3D FV Simulation of the Orthogonal Azimuth Electromagnetic Tool Response Logging While Drilling with Multi Annular Grooves Using Potentials

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Abstract. In this paper, we use the 3D cylindrical finite volume (3D FV) method to simulate the Orthogonal Azimuth Electromagnetic Tool (OAEMT) responses Logging While Drilling (LWD) according to the special structure of the OAEMT with multi annular grooves. The algorithm allows the solution of the 3D Maxwell’s equation in inhomogeneous media with arbitrary conductivity and magnetic permeability distributions. For improvement of the computational efficiency and the modeling accuracy of the responses of OAEMT with annular grooves filled with ferrite material on steel mandrel in a completely anisotropic media, several techniques are applied: 1) a 3-D cylindrical irregular grid to avoid stair-casing discretization errors in the transmitter, receiver, and mandrel geometries; 2) the electric field continuation to approximate the perfectly electric conducting (PEC) boundary condition for enhancement of the discrete accuracy of the Helmholtz equations on the surface of steel mandrel; 3) the standardization technique to determine the equivalent conductivity and permeability in a non-uniform element; 4) PARDISO direct solver to solve the discrete equation as far as possible for increase of solution stability. We validate the 3D FV results against the numerical mode matching method. The comparisons show very good agreement. Results from 3-D borehole problems in several complex formation conditions involving eccentric tools and dipping beds are given to demonstrate the robustness of the method.

1. Introduction
After about three decades of development, electromagnetic (EM) logging while drilling (LWD) has become one of the most commonly used tools for geo-steering and formation evaluation. Conventional EM LWD tools usually consist of only coaxial multiple transmitting antennas and two coaxial receiving antennas mounted coaxially on a steel drill collar to provide multiple depths of investigation and to suppress borehole irregularity and other effects. The tool mainly measures the attenuation (Att) and phase shift (Ps) of induced voltages between the two receivers to evaluate formation resistivity and formation boundary or oil-water contact (OWC) and to ensure optimal well placement within the target reservoir. However, conventional EM LWD tools are usually insensitive to a conductivity anisotropy, and the direction of the bed boundary because they are composed of coaxial coils only. It is difficult to determine simultaneously horizontal and vertical conductivities and efficiently distinguish the orientation of bed boundary, which a bit approach to only from the conventional LWD tools.
Azimuth EM LWD provides important azimuth resistivity information for the geo-steering, which can measure the inducted EM field around the drill collar in real-time and predict the position of the formation interface and the change of conductivity around the borehole. Resistivity information is particularly important in horizontal drilling to help determine the boundary position of the reservoir relative to the drill bit, to ensure that the bit is always within the target formation, optimize the hole trajectory, and maximize oil and gas production in a single well. Therefore, it is the basis of the geo-steering to study the numerical simulation technology and investigate the response characteristics of azimuth EM LWD under various complicated conditions.

At present, the main methods used in numerical simulation of EM LWD often replace the steel drill collars with smooth cylindrical conductors and assume that the receiving and transmitting coils are wrapped around the outside of the smooth drill collars, which can greatly simplify the algorithms. In fact, in order to improve the seismic capability and the transmitting efficiency \[1\], annular grooves are cut into the drill collar of the azimuth LWD tool. The grooves are filled with ferrite materials with high permeability, while the transmitting and receiving coils are installed inside the ferrite. Grooves make the surface of the steel drill collar no longer a smooth cylinder, which makes it difficult to model accurately. However, few published papers and related research results have considered the structure of the real azimuth LWD tool.

To investigate the OAEMT response LWD under the real drill collar structure, we establish the standardization equivalent conductivity and permeability calculation method of the heterogeneous element on the Yee's staggered grids in the cylindrical coordinate system. Based on 3D finite volume method (3D FV) and electric field continuation boundary conditions, the equations of the electric field coupling potentials in the heterogeneous conductivity and permeability models are discretized to form a large algebraic equation set about the unknown coupling potentials. The PARDISO direct solver is used to solve the discrete equation. The EM field intensity at any point in space is calculated by three-dimensional linear interpolation to determine the induced voltage at any receiver further. Finally, the effects of borehole dip angles, the permeability of the ferrite materials, and formation conductivity on the principal components and cross components responses of the azimuth logging are investigated through numerical results.

