Simulation of Resistivity Logging Instruments with Mandrel Using a Self-Adaptive Goal-Oriented $hp$-Finite Element Method

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Institute for Computational Engineering and Sciences (ICES)
The University of Texas at Austin
OVERVIEW

1. Overview

2. Main Idea of $h_p$ Goal-Oriented Adaptivity

3. Current Stage of the 2D High Performance FE Software
   - Flexibility
   - Reliability
   - Accuracy
   - Performance

4. Simulation of Resistivity Logging Instruments with Mandrel

5. Conclusions and Future Work (3D Problems)
**The $h$-Finite Element Method**

1. Convergence limited by the polynomial degree, and large material contrasts.
2. Optimal $h$-grids do NOT converge exponentially in real applications.
3. They may “lock” (100% error).

**The $p$-Finite Element Method**

1. Exponential convergence feasible for analytical ("nice") solutions.
2. Optimal $p$-grids do NOT converge exponentially in real applications.
3. If initial $h$-grid is not adequate, the $p$-method will fail miserably.

**The $hp$-Finite Element Method**

1. Exponential convergence feasible for ALL solutions.
2. Optimal $hp$-grids DO converge exponentially in real applications.
3. If initial $hp$-grid is not adequate, results will still be great.
THE $h_p$-FINITE ELEMENT METHOD

Model Problem with Steel Casing

- Frequency: 10 Hz.
- Casing resistivity: $10^{-6}$ Ohm \cdot m.
- Casing width: 0.01127 m
- Discretization error < 0.1 %
- Toroidal antennas
- Size (domain): 500m x 4000m

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High Performance Finite Element Software
GOAL-ORIENTED ADAPTIVITY

Representation Formula

\[ V = L(\Psi) = \int \bar{\sigma} \nabla \Psi \cdot \nabla G \]
GOAL-ORIENTED ADAPTIVITY

Movie Presentation (Sensitivity Functions)

We want to study resolution and depth of investigation of a logging instrument.

We have: \[ |L(\Psi)| = \left| \int S \, dV \right| \leq \int |S| \, dV. \]

In the next movies, we display: \( \log_{10} |S| \).

Scales:

- **Red** \( \rightarrow |S| = |L(\Psi)| \times 10^4. \)
- **Blue** \( \rightarrow |S| = |L(\Psi)| \times 10^{-2}. \)

Direct Current
**SELF-ADAPTIVE GOAL-ORIENTED $hp$-FEM**

Algorithm for Goal-Oriented Adaptivity

1. Solve DIRECT and DUAL problems on Grid $hp$.
   
2. Compute $e = \Psi_{h/2,p+1} - \Psi_{hp}$, and $\tilde{e} = \Psi_{h/2,p+1} - \Pi_{hp} \Psi_{h/2,p+1}$.
3. Compute $\epsilon = G_{h/2,p+1} - G_{hp}$, and $\tilde{\epsilon} = G_{h/2,p+1} - \Pi_{hp} G_{h/2,p+1}$.
4. Apply the fully automatic $hp$-adaptive algorithm.

   $|L(e)| = |b(e, \epsilon)| \sim |b(\tilde{e}, \tilde{\epsilon})| \leq \sum_K |b_K(\tilde{e}, \tilde{\epsilon})| \leq \sum_K \| \tilde{e} \|_{E,K} \| \tilde{\epsilon} \|_{E,K}$. 

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High Performance Finite Element Software
Model Problem with Steel Casing

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- Discretization error < 0.1%
- Toroidal antennas
- Size (domain): 500m x 4000m
CURRENT STAGE OF THE 2D $hp$-FE SOFTWARE

Flexibility (What Problems Can We Solve?)

