Pseudoanalytical Modeling of Electromagnetic Well-Logging Sensors Inside Directional Wells

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Abstract

Logging-while-drilling (LWD) electromagnetic sensors provide real-time resistivity data of the geophysical Earth formation for oilfield exploration. Proactive geosteering allows the exploration of deviated and horizontal wells by means of real-time adjustments in the drilling direction to steer the well towards a target region. In this paper, we describe a new pseudoanalytical technique to analyze LWD tools inside directional wells by using sections of toroidal structures, where axial bending is present. Preliminary results demonstrate the ability of our method to accurately modeling LWD tools in deviated drilling conditions.

1 Introduction

Compared to convention (i.e. strictly vertical) drilling, directional drilling yield several advantages for oil and gas exploration as oilfield productivity can be increased by deploying multiple wells drilled from a single platform. Additional benefits of directional drilling include: (a) drilling of a new well to intersect and recover an uncontrolled well, (b) sidetrack an old well to prospect new reservoirs, (c) horizontal wells placement, among others.

Logging-while-drilling (LWD) tools are electromagnetic sensors placed around a metallic mandrel within the well, as illustrated in Fig. 1, that can provided real-time data about the resistivity of the soil formation around the well borehole. Real-time logging interpretation allows the change in drilling direction towards a desired target region. Electromagnetic simulations of well-logging sensors within complex earth formations can be done by brute-force techniques such as finite differences, finite elements, or finite volumes [1–3]; however, their computational cost can become prohibitive for large problems. As an alternative, pseudoanalytical methods based on the Fourier-Bessel transform [4] or numerical mode-matching (NMM) [5, 6] can be used. However, the modeling of more complex geophysical formations as those of directional wells remains a challenging task to such pseudoanalytical methods. In this work, we extend the range of applicability of these methods by considering the modeling of directional well as junctions of finite-curvature sectors of radially-stratified toroidal waveguides. The proposed method can efficiently analyze the effects of curved boreholes on LWD sensor responses.

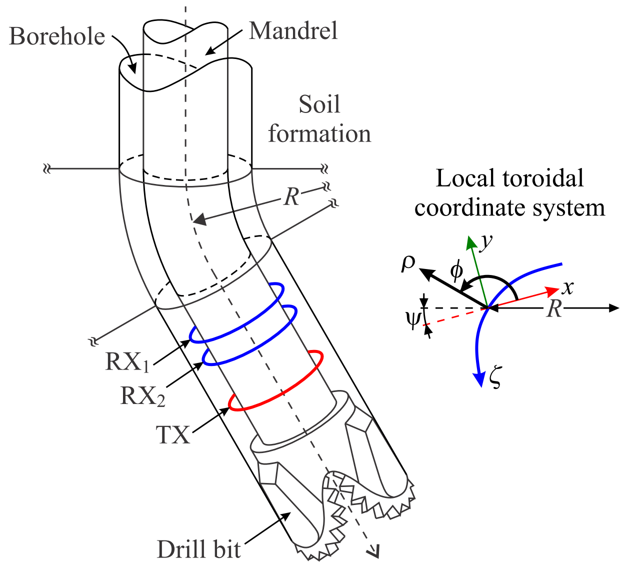

Figure 1. Geometry of a well-logging sensor within a directional well. An auxiliary coordinate system is presented.

2 Formulation Overview

The Helmholtz equation in toroidal coordinates is not separable as the product of three functions, each one with an exclusive dependence with one spatial coordinate, and the exact eigenmode solution involve complicated hypergeometric functions. A feasible approach to decouple and solve the fields in toroidal structures was presented in [7] using a perturbation method in terms of the torus curvature, viz., R^{-1}, such that the zeroth-order solution recovers the well-known eigenfields in cylindrical coordinates. Assuming and omitting the time-harmonic factor $\exp(-i\omega t)$, the vector fields in the local toroidal coordinates (ρ, ϕ, ζ) (see Fig. 1) can be written as

$$\mathbf{F}(\rho,\phi,\zeta) = \left[\mathbf{F}^{(0)}(\rho,\phi) + \sum_{j=1}^{\infty} R^{-j}\mathbf{F}^{(j)}(\rho,\phi)\right] e^{ik_\zeta \zeta}, \quad (1)$$