![Figure 1](image.png)

**Figure 1.** The structure of the drill collar with annular grooves of the OAEMT LWD. (a) The annular grooved drill collar and distribution of transmitting and receiving coils. (b) The annular groove structure and coaxial coil winding mode (c) Longitudinal section diagram and filling distribution around annular grooves

### 2. Formulation

Figure 1 is the structure diagram of the steel drill collar with annular grooves of the OAEMT LWD, which includes two pairs of axial transmitting antennas (TZ1/TZ2, TZ3/TZ4), one pair of axial receiving antennas (RZ1/RZ2) and one pair of transverse receiving antennas (RX1/RX2). Eight circular grooves are cut into the steel drill collar. The grooves are filled with ferrite and fiberglass materials, and the coils are wound around the ferrite in the annular grooves. Ferrite materials have high permeability. The drill collar can no longer be treated as a smooth homogeneous ideal conductor.
We select the attenuation ($\text{ATT}(m=1,2,3,4; n=1,2)$) and phase shift ($\text{PS}(m=1,2,3,4; n=1,2)$) of the induced voltage on the two axial receiving antennas as the principal components, and choose the real and imaginary part of the linear combination ($\text{V}_{i,x,y}(l=1,2; m=1,2...16; n=1,2)$) of the induced voltage of two symmetrical transmitting antennas on two transverse receiving antennas as the cross components, where the $m=1,2...16$ represents 16 different azimuth angles, and the $n=1,2$ represents two operating frequencies.

To investigate the OAEMT response characteristics, the following Maxwell equations are used:

$$\nabla \times \mathbf{E}(r, r_f) = i\omega \mu \mathbf{H}(r, r_f)$$

$$\nabla \times \mathbf{H}(r, r_f) = \sigma \mathbf{E}(r, r_f) + I_n L e^\sigma \delta(r - r_f)$$

where $\sigma$ is the complex conductivity tensor of the formation; $\mu$ is the permeability; $L$ is the length of the transmitting antennas. We introduce the coupling potential equation of electric field intensity $\mathbf{A}(r, r_f) = \mathbf{A}(r, r_f) + \nabla \phi(r, r_f)$, and combine it with the Coulomb gauge condition $\mathbf{V} \cdot \mathbf{A}(r, r_f) = 0$, the forward modeling is transformed into solving the Helmholtz equation as follows:

$$\nabla \times \nabla \mathbf{A}(r, r_f) - \nabla \nabla \mathbf{A}(r, r_f) - i\omega \mu \mathbf{A}(r, r_f) + \nabla \phi(r, r_f) = i\omega \mu L e^\sigma \delta(r - r_f)$$

The vector potential and standard potential meet the perfectly electric conducting (PEC) boundary condition:

$$\mathbf{n} \times \mathbf{A}(r, r_f)|_{\rho = \rho_m} = 0; \quad \phi(r, r_f)|_{\rho = \rho_m} = 0$$

Where, $\rho_m$ and $\rho_m$ represent drill collar boundary and infinity, respectively.

In order to ensure the accuracy of discretization, the PEC boundary condition is approximated by the electric field continuation:

$$A_{r_f}|_{\rho = \rho_m} = A_{r_f}|_{\rho = \rho_m}, \quad A_{r_f}|_{\rho = \rho_m} = -A_{r_f}|_{\rho = \rho_m}, \quad A_{r_f}|_{\rho = \rho_m} = -A_{r_f}|_{\rho = \rho_m}, \quad \phi|_{\rho = \rho_m} = 0$$

According to the finite volume method in literature [2], combined with Stokes formula, the surface integral of equation (2) is carried out on the outer surfaces $S_\alpha (\alpha = \rho, \phi, z)$ of the three positive directions of the grids $V_{i,j,k}$; the Gaussian divergence theorem is applied to calculate the volume average of equation (3) on the grids:

$$\int_{S_\alpha} \mathbf{n} \times \nabla \mathbf{A}(r, r_f) \cdot d\mathbf{l} = \frac{1}{|S_\alpha|} \iint_{S_\alpha} [\nabla \nabla \mathbf{A}(r, r_f)] \cdot d\mathbf{S}$$

$$-i\omega \mu L \iint_{S_\alpha} \nabla \phi(r, r_f) \cdot d\mathbf{S} = \iint_{S_\alpha} (I_n L e^\sigma \delta(r - r_f)) \cdot d\mathbf{S}$$

$$\int_{V_{i,j,k}} \nabla \cdot \mathbf{A}(r, r_f) + \nabla \cdot \phi(r, r_f) \cdot dV = \frac{1}{V_{i,j,k}} \iint_{V_{i,j,k}} \nabla \cdot [I_n L e^\sigma \delta(r - r_f)] dV$$

Combined with the mean value theorem of integrals, the equations (5) and (6) are discretized on Yee's staggered grids in the cylindrical coordinate system, and the following discrete equations are obtained:

$$FX = b$$
where $F$ is a large sparse asymmetric complex matrix, and the compressed sparse row (CSR) format is used to store the matrix, $X$ is an unknown vector made up of the vector potentials and the scalar potentials, $b$ is the discrete vector of the transmitting source.

