Electromagnetic Modeling of Induction Tool Responses in Layered Earth Formation

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Outline

Introduction of Directional Induction Tools

- Maxwell equation- Induction tool (20KHz-2MHz)

$$\sigma >> \omega\varepsilon$$

$$\nabla \times \overline{E} = i\omega\mu\overline{H}$$

$$\nabla \times \overline{H} = (\sigma - i\omega\varepsilon)\overline{E} + \overline{J}_s \approx \sigma\overline{E} + \overline{J}$$

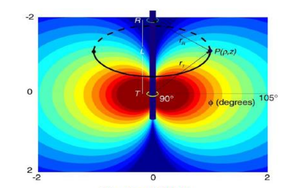
- Steady-state equation- conduction tool(30-300Hz)

$$\omega \approx 0$$

$$\nabla \times \overline{E} = i\omega\mu\overline{H} \approx 0 \quad \Rightarrow \quad \overline{E} = -\nabla\varphi$$

$$\nabla \bullet \sigma\overline{E} = -\nabla \bullet \overline{J}_s \quad \Rightarrow \quad \nabla \bullet \sigma\nabla\varphi = \nabla \bullet \overline{J}_s$$

- Transverse Isotropy: $\overline{\overline{\sigma}}_{eff} = \begin{bmatrix} \sigma_h & 0 & 0 \\ 0 & \sigma_h & 0 \\ 0 & 0 & \sigma_v \end{bmatrix}$

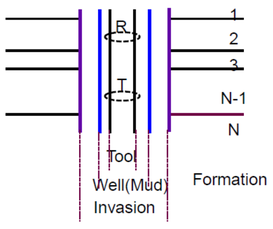


- Conventional induction tools are built with coils that have magnetic moments directed along the tool axis for horizontal conductivity.
- Directional induction tools are built with 3 perpendicular transmitter and receiver coils for formation anisotropy(transverse isotropy).

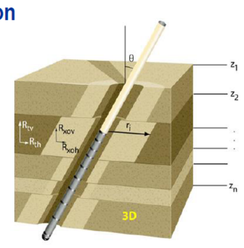
2D v.s. 3D Well Models

2D/3D Model

- Vertical wells/Deviated or Horizontal well
- Varies with depth and radius/ and azimuth
- Axially symmetric/Asymmetric
- Circular invasion / Asymmetric invasion



2D Well Model



3D Well Model

COMSOL and LWD Simulations

- COMSOL Multiphysics is used to simulate electromagnetic fields around the induction coils. Both Radio Frequency (RF) module and Magnetic Field (MF) module are used.
- A line source (I = 1A) is assigned to transmitter loop as "edge current".
- Complex voltages at two receiver loops are evaluated using the integration.
- Maxwell's equation for RF solver:

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - \omega^2 \epsilon_o \mu_o \left(\epsilon_r - j\frac{\sigma}{\omega \epsilon_o}\right)\mathbf{E} = 0$$

- Maxwell's equation for MF solver:

$$\nabla \times \mu^{-1}(\nabla \times \mathbf{A}) + \left(j\omega\sigma - \omega^2 \epsilon\right)\mathbf{A} = \mathbf{J}_s$$

- Other equations:

$$v = \oint_c \mathbf{E} \cdot \hat{t}\, dl \qquad Att = 20 \log_{10}\frac{|V1|}{|V2|}$$

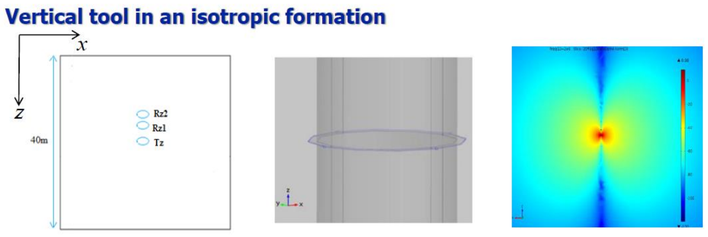
$$v = i\omega \oint_c \mathbf{A} \cdot \hat{t}\, dl \qquad \text{Phase Shift} = [\Theta(V_1) - \Theta(V_2)]$$

COMSOL and LWD Simulations

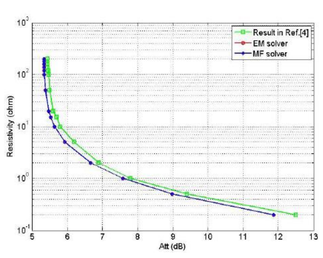
- Operating frequency is 2 MHz.
- TR spacing is 28 inches and RR spacing is 6 inches.
- Finite size transmitter and receiver loop antenna of radius 4.5 inches.
- Scattering boundary condition.
- Both transmitter and receivers are z- or x- directed.
- Formation conductivities are TI-anisotropic.

Simulation Example I

- Vertical tool in an isotropic formation

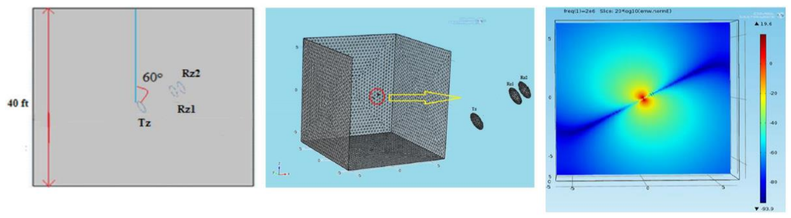


- Normal mesh, # of tetrahedra is 17,976.
- Maximum element of 4 m and minimum element of 0.72 m.
- Memory cost is 785 MB and simulation time is 12 sec for one conductivity value point.

