EIGER / GEMMA Electromagnetic Code Capabilities

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Overview

Problem Explained

Code Description EIGER / GEMMA

Solution Methods

Example Problem

Conclusions / Future Effort
Background

What?
- Provide high-fidelity, robust, computational tools based on Maxwell’s Equations.
  - Frequency Domain → EMR/EMI Interaction with system / components

Why?
- To aid in weapons qualification in conjunction with experiments.
  - Design of experiments
- Weapon component and subsystem modeling.
  - Design guidance
- In addition, can be used to address problems for external customers.

How?
- Frequency domain boundary element formulation.
  - EIGER
  - GEMMA → Next generation EIGER
EMR Problem Overview

Focus - coupling through gaps and external currents

- Metal Enclosure (Shield)
- Induced currents
- Magnetic diffusion
- Filter
- Connector
Electromagnetic Environment

Ground Based System

External to System
Code Description EIGER / GEMMA
EIGER / GEMMA Basic Formulation

Frequency-domain method of moments solution
- Steady state solution
- With specialized algorithms (thin-slot, etc.)

Boundary element formulation
- Mesh surfaces of parts – interface between regions

Exact radiation boundary condition
- Due to Green's function

Formulation results in dense (fully populated) matrix
- Simulations can be limited by available memory
- Entries are double precision complex
Maxwell’s Equations:

Faraday: \( \nabla \times \mathbf{E} = -j\omega \mathbf{B} \)

Ampere – Maxwell: \( \nabla \times \mathbf{H} = \mathbf{J} + j\omega \mathbf{D} \)

Electric Gauss: \( \nabla \cdot \mathbf{D} = \rho \)

Magnetic Gauss: \( \nabla \cdot \mathbf{B} = 0 \)

Wave Equations:

\[
\begin{align*}
\nabla^2 \mathbf{A} + \omega^2 \mu_0 \epsilon \mathbf{A} &= -\mu \mathbf{J} \\
\nabla^2 \Phi + \omega^2 \mu_0 \epsilon \Phi &= \rho / \epsilon 
\end{align*}
\]

For a linear homogeneous, unbounded medium:

\[
\begin{align*}
\mathbf{A} &= \int_V \mu \mathbf{J}(\mathbf{r}') g(\mathbf{r}|\mathbf{r}') d\mathbf{v}' \\
\Phi &= -\int_V \frac{\rho(\mathbf{r}')}{\epsilon} g(\mathbf{r}|\mathbf{r}') d\mathbf{v}'
\end{align*}
\]

Vector and Scalar Potentials:

\[
\begin{align*}
\mathbf{E} &= -j\omega \mathbf{A} - \nabla \Phi \\
\mathbf{B} &= \nabla \times \mathbf{A} \\
\end{align*}
\]

Lorenz gauge condition:

\( \nabla \cdot \mathbf{A} = -j\omega \epsilon \mu \Phi \)

Instead of solving Maxwell’s equations in 3D space via the wave equations, we solve them on the boundary between regions.

Free-Space Green’s Function:

\[
g(\mathbf{r}|\mathbf{r}') = \frac{e^{-jk|\mathbf{r} - \mathbf{r}'|}}{4\pi|\mathbf{r} - \mathbf{r}'|}
\]
Integral Equations (Boundary Element Method – BEM)

Example of an electric field integral equation (EFIE) for metallic scatterer:

Through the equivalence principle, we consider the current on an object's boundary instead of the field around and inside the object. Enforcing the boundary condition at the surface:

\[ \hat{n} \times (E_{\text{inc}} + E_{\text{scat}}) = 0 \]

\[ E_{\text{scat}} = -j\omega \mu \int_{S'} \left( J_S(r')g(r|r') + \frac{1}{\omega^2 \mu \epsilon} \nabla' \cdot J_S(r') \nabla g(r|r') \right) ds' \]

results in the following integral equation:

\[ \int_{S'} \hat{n} \times \left( J_S(r')g(r|r') + \frac{1}{\omega^2 \mu \epsilon} \nabla' \cdot J_S(r') \nabla g(r|r') \right) ds' = \frac{1}{j\omega \mu} \hat{n} \times E_{\text{inc}} \]

\[ L \{ J_S \} = \frac{1}{j\omega \mu} \hat{n} \times E_{\text{inc}} \]
**Method of Moments (MoM)**

Numerical solution of integral equation:

\[ L \{ J_S \} = \frac{1}{j \omega \mu} \hat{n} \times E_{\text{inc}} \]