Time-Harmonic Maxwell’s Equations

\[
\nabla \times \mathbf{H} = (\bar{\sigma} + j\omega \bar{\varepsilon})\mathbf{E} + \mathbf{J}^{imp} \quad \text{Ampere’s law}
\]
\[
\nabla \times \mathbf{E} = -j\omega \bar{\mu} \mathbf{H} - \mathbf{M}^{imp} \quad \text{Faraday’s law}
\]
\[
\nabla \cdot (\bar{\varepsilon}\mathbf{E}) = \rho \quad \text{Gauss’ law of Electricity}
\]
\[
\nabla \cdot (\bar{\mu}\mathbf{H}) = 0 \quad \text{Gauss’ law of Magnetism}
\]

E-VARIATIONAL FORMULATION:

\[
\begin{align*}
\text{Find } \mathbf{E} &\in \mathbf{E}_D + \mathbf{H}_D(\text{curl}; \Omega) \text{ such that:} \\
\int_{\Omega} (\bar{\mu}^{-1} \nabla \times \mathbf{E}) \cdot (\nabla \times \mathbf{F}) \, dV - \int_{\Omega} (\bar{k}^2 \mathbf{E}) \cdot \mathbf{F} \, dV &= -j\omega \int_{\Omega} \mathbf{J}^{imp} \cdot \mathbf{F} \, dV \\
+ j\omega \int_{\Gamma_N} \mathbf{J}^{imp}_{\Gamma_N} \cdot \mathbf{F}_t \, dS - \int_{\Omega} (\bar{\mu}^{-1} \mathbf{M}^{imp}) \cdot (\nabla \times \mathbf{F}) \, dV &\quad \forall \mathbf{F} \in \mathbf{H}_D(\text{curl}; \Omega)
\end{align*}
\]
CURRENT STAGE OF THE 2D $h_p$-FE SOFTWARE

Flexibility (What Problems Can We Solve?)

AXISYMMETRIC PROBLEMS

$E_\phi$ -Variational Formulation (Azimuthal)

\[
\begin{align*}
\text{Find } & E_\phi \in E_{\phi,D} + \tilde{H}_D^1(\Omega) \text{ such that:} \\
& \int_\Omega (\tilde{\mu}_{\rho,z}^{-1} \nabla \times E_\phi) \cdot (\nabla \times \bar{F}_\phi) \, dV - \int_\Omega (k^2_\phi E_\phi) \cdot \bar{F}_\phi \, dV = -j\omega \int_\Omega J^{imp}_{\phi} \bar{F}_\phi \, dV \\
& \quad + j\omega \int_{\Gamma_N} J^{imp}_{\phi,\Gamma_N} \bar{F}_\phi \, dS - \int_\Omega (\tilde{\mu}_{\rho,z}^{-1} \vec{M}^{imp}_{\rho,z}) \cdot \bar{F}_\phi \, dV \quad \forall \, F_\phi \in \tilde{H}_D^1(\Omega)
\end{align*}
\]

$E_{\rho,z}$ -Variational Formulation (Meridian)

\[
\begin{align*}
\text{Find } & (E_{\rho}, E_z) \in E_D + \tilde{H}_D(\text{curl}; \Omega) \text{ such that:} \\
& \int_\Omega (\tilde{\mu}_{\phi}^{-1} \nabla \times E_{\rho,z}) \cdot (\nabla \times \bar{F}_{\rho,z}) \, dV - \int_\Omega (k^2_{\rho,z} E_{\rho,z}) \cdot \bar{F}_{\rho,z} \, dV = \\
& \quad - j\omega \int_\Omega J^{imp}_{\rho} \bar{F}_{\rho} + J^{imp}_{z} \bar{F}_{z} \, dV + j\omega \int_{\Gamma_N} J^{imp}_{\rho,\Gamma_N} \bar{F}_{\rho} + J^{imp}_{z,\Gamma_N} \bar{F}_{z} \, dS \\
& \quad - \int_\Omega (\tilde{\mu}_{\phi}^{-1} \vec{M}^{imp}_{\phi}) \cdot \bar{F}_{\rho,z} \, dV \quad \forall \, (F_\rho, F_z) \in \tilde{H}_D(\text{curl}; \Omega)
\end{align*}
\]
CURRENT STAGE OF THE 2D $h^p$-FE SOFTWARE

**Flexibility (What Problems Can We Solve?)**

- Physical Devices: Casing, Casing Imperfections, Mandrel, Magnetic Buffers, Insulators, Displacement Currents, Combination of All, etc.