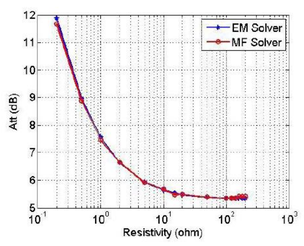


Simulation Example II

- Dipping tool in the homogeneous formation

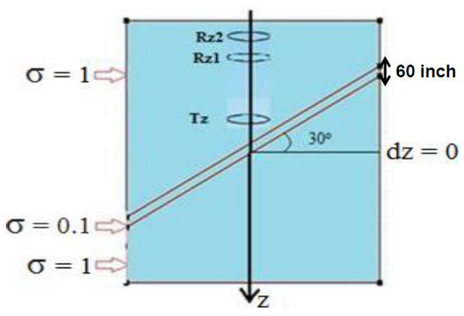


- Extra fine mesh, # of tetrahedra is 418,903.
- Maximum element size of 0.427 m.
- Memory size is 1.44 GB and simulation time is 363.6 sec for one conductivity value point.

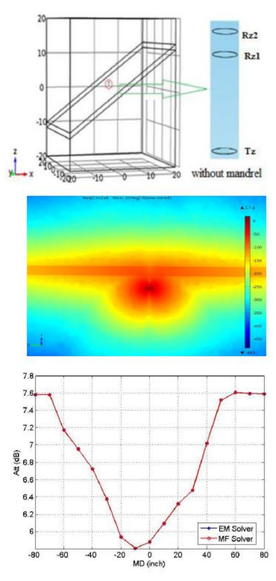


Simulation Example III

- Vertical tool in three layer formations

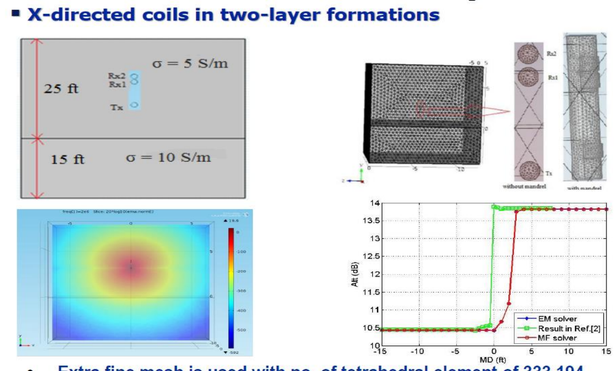


- # of tetrahedra 110,947.
- Maximum element size of 2.2 m.
- Memory size is 1.17 GB and simulation time is 69 sec for one measured depth point.



Simulation Example IV

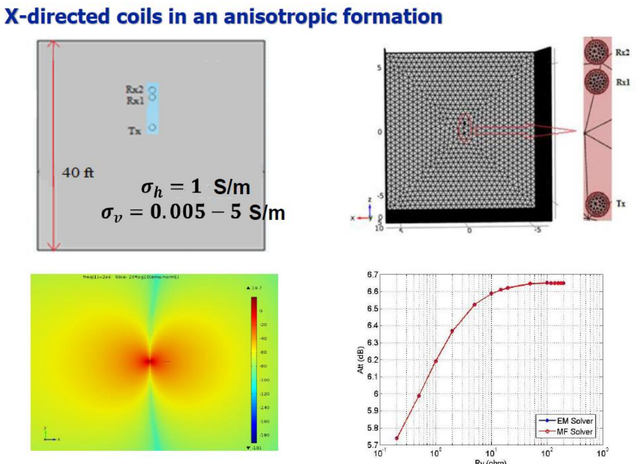
- X-directed coils in two-layer formations



- Extra fine mesh is used with no. of tetrahedral element of 333,194.
- Maximum element size value of 0.427 m.
- Memory size is 1.17 GB and simulation time is 245.4 sec for one measured depth.

Simulation Example V

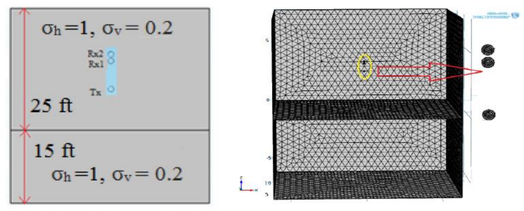
- X-directed coils in an anisotropic formation



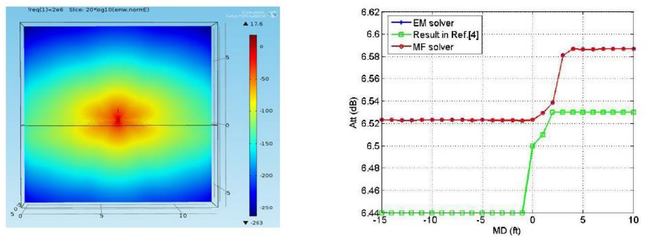
- Extra fine mesh is used with no. of tetrahedral element of 424,979.
- Maximum element size value of 0.427 m.

Simulation Example VI

- X-directed coils in two-layer anisotropic formations



- Extra fine mesh with no. of tetrahedral element of 333,194.
- Maximum element size value of 0.48 m.
- Memory size is 1.25 GB and simulation time is 248.4 sec for one measured depth.



Conclusions

- **COMSOL RF and MF solvers are applied to model the directional tool responses in layered Earth formations.**
- **Simulation results are verified by comparison between the two solvers and with reference results.**

References

1. H. G. Doll, Introduction to Induction Logging and Application to Logging of Wells Drilled with Oil Base Mud, Petroleum Technology, Vol. 1 (1949)
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5. D. Omeragic, L. Sun, V. Polyakov, Y. Chen, X. Cao, T. Habashy, T. vok, J. Rasmus and J. Denichou, Characterizing Teardrop Invasion in Horizontal Wells in the Presence of Boundaries using LWD Directional Resistivity Measurements, 54th (2013)

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