The inverse matrix $F^{-1}$ is obtained by using PARDISO direct solver. Then the solution of the equation is obtained by multiplying the matrix multiple $X = F^{-1}b$ times for different emission sources. Newton interpolation formula is used to calculate the responses of the azimuth tool.

3. Numerical results

Firstly, in a cylindrical formation model with a horizontal conductivity of 0.1 S/m and an anisotropy coefficient of 1, in the case of the vertical borehole, the spatial distribution of electromagnetic fields calculated by the NMM method \[3\] is compared to verify our 3D FV algorithm. It can be seen from Figure 2 (a) and (b) that the spatial distribution of electromagnetic fields calculated by the two methods is basically the same, ignoring the effect inside the steel drill collar.

![Figure 2. Comparison of the spatial EM field.](image)

Figure 3 shows the influence of relative permeability change of the ferrite materials on EM response under different formation conductivities. The results show that the principal components are less affected by the change of the permeability and stable in the high resistivity formation. But the cross components are greatly affected. The cross components fluctuate abnormally when the relative permeability change from 75 to 400. And the higher the horizontal resistivity, the smaller the fluctuation range. Therefore, it is concluded that the permeability of the ferrite and the resistivity of the formation have significant effects on the response of the LWD tool.

Figure 4 shows the EM responses of 60° inclined borehole under different conductivities and anisotropy coefficients in a completely cylindrical medium. Figure 5 shows the variation of tool responses with anisotropic coefficients (ANCF) and borehole dip angles when the horizontal conductivity of the columnar formation model is 0.02 S/m. As can be seen from the Fig4, the drill collar has a great influence on the responses of the short spacing transmitting coils, which is caused by the small detection range of the short spacing. The presence of the steel drill collar slows the decay of the surrounding space field. The $P_s$ is very little affected by the steel drill collar under the condition of high
resistivity. This numerical result also proves the rationality of selecting phase differences to calculate formation conductivity at present. Drill collar has a great influence on cross components, and the cross components are very sensitive to the ANCF.

![Graph 1](image1)

**Figure 3.** The influence of permeability changes of the ferrite on the EM response under different formation conductivities of the 60° inclined borehole

(a) The principal components: ATT and PS

(b) The cross components

**Figure 4.** The EM response of 60° borehole of anisotropic columnar formation
The ATT and PS of the principal components vary monotonically with the horizontal conductivities of the formation in a certain range, while the cross components are the opposite, which makes it more difficult to extract the conductivity information in the actual logging process. Both principal and cross components vary monotonically with the ANCF. The principal components also vary linearly with the dip angles. While the cross components vary nonlinearly with the dip angles, which becomes an uncertain factor influencing the horizontal conductivity extraction in the actual logging process.

4. Conclusions
The numerical results show that the principal component of the OAEMT responses LWD is less affected by the drill collar, while the cross components can show a good probing ability, but it is greatly affected by the drill collar, borehole mud conductivity, anisotropy, and other factors. Therefore, the previous data processing and inversion methods based on layered media may be invalid, so it is necessary to study the 3D inversion method containing the impact of drill collars and boreholes to process the azimuth LWD data.

References
[1] Wang T and Signorelli J 2004 Finite-difference modeling of electromagnetic tool response for logging while drilling *Geophysics* 69 152-160
[2] Wang H S, Yang S W, Bai Y, Chen T and Wang H N 2016 Three-dimensional finite volume simulation of the response of azimuth electromagnetic wave resistivity while drilling in inhomogeneous anisotropic formation *Acta Physica Sinica* 65 079-101
[3] Wang H, So P, Yang S, Hoefer W J and Du H 2008 Numerical modeling of multicomponent induction well-logging tools in the cylindrically stratified anisotropic media *IEEE transactions on geoscience and remote sensing* 46 1134-1147