSTEADY FLOWS ON ADAPTIVE, UNSTRUCTURED GRIDS USING A "MULTI-SEQUENCE RUNGE-KUTTA METHOD"

Unsteady flow are of large importance in fluid dynamics. Typical examples are viscous, separable and vortical flows or chemical driven flow.

Computations of such flows are very time consuming, mainly due to the small scales in time to be resolved. Therefore several studies are made to improve the performance of algorithms. Former studies based a time-consistent FAS multigrid applied to explicit time-stepping scheme have shown only moderate success.

Better performance was achieved with the so-called Runge-Kutta Method with Multi-Sequences, which reduces the severe stability restrictions of an explicit scheme.

In this way the stability limit for Δt could be satisfied nearly locally by ordering the grid cells in groups of similar size.

Time consistency could be preserved by a suited synchronization of the Runge-Kutta Scheme. Comparative studies have shown a gain in CPU of a factor 5 to 10 compared to standard Runge-Kutta and of 2 to 5 compared to the unsteady FAS-multigrid.

Monday, Afternoon Session

U. Rüde:

IMPLICIT MULTILEVEL EXTRAPOLATION METHODS

Multilevel methods can be combined naturally with extrapolation-like techniques for raising the approximation order. A special algorithm of this type is the τ-extrapolation method for multigrid algorithms. This technique presents an implicit application of the extrapolation principle that does not need global asymptotic error expansions. It is therefore well suited to be used locally in combination with local grid refinement. The analysis of these methods is based on asymptotic error expansions for combined differentiation/integration rules in combination with appropriate stability conditions.

J. E. Dendy:

VARIANTS OF THE FREQUENCY DECOMPOSITION MULTIGRID METHOD

We discuss several variants of the frequency decomposition method motivated by an application to global ocean modeling. It is shown how to achieve robustness for problems with anisotropic and discontinuous coefficients, and the application in global ocean modeling is discussed.

R. Stevenson:

FREQUENCY DECOMPOSITION MULTILEVEL METHODS

Without a special choice of a smoother, a standard multi-grid method is not robust for anisotropic second order boundary value problems. In three dimensions suitable smoothers with reasonable costs are hard to find. For this reason Hackbusch proposed in '88 the so-called Frequency Decomposition (FD) multi-level method for application to tensor product grids. The characteristic feature of this method is the use of more than one coarse-grid correction in which case the smoother can be dropped.

In a somewhat modified form, the FD method can be seen as an additive Schwarz preconditioner based on a multiscale decomposition of the finite element space into a set of spaces that are mutually orthogonal w.r.t. discrete (but (L_2)-like) scalar products. In this talk, we will show how this concept can be applied to general nested sequences of finite element spaces, including those that correspond to locally refined grids. The resulting preconditioners have optimum condition numbers for zeroth and second order problems and are suitable for application to anisotropic problems.

Tuesday, 2nd, Morning Session

S. Vandewalle, M. Holst:

SCHWARZ METHODS: TO SYMMETRIZE OR NOT TO SYMMETRIZE

We present a preconditioning theory for Schwarz methods. The theory establishes sufficient conditions for multiplicative and additive multi-level Schwarz methods to yield self-adjoint positive definite preconditioners. It is applied to multigrid and domain decomposition methods. The theory does not require any variational conditions to be satisfied, and allows for the use of non-convergent Schwarz methods as preconditioners.

We show that symmetrizing may be a bad idea for linear methods. We conjecture that enforcing minimal symmetry achieves the best results when combined with conjugate gradient acceleration. Also, it is shown that absence of symmetry in the linear preconditioner is advantageous when the linear method is accelerated by using the Bi-CGstab method.

Numerical examples are presented for two test problems which illustrate the theory and conjectures.

