Introduction

As hydrocarbon exploration extends and develops, logging while drilling (LWD) technology is increasingly applied in high-angle and horizontal (HA/HZ) wells. To solve the production challenges in complex oil and gas reservoirs, LWD resistivity must be improved in the process of developing advanced LWD technology. Compared with gamma LWD, acoustic LWD, and other conventional electrical logging technologies, azimuthal electromagnetic (EM) resistivity LWD can provide comprehensive formation information and plays an important role in the boundary identification of oil-gas field development. Related azimuthal EM resistivity LWD innovations have been applied in reservoir mapping, geosteering HZ wells, and landing HA wells. Numerous azimuthal EM resistivity LWD designs exist, however, the process of signal processing for identification and formation evaluation is complicated in complex reservoirs, particularly in anisotropic formation. Therefore, the azimuthal signals of azimuthal EM resistivity LWD in anisotropic reservoirs must be analyzed to determine the most appropriate tool design.

In this paper, a forward numerical simulation of azimuthal EM resistivity LWD is created based on fast Hankel transform (FHT). Four kinds of azimuthal electromagnetic (EM) resistivity LWD tool are then introduced. The effect law of anisotropy on logging response is simulated in simple three-layer models in a HA well. Next, the anisotropy, thin target layer, and surrounding rock influence on azimuthal signals and apparent resistivity is analyzed using complex seven-layer models under different inclination angles. The applications of four kinds of azimuthal EM LWD tools are compared according to boundary identification and formation evaluation. The tool comparison provides substantial technical support in tool design and real-time formation evaluation, particularly for geosteering in the future.

Theory

The basic structure of the azimuthal EM resistivity logging tool is comprised of a single transmitter and receiver, as shown in Figure 1(a). $\theta_T$ and $\theta_R$ represent the angle between the instrumental axis and magnetic moment direction of the transmitter and receiver, respectively.

![Figure 1](image)

\textit{Figure 1} (a) Single transmitter-receiver tool; (b) Symmetrical double-transmitter-receiver tool; (c) Anti-symmetrical double-transmitter-receiver tool; (d) Common symmetrical double-transmitter-receiver tool.

The induced electromotive force at the receiving coil can be simplified as $V = -i\omega\mu H_n N_A A_r = a_0 + a_1 \cos \beta$, where $a_0$ and $a_1$ denote the coefficients of frequency, formation magnetic permeability, turns of the receiving coil, and surface area of the receiving coil, and $\beta$ denotes the rotation angle of the tool. The receiving signal shows a cosine change with $\beta$ and contains azimuthal information of the formation, indicating azimuthal recognition of the tool. The azimuthal signal is calculated using information at two different rotation angles (180° difference), representing the magnetic field difference between two directions. The maximum signal difference is defined as the azimuthal amplitude attenuation ($\text{Att}$) and azimuthal phase shift ($\text{PS}$) of the single transmitter-receiver in Eq. (1) and Eq. (2), respectively.

$$\text{Att} = -10\log\left[\frac{\text{Re}(a_0) + \text{Re}(a_1)}{\text{Re}(a_0) - \text{Re}(a_1)}\right] + \frac{[\text{Im}(a_0) + \text{Im}(a_1)]}{[\text{Im}(a_0) - \text{Im}(a_1)]}$$

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Due to the short time difference between drilling and logging, EM resistivity LWD is less affected by drilling filtrate invasion. The boundary of each layer is at \( d_n \) (n=1,2,..., N) in the formation model. It is assumed that the emission source is contained in the \( m_{th} \) layer, and there are N layers above it. The top layer and the bottom layer are both semi-infinite thick media. The z-axis is the formation normal direction, and the x-axis is the horizontal projection direction of the borehole axis. The electromagnetic field distribution can be calculated based on the transmission and reflection law of the transverse-electric (TE) and transverse-magnetic (TM) wave. The component of the magnetic field is in Sommerfeld integral form, which contains the Bessel function as shown in Eq. (3), and can be solved using the fast Hankel transform (FHT) method.

\[
g(\rho) = \int_{0}^{\infty} k_{\rho} f(k_{\rho}) J_{\nu}(k_{\rho} \rho) dk_{\rho}
\]

Compared with the analytical solution, the numerical simulation of amplitude attenuation and phase shift are thus determined to be correct. For the FHT method, the amplitude attenuation accuracy is 99.77%, and the phase shift accuracy is 99.79%. Therefore, this simulation method is determined as suitable for the EM resistivity LWD response in different formation models.