- Materials: Isotropic, Anisotropic*.

- Sources: Toroidal Antennas, Solenoidal Antennas, Dipoles in Any Direction, Electrodes, Finite Size Antennas, Combination of All, etc.

- Logging Instruments: Logging While Drilling (LWD), Laterolog, Normal, Induction, Dielectric Instruments, Cross-well, etc.

- Any Frequency (0-10 Ghz).

**ALL AXISYMMETRIC RESISTIVITY LOGGING PROBLEMS**
CURRENT STAGE OF THE 2D $hp$-FE SOFTWARE

Reliability (Can We Trust the Solutions?)

- **Comparison Against Analytical Results.**
  1. Exact solution in a homogeneous media.
  2. Exact solution in a homogeneous media with a mandrel.
  3. Exact solution in a homogeneous media with casing.

- **Verification of Physical Properties.**
  1. Reciprocity principle (Gregory Itskovich).
  2. Discrete divergence free approximation for edge elements.

- **Numerical Verifications.**
  1. Different size of domain and antennas.
  2. Comparison against other numerical software (Yang Wei).
  3. Error control provided by the fine grid solution.
  4. Comparison between continuous elements vs. edge elements.
CURRENT STAGE OF THE 2D $h^p$-FE SOFTWARE

Reliability (Can We Trust the Solutions?)

Problem with casing at 10 kHz.

Continuous Elements

<table>
<thead>
<tr>
<th>Quantity of Interest</th>
<th>Real Part</th>
<th>Imag Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>COARSE GRID</td>
<td>0.1516098429E-08</td>
<td>-0.1456374493E-08</td>
</tr>
<tr>
<td>FINE GRID</td>
<td>0.1516094029E-08</td>
<td>-0.1456390824E-08</td>
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Edge Elements

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<td>0.1516093804E-08</td>
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Error control provided by the fine grid solution.
CURRENT STAGE OF THE 2D $h/p$-FE SOFTWARE

Reliability (Can We Trust the Solutions?)

Problem with casing at 10 kHz.

Continuous Elements

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Comparison between continuous elements vs. edge elements.
CURRENT STAGE OF THE 2D $hp$-FE SOFTWARE

Reliability (Can We Trust the Solutions?)

- **Comparison Against Analytical Results.**
  1. Exact solution in a homogeneous media.
  2. Exact solution in a homogeneous media with a mandrel.
  3. Exact solution in a homogeneous media with casing.

- **Verification of Physical Properties.**
  1. Reciprocity principle (Gregory Itskovich).
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- **Numerical Verifications.**
  1. Different size of domain and antennas.
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  3. Error control provided by the fine grid.
  4. Comparison between continuous elements vs. edge elements.

HIGHLY RELIABLE SOFTWARE
CURRENT STAGE OF THE 2D $hp$-FE SOFTWARE

Accuracy (Are the Solutions Accurate?)

Problem with Casing (Convergence Curve)

Frequency: 10 Hz

Relative Error in %

Number of Unknowns $N$ (scale $N^{1/3}$)

EXTREMELY ACCURATE SOFTWARE
CURRENT STAGE OF THE 2D $hp$-FE SOFTWARE

Performance (How Fast Can We Solve the Problems?)

