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Scalable Implicit / IMEX Resistive MHD with Stabilized Finite Element Methods and Fully-coupled Newton-Krylov-AMG Solution Methods

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Scalable Implicit / IMEX Resistive MHD with Stabilized Finite Element Methods and Fully-coupled Newton-Krylov-AMG Solution Methods*

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Abstract

The resistive magnetohydrodynamics (MHD) model describes the dynamics of charged fluids in the presence of electromagnetic fields. MHD models are used to describe important phenomena in the natural physical world and in technological applications. This model is non-self adjoint, strongly coupled, highly nonlinear and characterized by multiple physical phenomena that span a very large range of length- and time-scales. These interacting, nonlinear multiple time-scale physical mechanisms can balance to produce steady-state behavior, nearly balance to evolve a solution on a dynamical time-scale that is long relative to the component time-scales, or can be dominated by just a few fast modes. These characteristics make the scalable, robust, accurate, and efficient computational solution of these systems extremely challenging. For multiple-time-scale systems, fully-implicit methods can be an attractive choice that can often provide unconditionally-stable time integration techniques. The stability of these methods, however, comes at a very significant cost, as these techniques generate large and highly nonlinear sparse algebraic systems of equations that must be solved at each time step.

This talk describes the development of a scalable fully-implicit / IMEX stabilized unstructured finite element (FE) capability for 3D resistive MHD. The brief discussion considers the development of the stabilized / variational multiscale (VMS) FE formulation and the underlying fully-coupled preconditioned Newton-Krylov (NK) nonlinear iterative solver. The VMS formulation and the fully-coupled NK solution methods allow the simulation of flow systems that range from incompressible to low Mach number compressible flows, as well as the development of a number of solution methods beyond forward simulation. The solution methods include parameter continuation, bifurcation, optimization, and adjoint-based methods for sensitivity analysis, error-estimation and UQ.

To enable robust, scalable and efficient solution of the large-scale sparse linear systems generated by the Newton linearization, fully-coupled multilevel preconditioners are developed. The multilevel preconditioners are based on two differing approaches. The first technique employs a graph-based aggregation method applied to the nonzero block structure of the Jacobian matrix. The second approach utilizes approximate block decomposition methods and physics-based preconditioning approaches that reduce the coupled systems into a set of simplified systems to which multilevel methods are applied. To demonstrate the capability of these approaches representative results are presented for the solution of challenging prototype MHD problems. These include duct flows, an unstable hydromagnetic Kelvin-Helmholtz shear layer, and an island coalescence problem used to model magnetic reconnection. In this context robustness, efficiency, and the parallel and algorithmic scaling of solution methods are discussed. Initial results that explore the scaling of the MHD solution methods are also presented on up to 256K processors for problems with up to 1.8B unknowns. (This is joint work with Roger Pawlowski, Eric Cyr, Edward Phillips, Ray Tuminaro, Paul Lin, and Luis Chacon.)

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