A. Meyer:

PRECONDITIONING THE PSEUDO-LAPLACIAN FOR CFD-SIMULATION

If the simulation of time-dependent incompressible flow uses finite elements and some idea of projection methods that require the solution of a pressure correction equation, a linear system of the type $B^T M_L^{-1} B\tilde{p} = -B^T\tilde{u}$ arises. In order to use hierarchical techniques for efficient preconditioning this matrix, we proved the spectrally equivalence to a true "Laplacian". The introduction of a coarse mesh solver causes some problems due to the fact that often no 1st type boundary conditions for the pressure are possible. It is discussed how to overcome this difficulty.

M. Jung:

ON THE PARALLELIZATION CF MULTI-GRID METHODS USING A NON-OVERLAPPING DD-DATA STRUCTURE

We discuss the parallelization of multi–grid methods using a non–overlapping domain decomposition data structure. The algorithms are implemented on parallel machines with MIMD architecture.

Especially, we propose a new variant of a parallel smoothing procedure of Gauss–Seidel type which needs the same communication as a Jacobi smoother. For solving the systems of algebraic equations on the coarsest grid we use the preconditioned conjugate gradient method applied to the corresponding Schur complement system.

Numerical examples show the efficiency of our algorithms.

G. Haase, U. Langer:

DIRICHLET DOMAIN DECOMPOSITION VERSUS GLOBAL MULTIGRID METHODS

This talk presents some new results in the development of fast Dirichlet ASM-DD-preconditioners and compares the DD-preconditioned conjugate gradient (cg) method with a global multigrid method parallelized on the basis of some non-overlapping domain decomposition (DD) data structure. The most sensitive part in the Dirichlet DD-preconditioner is the approximate execution of the operation

$$\underline{v}_I = -K_I^{-1} K_{IC} \underline{w}_C \qquad \text{(harmonical extension)}$$

which will be done by a hierarchical extension technique with an exact harmonical extension on the coarsest level and postsmoothing sweeps ($S_{I,k}$ - Gauss-Seidel smoother) on all other levels :

$$\begin{aligned} \tilde{E}_{IC,2} &= S_{I,2}^{\nu_2}\left[Q_{I,2}K_{I,1}^{-1}(-K_{IC,1}) + Q_{IC,2}\right]Q_{C,2}^{-1} \\ \tilde{E}_{IC,k} &= S_{I,k}^{\nu_k}\left[Q_{I,k}\tilde{E}_{IC,k-1} + Q_{IC,k}\right]Q_{C,k}^{-1} \qquad \forall k = \overline{3,\ell}, \end{aligned}$$

where Q is the transformation from the hierarchical basis into the usual FE-nodal basis and $K = K^T$ p.d. denotes the finite element stiffness matrix the block partitioning $(K_C, K_{CI} : K_{IC}, K_I)$ of which corresponds to the DD as usual. Due to the fact that E_{IC}^T includes the first part of a V-multigrid-cycle an algorithmic improvement results additionally in a cheaper preconditioner. A parallelized version of the cg-method using this DD-preconditioner solves a linear system of equations (magnetic field of an electrical motor, complex interface geometry, large jumps in the coefficients, FEM-discretization) with 375 000 unknowns in 46 seconds on the PowerXplorer with 16 processors.

A parallelized global multigrid solver using the same DD data structures (talk of M. Jung) is approximately 3 times faster on the finer grid for the same problem on the same computer. However, the DD methods offer the opportunity to couple FEM and BEM. Thus, the combination of both methods can be quite useful.

Tuesday, Afternoon Session

S. Brenner:

CONVERGENCE OF NONCONFORMING OR NONNESTED MULTIGRID METHODS WITHOUT FULL ELLIPTIC REGULARITY

We consider nonconforming or nonnested multigrid methods for second and fourth order elliptic boundary value problems which do not have full elliptic regularity. We prove that the contraction number of the W-cycle algorithm with a sufficiently large number of smoothing steps is bounded away from 1 uniformly. We also show that the symmetric variable V-cycle algorithm is an optimal preconditioner.

S. Turek:

ON ROBUST AND EFFICIENT MULTILEVEL SCHUR-COMPLEMENT SOLVERS FOR THE INCOMPRESSIBLE NAVIER-STOKES EQUATIONS

We present multilevel acceleration techniques for the "discrete projection methods" which are discrete versions of the well known continuous projection schemes (cf. Chorin, van Kan). We show that, in combination with special smoothing operators in additive form, these methods are very efficient for stationary as well as nonstationary calculations, and that this approach seems to have no problems with gird anisotropies. Numerical test confirm our theoretical considerations.