<table>
<thead>
<tr>
<th></th>
<th>$10^{-6} \Omega \cdot m$</th>
<th>$10^{-5} \Omega \cdot m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 Vert. Pos.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toroid (10 Khz)</td>
<td>19’ 46”</td>
<td>16’ 28”</td>
</tr>
<tr>
<td>Ring of Vert. Dipoles (10 Khz)</td>
<td>22’ 47”</td>
<td>17’ 02”</td>
</tr>
<tr>
<td>Ring of Horiz. Dipoles (10 Khz)</td>
<td>19’ 25”</td>
<td>13’ 25”</td>
</tr>
<tr>
<td>Electrodes (0 Hz)</td>
<td>10’ 10”</td>
<td>8’ 35”</td>
</tr>
</tbody>
</table>

IBM Power 4 compiler 1.3 Ghz (4 years old)

Possible improvements in performance:

- To use a 3.4 Ghz processor.
- To execute the code in 8 processors (10 positions per processor).
- To improve implementation.

HIGH PERFORMANCE SOFTWARE
SIMULATION OF LOGGING INSTRUMENTS

Comparison Against Analytical Solutions

Solutions in a Homogeneous Lossy (1 \( \Omega \) m) Media (2 Mhz)

Solenoid Antenna

Toroid Antenna

Electric Field

Magnetic Field
SIMULATION OF LOGGING INSTRUMENTS

Comparison Against Analytical Solutions

Solutions in a Homogeneous Lossy \( (1 \, \Omega \, m) \) Media (2 Mhz) in Presence of a Conductive Mandrel

Solenoid Antenna

Toroid Antenna

Electric Field

Magnetic Field
SIMULATION OF LOGGING INSTRUMENTS

Description of Antennas

Goal: To Compute First Difference of Potential on Receiving Antennas

Magnetic Buffer
10000 Ohm m
10000 Rel. Perme.

Borehole
0.1 Ohm m
Radius=10.8 cm

Radius 7.6 cm

100 Ohm m
10000 Ohm m
1 Ohm m
0.000001 Ohm m

0.1 Ohm m
0.00001 Ohm m
100 cm
50 cm
100 cm
15 cm
100 cm
SIMULATION OF LOGGING INSTRUMENTS

First. Vert. Diff. $E_\phi$ (solenoid). Position: 0.475m

![Graph showing relative error in % vs. number of unknowns N (scale $N^{1/3}$)]

- **Goal-Oriented hp-Adaptivity**
  - Upper bound for $|L(e)|/|L(u)|$
  - $|L(e)|/|L(u)|$

- **Energy-norm hp-Adaptivity**
  - Energy-norm error
  - $|L(e)|/|L(u)|$
SIMULATION OF LOGGING INSTRUMENTS

Goal-Oriented vs. Energy-norm $h_p$-Adaptivity

Problem with Mandrel at 2 Mhz.

Continuous Elements (Goal-Oriented Adaptivity)

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<th>Imag Part</th>
</tr>
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<tbody>
<tr>
<td>COARSE GRID</td>
<td>-0.1629862203E-01</td>
<td>-0.4016944732E-02</td>
</tr>
<tr>
<td>FINE GRID</td>
<td>-0.1629862347E-01</td>
<td>-0.4016944223E-02</td>
</tr>
</tbody>
</table>

Continuous Elements (Energy-norm Adaptivity)

<table>
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<tr>
<th>Quantity of Interest</th>
<th>Real Part</th>
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</tr>
</thead>
<tbody>
<tr>
<td>0.01% ENERGY ERROR</td>
<td>-0.1382759158E-01</td>
<td>-0.2989492851E-02</td>
</tr>
</tbody>
</table>

It is critical to use GOAL-ORIENTED adaptivity.
SIMULATION OF LOGGING INSTRUMENTS

First. Vert. Diff. $E_\phi$ (solenoid). Position: 0.475m

ENERGY-NORM HP-ADAPTIVITY

2Dhp90: A Fully automatic hp-adaptive Finite Element code
First. Vert. Diff. $E_\phi$ (solenoid). Position: 0.475m

