Multilevel techniques for Reservoir Simulation

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The subject of this thesis is the development, application and study of novel multilevel methods for the acceleration and improvement of reservoir simulation techniques. The motivation for addressing this topic is a need for more accurate predictions of porous media flow and the ability to carry out these computations in a timely manner. This will lead to better decision making in the production of oil and gas. The goal is attained in various ways throughout the thesis work. Specifically, three fields of multilevel methods have been addressed in this work, namely

• Nonlinear multigrid (the Full Approximation Scheme)
• Variational (Galerkin) upscaling
• Linear solvers and preconditioners

First, a nonlinear multigrid scheme in the form of the Full Approximation Scheme (FAS) is implemented and studied for a 3D three-phase compressible rock/fluids immiscible reservoir simulator with a coupled well model. In a fair way, it is compared to the state-of-the-art solution scheme used in industry and research simulators. It is found that FAS improves time-to-solution by having a larger basin of attraction, faster initial convergence, data locality and a lower memory footprint. The study is extended to include a hybrid strategy, where FAS is combined with Newton’s method to construct a multilevel nonlinear preconditioner. This method demonstrates high efficiency and robustness.

Second, an improved IMPES formulated reservoir simulator is implemented using a novel variational upscaling approach based on element-based Algebraic Multigrid (AMGe). In particular, an advanced AMGe technique with guaranteed approximation properties is used to construct a coarse multilevel hierarchy of Raviart-Thomas and L2 spaces for the Galerkin coarsening of a mixed formulation of the reservoir simulation equations. By experimentation it is found that the AMGe based upscaling technique provided very accurate results while reducing the computational time proportionally to the reduction in degrees of freedom. Furthermore, it is demonstrated that the AMGe coarse spaces (interpolation operators) can be used for both variational upscaling and the construction of linear solvers. In particular, it is found to be beneficial (or even necessary) to apply an AMGe based multigrid solver to solve the upscaled problems. It is found that the AMGe upscaling changes the spectral properties of the matrix, which renders well-known state-of-the-art solvers for this type of system useless.

Third, FAS is combined with AMGe with guaranteed approximation properties to obtain a nonlinear multigrid solver for unstructured meshes. The FAS-AMGe solver is applied to a simplistic but numerically challenging mixed (velocity/pressure) model for porous media flow. In a fair way, FAS-AMGe is compared to Newton’s method and Picard iterations. It is found that FAS-AMGe is faster for the cases considered.

Finally, a number of multigrid linear solvers and preconditioners are implemented for various linear systems. In particular AMGe are used in the construction of multigrid preconditioners. These are compared to two state-of-the-art block diagonal preconditioners based on 1) a Schur complement with an Algebraic Multigrid (AMG) solver and 2) an augmented Lagrangian formulation using the Auxiliary Space AMG solver.

In addition to the research mentioned above, a sequential in-house COmpositional reservoir SImulator (COSI) with many features is parallelized in a distributed setting (MPI) using the PETSc framework. A parallel preconditioner based on the Constrained Pressure Residual method, Algebraic Multigrid and Restricted Additive Overlapping Schwarz with Incomplete LU solves on each subdomain is implemented. It is found that switching the traditionally used method, namely parallel ILU, with Restricted Additive Overlapping Schwarz results in a significant increase in parallel scalability while still maintaining similar robustness and efficiency.

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