D. Braess:

EFFICIENT SMOOTHING OF THE NAVIER-STOKES EQUATIONS BY U-DOMINANT ITERATIONS

When iterations for the solution of a saddle point problem

$$\begin{pmatrix} A & B^T \\ B & \end{pmatrix} \begin{pmatrix} u \\ p \end{pmatrix} = \begin{pmatrix} f \\ g \end{pmatrix}$$

are investigated as smoothers, a classification is helpful:

An iteration is called u-dominant or direct (p-dominant or Schur complement iteration, resp.) if (u_{k+1}, p_{k+1}) mainly depends on u_k (on p_k, resp.). SIMPLE C turns out to be p-dominant and not to be a good smoother.

A u-dominant iteration which is a good smoother is obtained when the given equation is approximately solved via

$$\begin{pmatrix} \alpha I & B^T \\ B & \end{pmatrix} \begin{pmatrix} u \\ p \end{pmatrix} = \begin{pmatrix} f \\ g \end{pmatrix}$$

and if $g = 0$. The crucial point is the fact that the new values do not depend on the old approximation of p. The iteration is known from the pressure correction method, but is a big difference whether $f = 0$ or $g = 0$.

Wednesday, 3rd, Morning Session

M. Feistauer:

NUMERICAL SOLUTION OF NONLINEAR CONVECTION-DIFFUSION PROBLEMS

The paper is concerned with numerical solution of nonlinear convection-diffusion problems appearing mainly in fluid dynamics. The method is based on upwind flux vector splitting finite volume schemes on unstructured grids used for the discretization of nonlinear convective terms, combined with the finite element approximation of viscous dissipative terms The resulting scheme can be treated as a fully implicit, semiimplicit or purely explicit method. Special attention is devoted to a suitable adaptive technique for precise shock capturing. The combined finite volume-finite element scheme is theoretically studied on a model nonlinear scalar conservation law equation with a diffusion term. Namely, the convergence of the scheme is proved with the aid of suitable a priori estimates, discrete maximum principle and some compactness results. The method is applied to the numerical simulation of viscous compressible flow. Some computational results will be presented.

A. Reusken:

MULTIGRID FOR CONVECTION-DIFFUSION EQUATIONS

In this talk we consider a two-grid method based on approximation of the Schur complement. We study the dependence of the two-grid convergence rate on certain problem parameters. As test problem we take the rotated anisotropic diffusion equation and the convection-diffusion equation. Using Fourier analysis and discrete Greens functions we analyze the robustness of the two-gird method w.r.t. variation in the relevant problem parameters. For the multigrid we use a standard W-cycle. This multigrid method then has the same algorithmic structure as a standard multigrid method and is fairly efficient. Moreover, when applied to the two test problems then, as in the two-grid method, we have a strong robustness w.r.t. variation in the problem parameters. This is shown by numerical results for the test problems.

J. Fuhrmann:

ON ALGEBRAIC MULTILEVEL METHODS FOR PARTIAL DIFFERENTIAL EQUATIONS

It is well known that in the one-dimensional case, the method of cyclic reduction can be interpreted as an exact multigrid method with operator dependent transfer operators. Starting with this observation, a more or less heuristic scheme is discussed which allows the derivation of multigrid components in higher dimensions.

Within this framework, a multigrid method for two- and three-dimensional logically orthogonal meshes is described. It works well for both symmetric and nonsymmetric problems and show robustness with respect to coefficient jumps not aligned to coarse mesh boundaries.

Further, a generalization to the case of unstructured meshes is proposed which allows the implementation of an algebraic multilevel method which is able to utilize structure information if possible.

Numerical examples for bot methods are discussed.

