

随钻电磁波测井仪器偏心条件下响应模拟与分析

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摘要:为模拟仪器偏心条件下随钻电磁波测井响应,为随钻仪器偏心校正提供理论基础,基于时域有限差分(FDTD)进行随钻电磁波仪器偏心条件下响应模拟与分析。采用柱坐标系非均匀网格与“阶梯近似”实现对井眼、线圈和仪器偏心的精细模拟,采用各向异性完全匹配层(UPML)实现对反射场的吸收,以减小模型计算规模,从而提高计算速度。通过与一维解析解和偏心条件下半解析解对比,验证了算法的正确性。采用哈里伯顿 EWR-Phase4 随钻电磁波测井仪,对不同钻井液电阻率、井眼尺寸、发射频率与不同线圈距条件下的仪器响应进行模拟。结果表明:相位差电阻率较幅度比电阻率更易受仪器偏心的影响;线圈距越大、井眼越大、发射频率越高,测井响应受仪器偏心影响越大;对常规砂泥岩地层,当发射频率为 2 MHz,钻井液电阻率小于 $0.1 \Omega \cdot \text{m}$ 时,需要对中源距与深源距响应进行偏心校正。

关键词:随钻电磁测井; 仪器偏心; 时域有限差分; 各向异性吸收边界

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Numerical modeling and analysis of responses of eccentric electromagnetics logging while drilling tool

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Abstract: In order to model the electromagnetic logging responses while drilling with tool eccentricity and to provide theoretic basis for the eccentricity correction, the responses with tool eccentricity were simulated and analyzed based on the finite-difference time-domain (FDTD) framework. Non-uniform gridding technique in cylindrical coordinates and staircase approximation technique were utilized to reach fine simulation of borehole, coils, tool eccentricity. In addition, the UPML absorbing boundary condition was implemented to absorb reflection field, which could reduce the model size and improve simulation speed. By comparing the simulation results with the one-dimension analytical solution and the semi-analytic results with tool eccentricity, the algorithm was verified favorably. In addition, the responses of the Halliburton EWR-Phase4 Electromagnetic LWD tool under different eccentricity distances, mud resistivity, borehole sizes, coil-spacing and frequencies were simulated. The results show that the phase difference resistivity is affected more by tool eccentricity than the attenuation resistivity. With larger coil-spacing and borehole size and higher frequency, the responses are more sensitive to tool eccentricity. In conventional sand-shale reservoirs, for 2 MHz frequency, eccentricity correction needs to be applied to the responses of middle coil-spacing and long coil-spacing when the mud resistivity is less than $0.1 \Omega \cdot \text{m}$.

Key words: electromagnetic logging-while-drilling; tool eccentricity; finite-difference time-domain; anisotropic absorbing boundary

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随着大斜度井/水平井(HA/HZ)等特殊钻井工艺的不断推广应用,随钻电磁波测井因其受钻井环境影响较小、且能够提供实时地质导向与储层评价功能而备受关注。杨锦舟、杨震、Teixeira 以及 Liu 等对电磁波测井响应进行了模拟^[1-5],魏宝君、Hue 等^[6-7]对偏心条件下随钻电磁波响应进行了模拟,并定性分析了不同偏心距、不同钻井液电阻率条件下的测井响应特征。国内随钻测井技术尚属起步阶段,对复杂地层条件下的随钻电磁波测井响应特征的认识不够系统全面,尤其对 HA/HZ 井中由重力影响造成的仪器偏心研究较少^[8-10]。笔者采用圆柱坐标系时域有限差分方法(FDTD)对偏心条件下随钻电磁波测井响应进行全面、系统的模拟与分析,并对随钻电磁波测井需要进行偏心校正的条件进行定量分析,为基于随钻电磁波测井资料进行地质导向与储层评价提供理论基础。