where the axial propagation constant is expanded as

$$k_\zeta = k_z\left(1 + \sum_{j=1}^{\infty} R^{-j}\alpha_j\right). \quad (2)$$

The quantities $\mathbf{F}^{(0)}(\rho,\phi)$ and k_z are the vector fields and axial propagation constant in cylindrical coordinates (ρ,ϕ,z), respectively. The jth finite-curvature correction is hence expressed in terms of $\mathbf{F}^{(j)}(\rho,\phi)$ and α_j. We generalized the technique presented in [8] to proper account the new fields in the local toroidal coordinates and then we used the Lorentz reciprocity theorem to expand the source (antenna TX shown in Fig. 1) in terms of modal fields (1) propagating in the axial direction (to $\pm\zeta$). Finally we obtained the LWD response (received voltages) by integrating the fields along the receiver antennas RX_1 and RX_2 (shown in Fig. 1).

3 Results

We present simulation results of a triaxial logging tool consisting of one transmitter and two receivers inside an directional-well borehole of constant curvature. Each antenna consists of a 5.5-in-radius coil wrapped around a 4-in-radius metallic mandrel inside a 7-in-radius borehole, where 1 in $= 2.54\times10^{-2}$ m. The borehole is filled with oil-based mud having conductivity equal to 5×10^{-4} S/m and the soil formation has conductivity equal to 1 S/m. The receivers RX_2 and RX_1 are placed axially (along the ζ-axis) at 24-in and 30-in away from the TX antenna, respectively. Fig. 2 shows the voltages (e.m.f.) evaluated at RX_2 and RX_1 for a LWD tool operating in the frequency range of 500 kHz to 2 MHz, for three curvature configurations: $R\to\infty$, $R = 400$ in and $R = 200$ in. Good agreement is observed versus the finite-difference time-domain (FDTD) results from CST [9]. The radial domain was truncated at 10-in in order to reduce the mesh size required by the FDTD model. For the sources considered here, only azimuthally independent transversal-electric to z modes would be produced in vertical borehole. In contrast, the finite-curvature case couples the axial fields and excites azimuthally non-symmetric hybrid modal fields. We have employed perturbed corrections up to order R^{-1}, and 10 modes with azimuthal indexes 0 and 1.

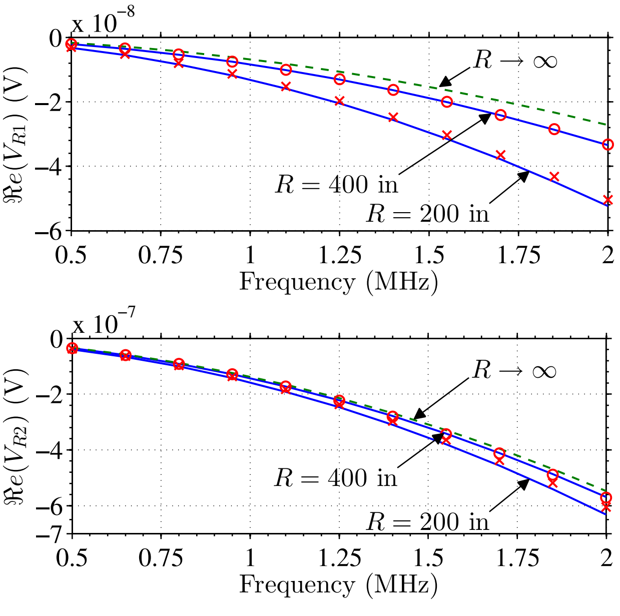

Figure 2. Voltages at RX_1 and RX_2. Zeroth-order results are shown by dashed-lines. The combination of the zeroth- and 1st-order perturbation corrections are indicated by solid lines. The small circles (for $R = 400$ in) and crosses (for $R = 200$ in) are FDTD results.

4 Conclusion

We have introduced a new formulation to model the response of well-logging tools in directional wells. The combination of closed-form solutions of Maxwell's equations in cylindrical coordinates with a perturbation technique allow us to express the fields inside an axially-toroidal and radially-layered Earth formation. Numerical results showed that the presented method can accurately model the electromagnetic propagation inside curved boreholes. This technique can be extended in the future to analyze more complex LWD tools inside directional wells with axial stratifications.

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