Thursday, 4th, Morning Session

N. Neuß:

HOMOGENIZATION AND MULTIGRID

For a linear elliptic equation of second order with oscillating coefficients (possibly with large jumps) we show convergence of a multilevel method that uses a coarse grid problem generated by a homogenization technique. This is a step towards real multiscale methods, and it also may influence the development of more efficient geometric-algebraic multigrid methods.

P. Oswald:

MULTILEVEL PRECONDITIONERS FOR NONCONFORMING DISCRETIZATIONS

We review recent approaches to preconditioners of hierarchical basis and BPX-type for nonconforming discretizations of second and fourth order elliptic boundary value problems. There are two main directions at present:

- Multilevel splittings of a nonconforming finite element space can be obtained from the natural sequence of nonconforming coarse grid spaces by using an appropriately designed set of intergrid transfer operators. Except for some simple cases, the control of all perturbations arising in a nonconforming setting remains a nontrivial task.
- The multilevel decomposition can be inherited from another element type. In this case (which is easier to deal with theoretically but depends on existing conforming preconditioning methods), the only issue is the design of an accurate two-level method to switch to the reference element.

Both approaches can be based on the additive Schwarz setting and complemented by adaptivity strategies. As an illustration, some specific element types (P1, rotated Q1, Morley, Zienkiewicz, nonconforming P1-P0 Stokes element) are discussed.

J. Junkherr:

MULTIGRID METHODS FOR WEAKLY SINGULAR INTEGRAL EQUATIONS OF 1ST KIND

The integral equation of 1st kind

$$Du = f\,,$$

with

$$D : H^{\gamma}(\Gamma) \to H^{-\gamma}(\Gamma)\,,\ \gamma < 0 \qquad (*)$$

is considered. Due to the negative order of the operator D, "classical" multigrid methods do not work efficiently: the smoothing iteration does not damp the oscillating parts of the error. A strategy is presented, how to design smoothing iterations for problem (*). Essential for this strategy is the construction of a prewavelet basis of boundary elements on general surfaces. By taking a simple ansatz, not depending on the well-known "refinement equation", it is possible to construct a prewavelet basis on Lipschitz surfaces. Numerical results show the efficiency of the constructed multigrid methods.

R. Kornhuber:

A POSTERIORI ERROR ESTIMATES FOR ELLIPTIC PROBLEMS

Let $u \in H$ be the exact solution of a given self-adjoint elliptic boundary value problem, which is approximated by some $\tilde{u} \in S$, S being a suitable conforming finite element space. Efficient and reliable a posteriori estimates of the error $\|u - \tilde{u}\|$, measuring the (local) quality of $\tilde{u}$, play a crucial role in termination criteria and in the adaptive refinement of the underlying mesh. A well-known class of error estimators can be derived systematically by localizing the discretized defect problem using domain decomposition techniques.

In our talk, we provide a guideline for the theoretical analysis of such error estimators. We further clarify the relation to other concepts. Our analysis leads to new error estimates, which are specially suited to three space dimensions. The theoretical results are illustrated by numerical computations.

Thursday, Afternoon Session

R. Bank, J. Xu:

AN ALGORITHM FOR COARSENING UNSTRUCTURED MESHES

We develop and analyze 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 analyze 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 for the usual case of structured, locally refined meshes. In particular, we show that the generalized condition numbers for such iterative methods are of order J^2, where J is the number of hierarchical basis levels.

S. Sauter, W. Hackbusch:

COMPOSITE FINITE ELEMENTS FOR THE APPROXIMATION OF PDES ON DOMAINS WITH COMPLICATED MICRO-STRUCTURES

Usually, the minimal dimension of a finite element space is closely related to the geometry of the physical object of interest. This means that sometimes the resolution of small micro-structures in the domain requires an inadequately fine finite element grid from the viewpoint of the desired accuracy.

This fact limits also the application of multi-grid methods to practical situations because the condition that the coarsest grid should resolve the physical object often leads to a huge number of unknowns on the coarsest level.

We present here a strategy for coarsening finite element spaces independently of the shape of the object. This technique can be used to resolve complicated domains with only few degrees of freedom and to apply multi-grid methods efficiently to PDEs on domains with complex boundary.