**Figure 2 Calculation accuracy of FHT method.**

**Examples**

To analyze the anisotropy influence on the logging response in vertical and HA wells (\( \alpha = 85^\circ \)), three-layer models were then constructed based on FHT method. The horizontal resistivity of the target layer was set to 20 \( \Omega \cdot \text{m} \), and the four resistivity anisotropy coefficients \( \frac{\lambda^2}{R} = \frac{R}{R_b} \) were 1, 2, 4, and 6.

As shown in Figure 3(a), in a reasonable range of formation anisotropy, the influence on phase shift is more obvious than amplitude attenuation. However, the phase shift cannot accurately identify anisotropy at the boundary. The existence of resistivity anisotropy in the target layer alters the azimuthal signal value so that it is no longer zero at the section far from the boundary. Given several unknown formation parameters, resistivity anisotropy presents obstacles for boundary prediction and can lead to false judgments. Figure 3(b) shows the response of the symmetrical double-transmitter-receiver tool. The azimuthal signals remain at zero in the anisotropic target layer far away from the boundary and are sensitive to the boundary, while the sensitivity to formation anisotropy is reduced compared to the single transmitter-receiver tool. Figure 3(c) illustrates that the azimuthal signals are sensitive to formation resistivity anisotropy when it is far away from the boundary and remains sensitive to the boundary. However, the signal is weaker than the single transmitter-receiver tool and fails to identify the azimuth of the boundary. In Figure 3(d), the common symmetrized azimuthal signals poorly identify the azimuth and anisotropy of the formation. Therefore, symmetrized and anti-symmetrized azimuthal signals are suitable for azimuthal detection in anisotropic formation.
Figure 3 (a) Single azimuthal signals; (b) Symmetrized azimuthal signals; (c) Anti-symmetrized azimuthal signals; (d) Common symmetrized azimuthal signals under different anisotropic three-layer formation conditions.

The anisotropy, thin target layer, and surrounding rock influence on azimuthal signals and apparent resistivity was then analyzed in complex seven-layer models under different inclination angles. As shown in Figure 4, a larger inclination angle creates stronger single azimuthal signals, symmetrized azimuthal signals, anti-symmetrized signals, apparent resistivity, and improved boundary recognition effect, while the weaker common symmetrized azimuthal signals. Under the complex reservoir condition in the HA well, the thicker the target layer is, the closer the amplitude attenuation resistivity is to the formation horizontal resistivity, and the closer phase shift resistivity is to formation vertical resistivity. When the surrounding rocks of the thin target layer are not symmetrized, the azimuthal signals are significantly affected by the surrounding rocks which fail to adequately identify the formation boundary. Compared with single azimuthal signals, symmetrized azimuthal signals are more accurate in obtaining the anisotropic formation boundary, especially in the vertical well and low angle well. Additionally, anti-symmetrized signals without azimuthal information are more sensitive to the anisotropic formation than single azimuthal signals and commonly used symmetrized azimuthal signals. The boundary identification ability of the commonly used symmetrized azimuthal signals is weaker than that of symmetrized signals. In summary, the response of all symmetrical double-transmitter-receiver tools can identify the thin layer boundary and anisotropic information more accurately than that of the single transmitter-receiver tool.
Figure 4 (a) Single azimuthal signals (b) Symmetrized azimuthal signals (c) Anti-symmetrized azimuthal signals (d) Common symmetrized azimuthal signals (e) Apparent resistivity in seven-layer model.

Conclusions and Discussions

Azimuthal signals of the EM resistivity LWD tool were found to be sensitive to the formation boundary, even for thin target layers. The tool also demonstrated a strong ability for azimuthal information identification, especially in HA well applications. A symmetrical transmitter-receiver structure should therefore be applied in the tool design of azimuthal EM LWD. For signal processing, symmetrized azimuthal signals should be used for boundary identification, while anti-symmetrized azimuthal signals as well as measured resistivity are recommended for formation evaluation. This tool comparison offers substantial technical support for tool design and real-time formation evaluation, particularly in future geosteering applications.

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