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Adaptive MHD Simulations using TSTT Technologies

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Summary

Simulating the necessary physics for fusion reactors is recognized as a serious computational challenge. One portion of the complete physics is magnetohydrodynamics (MHD) which contains sharp gradients and highly localized features in the fields. The RPI TSTT team is working with fusion scientists to develop simulation tools that accurately capture the necessary physics.

The goal of this effort is to develop high-order adaptive discretization technologies for solving MHD problems of importance to the fusion community. The governing equations used to simulate MHD for fusion reactors, the Extended MHD equations, are a set of coupled, time-dependent, non-linear partial differential equations. To solve these equations, researchers at Princeton Plasma Physics Laboratory (PPPL) developed the M3D-C1 code. M3D-C1 is a time dependent, structured mesh, finite element code that uses C^1 continuous reduced quintic shape functions. While this code is a significant improvement over previous codes, mesh adaptation is needed to efficiently capture the sharp gradients and highly localized features of the fields (see, e.g., Figure 1.)

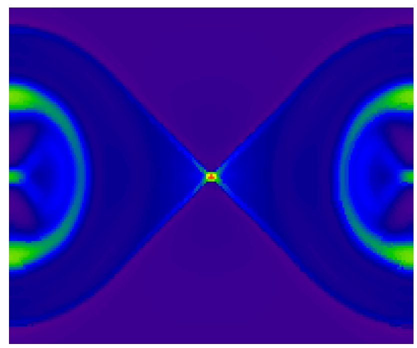

Figure . Contour plot of the component of current density vector normal to the plane for a magnetic reconnection simulation.

To meet application needs such as these, the Terascale Simulation Tools and Technologies (TSTT) Center provides unstructured mesh adaptation services. Researchers at RPI have collaborated with Steve Jardin (PPPL) to modify the M3D-C1 code to use TSTT unstructured meshes. The major obstacle in converting to an unstructured mesh formulation was modifying the computationally intensive computations needed to form the element matrix. For the structured code, a portion of the computations required$1.6*10^{10}$ operations for initialization and$1.0*10^5$ operations each time step for each combination of element shape and discretized governing term. This was deemed an acceptable cost for the structured mesh as there were only two element shape types and between three and twenty discretized governing equation terms (depending on the fidelity of the physics model). For an unstructured mesh where each element can have its own shape, this cost was unacceptably large.

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Working with the PPPL physicists, the RPI team developed a new method that utilizes interpolations to eliminate the initialization costs and requires $2.9*10^5$ operations per time step per element for each discretized governing equation term. This allows unstructured mesh simulations to run in reasonable time.

To demonstrate the impact of mesh adaptivity for Extended MHD simulations in more accurately capturing the gradients and localized field phenomena, an error indicator has been developed based on the jump in the second derivative of the magnetic flux on mesh edges. Target sizes for each mesh element are computed from this information to reduce the error indicator to an acceptable level over the mesh. The same TSTT mesh adaptation tools used on other applications, such as SLAC accelerator problems, are then used to modify the mesh to yield the desired element size distribution. An initial result is shown in Figure 2 where the adapted mesh accurately captures the tilting of an ideal column. This computation is more accurate than a coarse mesh at a fraction of the computational cost needed if a fine mesh were used throughout the domain. More importantly, the adaptive procedures increase the reliability of the

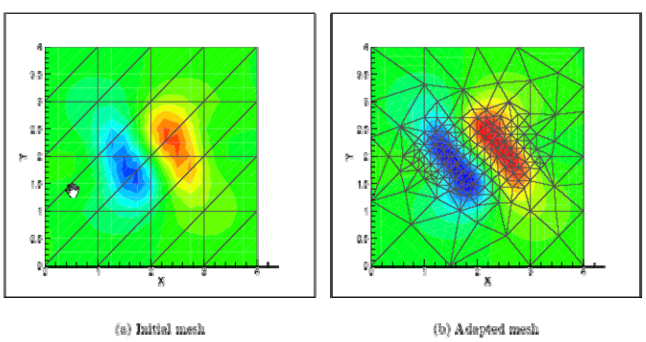

Figure2 . Initial (a) and adapted mesh (b) and contour plot of the magnetic flux function for a tilting of an ideal column simulation

computational procedures for the prediction of the key physical parameters of interest.

In addition to continued investigation of methods to increase the efficiency, current efforts include:

- Alternative C^1 continuous simplex element shape functions that will further increase the computational efficiency of the procedures.
- The introduction of a stabilization term derived from a variational multiscale analysis into the finite element formulation that maintain the method's stability while increasing its ability to accurately solve the governing physics equations.
- Identifying and addressing issues required to realize good scale-up of parallel, adaptive MHD simulation on petascale machines as needed to fully resolve all parameters of interest to the PPPL physicists.

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