GOAL-ORIENTED HP-ADAPTIVITY
SIMULATION OF LOGGING INSTRUMENTS

First. Vert. Diff. $E_\phi$ (solenoid). Position: 0.475m

GOAL-ORIENTED HP-ADAPTIVITY (ZOOM TOWARDS FIRST RECEIVER ANTENNA)
**SIMULATION OF LOGGING INSTRUMENTS**

\( E_\phi \) for a solenoid antenna

The graphs show the amplitude of the electric field \( E_\phi \) in volts per meter (V/m) as a function of the vertical position of the receiving antenna in meters (m). The phase in degrees is also plotted for different resistivity values: 100 Ohm-m, 10000 Ohm-m, and 1 Ohm-m. The plots illustrate the behavior of the electric field for no invasion and different resistivity scenarios.
SIMULATION OF LOGGING INSTRUMENTS

$H_\phi$ for different antennas

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High Performance Finite Element Software
SIMULATION OF LOGGING INSTRUMENTS

First Vert. Diff. $H_\phi$ for different antennas

Amplitude First Vert. Diff. Magnetic Field (A/m)

Phase (degrees)

Vertical Position of Receiving Antenna (m)

Vert. Dipoles (Ring)
Toroid

No Invasion

100 Ohm-m
1 Ohm-m
10000 Ohm-m
100 Ohm-m
100 Ohm-m
1 Ohm-m
10000 Ohm-m
100 Ohm-m
SIMULATION OF LOGGING INSTRUMENTS

First Vert. Diff. $E_z$ for a toroid antenna

No Invasion

Amplitude First Vert. Diff. $E_z$ (V/m²) vs. Vertical Position of Receiving Antenna (m)

Phase (degrees) vs. Vertical Position of Receiving Antenna (m)

100 Ohm-m

1 Ohm-m

10000 Ohm-m

100 Ohm-m
First Vert. Diff. $H_z$ for a solenoid antenna

![Graph showing the first vertical difference amplitude of $H_z$ for different resistivities.]
SIMULATION OF LOGGING INSTRUMENTS

First Vert. Diff. $E_\phi$ for a solenoid antenna

![Diagram showing the first vertical difference of the electric field amplitude ($E_\phi$) for a solenoid antenna under different resistivity conditions. The graphs illustrate the phase shift and amplitude change as the vertical position of the receiving antenna varies.](image-url)
SIMULATION OF LOGGING INSTRUMENTS

Use of Magnetic Buffers ($E_\phi$ for a solenoid)

- **No Invasion**
  - With Magnetic Buffers
  - Without Magnetic Buffers

- **Solenoid**
  - With Magnetic Buffers
  - Without Magnetic Buffers

- **First Vert. Diff. Amplitude of Electric Field (V/m)**
  - 100 Ohm–m
  - 1 Ohm–m
  - 10000 Ohm–m

- **Vertical Position of Receiving Antenna (m)**
  - 100 Ohm–m
  - 10000 Ohm–m

- **Phase (degrees)**
  - 100 Ohm–m
  - 10000 Ohm–m
SIMULATION OF LOGGING INSTRUMENTS

Use of Magnetic Buffers ($H_\phi$ for a toroid)

No Invasion

Toroid

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High Performance Finite Element Software
SIMULATION OF LOGGING INSTRUMENTS

Invasion study ($E_{\phi}$ for a solenoid)

**Invasion Study**
- No Invasion
- 0.15m Invasion
- 0.4m Invasion
- 0.9m Invasion

**Solenoid**
- No Invasion
- 0.15m Invasion
- 0.4m Invasion
- 0.9m Invasion

- 100 Ohm–m
- 10000 Ohm–m
- 1 Ohm–m

Amplitude First Vert. Diff. Electric Field (V/m²)
Vertical Position of Receiving Antenna (m)
Phase (degrees)
SIMULATION OF LOGGING INSTRUMENTS

Invasion study ($H_\phi$ for a toroid)

![Graph showing invasion study results for different resistivities and positions.]