Discretize the scatterer

Expand unknown in a set of basis functions:

\[ J_S(r) \approx \sum_n I_n f_n(r) \]

Test integral equation with basis functions.

\[ \int_S f_m \cdot L \{ J_S \} \, ds = \frac{1}{j \omega \mu} \int_S f_m \cdot (\hat{n} \times E_{\text{inc}}) \, ds \]

\[ Z \bar{I} = V \]

\[ Z_{m,n} = \int_{f_m} \int_{f_n} \left[ j \omega \mu f_m \cdot f_n - \frac{j}{\omega \varepsilon} \nabla \cdot f_m \nabla' \cdot f_n \right] e^{-ikr} \frac{1}{4\pi r} \]

Rao-Wilton-Glisson (RWG) basis functions
<table>
<thead>
<tr>
<th>Feature</th>
<th>EIGER</th>
<th>GEMMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Language</td>
<td>Fortran 2007</td>
<td>C++ 11</td>
</tr>
<tr>
<td>Parallel Implementation</td>
<td>MPI</td>
<td>MPI + Threading (CPU + GPU)</td>
</tr>
<tr>
<td>Solution Options</td>
<td>Direct Iterative Matrix Compression</td>
<td>Direct, Iterative - MLFMM, Matrix Compression*</td>
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<tr>
<td>Code Implementation</td>
<td>Pre-processor, solver Separate Codes</td>
<td>Pre-processor, solver Not separate</td>
</tr>
<tr>
<td>Code Enhancements Usage Algorithms</td>
<td>Enhanced with SAW / IWF integration</td>
<td>Deep Slot Formulation Enhanced with SAW / IWF integration</td>
</tr>
</tbody>
</table>

*Possible Future Enhancements
EIGER / GEMMA– Computational considerations

Problem Discretization Requirement
¶ Triangles, quadrilaterals, or bar elements (SURFACE MESH)
¶ Mesh requirements
  ¤ Average Edge length should be \( \sim \frac{\lambda}{10} \)
  ¤ \((\# \text{ faces } \times \lambda^2)/\text{surface area} > 250\)

Matrix memory requirements
¶ 16 * \( N^2 \) bytes (\( N \) order of the matrix)
¶ Example
  ¤ W88_alt meshed and prepared for 18 GHz
    ¤ \( N = 2 \) million
    ¤ Memory = 64 terabytes

Matrix Solution
¶ Fill is \( O(N^2) \)
¶ Solve is \( O(N^3) \) -- for Direct Solve
¶ The solution is the Current on the surfaces
  ¤ Using the Green’s function the fields can be determined.
Solution via Direct and Iterative Solve -> TRILINOS Packages

DIRECT Solve

• PLIRIS
  ▪ C – code
    ▪ MPI only no threading

• ADELUS
  ▪ New packaging of PLIRIS
  ▪ C++ code
    ▪ MPI + Threading
    ▪ Threading via KOKKOS
      ▪ GPUs, CPUs

• Key Implementation Features
  ▪ TORUS WRAP Distribution
    ▪ Blocks supplied by user
    ▪ No processor will have no more than 1 row or column than the other

Iterative Solve

• BELOS
  ▪ Preconditioner usage
Large-Scale EM Simulation with EIGER with Adelus

- Couple EIGER with ADELUS to perform large-scale electromagnetic simulations on the LLNL’s Sierra platform.
- First time Petaflops performance with a complex, dense LU solver: 7.72 Petaflops (16.9% efficiency) when using 7,600 GPUs on 1,900 nodes on a 2,564,487-unknown problem.
- ADELUS’s performance is affected by the distribution of the matrix on the MPI processes.
  - Assigning more processes per row yields higher performance.

### ON SIERRA

<table>
<thead>
<tr>
<th>N</th>
<th>Nodes (GPUs)</th>
<th>Solve time (sec.)</th>
<th>TFLOPS</th>
<th>Procs/row</th>
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<tbody>
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</table>
Example Problem
Example Problem

Example Mesh 10090 elements  ---  15565 unknowns
Example Problem -- Results

Cut Plane

494533 Unknowns

Magnitude of Electric Field on the Cut Plane

Incident Field
Conclusions
Conclusions / Future Effort

The EIGER /GEMMA codes have benefited from collaboration with the Trilinos team:

PLIRIS --> ADELUS, BELOS, KOKKOS

GEMMA

- Additional Algorithms being pursued:
  - Physics models
  - Advanced solution methods
  - Preconditioner identification

These will leverage and require continued teaming and support with the Trilinos team.