In this talk we will prove the approximation property of these generalized FE spaces.

R.H.W. Hoppe:

ADAPTIVE MULTILEVEL METHODS FOR MIXED FINITE ELEMENTS

We consider adaptive multilevel methods for mixed finite element discretization of second order elliptic boundary value problems. Emphasis is on the efficient iterative solution of the mixed discretized problems by multilevel preconditioned cg-iterations and on an efficient and reliable a posteriori error estimator as a criterium for local grid refinement. The multilevel preconditioner is constructed by means of appropriate multilevel decompositions of the mixed ansatz spaces. On the other hand, a cheaply computable a posteriori error estimator can be obtained by the principle of defect correction in higher order mixed ansatz spaces combined with a localization by a hierarchical two-level splitting of these ansatz spaces. The performance of the solution process and the error estimation is illustrated by numerical experiments.

Friday, 5th, Morning Session

F. Bornemann:

CASCADIC MULTIGRID METHODS

The theory of cascadic multi-grid methods will be presented taking adaptive, non-uniform triangulations into consideration. Numerical experiments will illustrate that interchanging the smoothing and approximation property of standard multi-grid methods is essential.

C. Wagner:

FREQUENCY FILTERING DECOMPOSITION

The frequency filtering decomposition, introduced by Wittum in 1992, are a special kind of incomplete block decompositions. With a suitable choice of test vectors smoothers or correctors can be constructed. The tangential frequency filtering decomposition and the adaptive testvector concept are presented. A possibility for the treatment of unsymmetric matrices with (tangential) frequency filtering decompositions is described. Using these methods the pollutant transport in an aquifer is simulated. Finally, some physical and numerical results are presented.

P. Vanek, J. Mandel, M. Brezina:

ALGEBRAIC MULTIGRID FOR ELASTICITY AND THIN ELASTICITY

The purpose of this talk is to report on a progress in the development of algebraic multigrid methods which have been described recently at a workshop in Meissdorf. More precisely, we will demonstrate the performance of the method for thin elasticity problems.

We present a rule-based automatic coarsening technique for discretized elliptic problems and their singular perturbations, particularly plates, shells and thin solids. The key idea of the coarsening procedure is a smoothing by Jacobi-like smoothers of prolongation operators given by aggregation. For uniformly V-elliptic problems or anisotropic problems, the coarsening process requires only the stiffness matrix. In the case of more difficult problems as, e.g., insufficient essential boundary condition, thin solids, plates, and shells, we need additional geometric input, namely the algebraic representation of the kernels of the bilinear form away from the essential boundary conditions, i.e., rigid body motions in the case of elasticity. The theory for scalar problems with H^1-equivalent forms is developed. The performance of the algorithm will be demonstrated on several real-life problems of structural mechanics.

W. Mulder, G. Meijling, G. Schmidt (†):

APPLICATION OF MULTIGRID TO POROUS MEDIA FLOW

The equations for incompressible, immiscible, two-phase porous media flow represent a highly simplified model for oil reservoir simulation. A common approach is to combine the incompressibility condition and Darcy's law into one equation for the total pressure. This equation is elliptic for given saturation. The saturation equation is parabolic for a fixed pressure field. Because the pressure often evolves on a much longer time scale than the saturation, operator splitting is often used, Here, the pressure equation is discretized by the lowest-order mixed finite elements of Raviart and Thomas, for locally refined blocks. The resulting linear system is solved by multigrid. A non-standard approach to operator weighting is used. The parabolic equation is split into a hyperbolic part that is integrated either by a non-conservative nonlinear characteristic method or by a conservative second order upstream scheme, and diffusive part that is treated implicitly.

Operator splitting is shown to fail for certain problems, in particular for highly unstable displacement or for gravity driven problems. This failure can be repaired, but at the expense of computational efficiency.

An alternative to operator splitting is the use of nonlinear multigrid for the coupled system of equations. Results for a homogeneous but strongly anisotropic two-dimensional problem are presented.

Berichterstatter: S. Sauter

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