- **Invasion Study**
  - Amplitude First Vert. Diff. Magnetic Field (A/m)
  - Vertical Position of Receiving Antenna (m)
  - Resistivities: 100 Ohm·m, 10000 Ohm·m, 1 Ohm·m

- **Toroid**
  - Phase (degrees)
  - Vertical Position of Receiving Antenna (m)
  - Resistivities: 100 Ohm·m, 10000 Ohm·m, 1 Ohm·m

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Invasion study ($E_\phi$ for a solenoid)

**Invasion Study**
- **No Invasion**
- **0.15m Invasion**
- **0.4m Invasion**
- **0.9m Invasion**

**Solenoid**
- **No Invasion**
- **0.15m Invasion**
- **0.4m Invasion**
- **0.9m Invasion**
Invasion study \( H_\phi \) for a toroid

**Amplitude First Vert. Diff. Magnetic Field (A/m)**

- **100 Ohm-m**
- **1 Ohm-m**
- **10000 Ohm-m**

**Vertical Position of Receiving Antenna (m)**

- No Invasion
- 0.15m Invasion
- 0.4m Invasion
- 0.9m Invasion

**Phase (degrees)**

- 100 Ohm-m
- 10000 Ohm-m

**Invasion Study**

- No Invasion
- 0.15m Invasion
- 0.4m Invasion
- 0.9m Invasion

**Toroid**

- No Invasion
- 0.15m Invasion
- 0.4m Invasion
- 0.9m Invasion

**Vertical Position of Receiving Antenna (m)**

- 100 Ohm-m
- 10000 Ohm-m

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*High Performance Finite Element Software*
SIMULATION OF LOGGING INSTRUMENTS

Invasion and mandrel magnetic permeab. \( (E_{\phi}) \)

Invasion Study

Solenoid

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SIMULATION OF LOGGING INSTRUMENTS

Invasion and mandrel magnetic permeab. \((H_\phi)\)

**Invasion Study**

- No Invasion
- 0.4/0.9 m Invasion
- 0.4/0.9m Invasion, Perm. Mandrel=100

**Toroid**

- No Invasion
- 0.4/0.9 m Invasion
- 0.4/0.9m Invasion, Perm. Mandrel=100

- 100 Ohm–m
- 2 Ohm–m (0.4m)
- 5 Ohm–m (0.9m)
- 1000 Ohm–m

- 100 Ohm–m
- 2 Ohm–m (0.4m)
- 5 Ohm–m (0.9m)
- 10000 Ohm–m
SIMULATION OF LOGGING INSTRUMENTS

Anisotropy ($H_{\phi}$)

![Graph showing anisotropy study and toroid results with different electrical conductivity values.]
CONCLUSIONS AND FUTURE WORK

• It is possible to simulate ANY axisymmetric resistivity logging instruments with mandrel (for example, LWD) by using the self-adaptive goal-oriented $hp$-FEM.

• We obtain fast, reliable and accurate solutions.

• For the discussed LWD problem, numerical results suggest to:
  
  1. Measure first vertical differences of the EM fields.
  
  2. Use solenoids for formations with low resitivitiy, and toroids for highly resistive formations.

  3. Use magnetic buffers in combination with solenoids, not with toroids.

  4. Use solenoids for studying invasion in formations with low resistivity. Use toroids for studying invasion in highly resistive formations.

Department of Petroleum and Geosystems Engineering, and Institute for Computational Engineering and Sciences (ICES)
FUTURE WORK

Simulation of 3D Resistivity Logging Problems

• PART I: Simulate 3D DC Resistivity Logging Problems.
  - Estimated completion time: 8-10 months (40 hours/week).
  - Main challenge: Speed.
  - Expected results: Similar results as in 2D.

• PART II: Simulate 3D AC Resistivity Logging Problems.
  - Estimated completion time: 8-10 months (40 hours/week).
  - Main challenge: Speed and Implementation.
  - Expected results: Similar results as in 2D.