1 圆柱坐标系时域有限差分方法

1.1 圆柱坐标系麦克斯韦方程

为了实现对井眼、线圈精细模拟,减小剖分造成的误差,采用圆柱坐标系下的时域有限差分方法(FDTD),使得仪器轴、井眼等与坐标系相匹配,地层模型见图 1,在无源区域麦克斯韦方程的微分形式^[11]可以表示为

$$\nabla \times H = \varepsilon \frac{\partial E}{\partial t} + \sigma E, \quad (1)$$

$$\nabla \times E = -\mu \frac{\partial H}{\partial t} - \sigma_m H. \quad (2)$$

式中, ε 、 μ 、 σ 及 σ_m 分别为地层的介电常数、磁导率、电导率和导磁率。

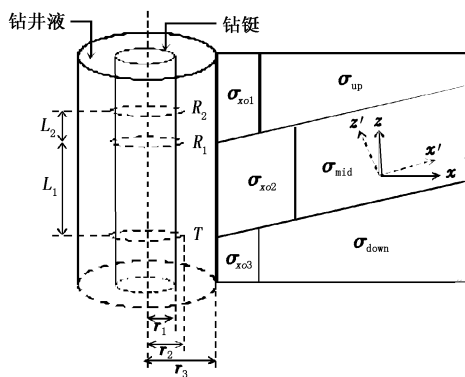


图 1 地层模型与仪器结构示意图

Fig. 1 Schematic drawing of formation model and logging tool

圆柱坐标系下麦克斯韦方程的分量形式为

$$\begin{cases} \frac{1}{r} \frac{\partial H_z}{\partial \phi} - \frac{\partial H_\phi}{\partial z} = \varepsilon \frac{\partial E_r}{\partial t} + \sigma E_r, \\ \frac{\partial H_r}{\partial z} - \frac{\partial H_z}{\partial r} = \varepsilon \frac{\partial E_\phi}{\partial t} + \sigma E_\phi, \\ \frac{1}{r} \frac{\partial (r H_\phi)}{\partial r} - \frac{1}{r} \frac{\partial H_r}{\partial \phi} = \varepsilon \frac{\partial E_z}{\partial t} + \sigma E_z. \end{cases} \quad (3)$$

$$\begin{cases} \frac{1}{r} \frac{\partial E_z}{\partial \phi} - \frac{\partial E_\phi}{\partial z} = -\mu \frac{\partial H_r}{\partial t} - \sigma_m H_r, \\ \frac{\partial E_r}{\partial z} - \frac{\partial E_z}{\partial r} = -\mu \frac{\partial H_\phi}{\partial t} - \sigma_m H_\phi, \\ \frac{1}{r} \frac{\partial (r E_\phi)}{\partial r} - \frac{1}{r} \frac{\partial E_r}{\partial \phi} = -\mu \frac{\partial H_z}{\partial t} - \sigma_m H_z. \end{cases} \quad (4)$$

为进行离散,定义以下参数: $\Delta r_1(i)$ 为径向上两相邻网格中心间的距离; $\Delta r_2(i)$ 为径向上每个网格的长度; $r(i)$ 和 $r(i + 1/2)$ 均代表网格上场点所在位置处到 z 轴的距离。采用中心差分格式如下:

$$E_r^{n+1}\left(i + \frac{1}{2}, j, k\right) = CA(m) E_r^n\left(i + \frac{1}{2}, j, k\right) + CB(m) \times \left[\frac{H_z^{n+\frac{1}{2}}\left(i + \frac{1}{2}, j + \frac{1}{2}, k\right) - H_z^{n+\frac{1}{2}}\left(i + \frac{1}{2}, j - \frac{1}{2}, k\right)}{r\left(i + \frac{1}{2}\right) \Delta \phi} - \frac{H_\phi^{n+\frac{1}{2}}\left(i + \frac{1}{2}, j, k + \frac{1}{2}\right) - H_\phi^{n+\frac{1}{2}}\left(i + \frac{1}{2}, j, k - \frac{1}{2}\right)}{\Delta z} \right], \quad (5)$$

其中, $m = (i + 1/2, j, k)$;

$$E_\phi^{n+1}\left(i, j + \frac{1}{2}, k\right) = CA(m) E_\phi^n\left(i, j + \frac{1}{2}, k\right) + CB(m) \times \left[\frac{H_r^{n+\frac{1}{2}}\left(i, j + \frac{1}{2}, k + \frac{1}{2}\right) - H_r^{n+\frac{1}{2}}\left(i, j + \frac{1}{2}, k - \frac{1}{2}\right)}{\Delta z} - \frac{H_z^{n+\frac{1}{2}}\left(i + \frac{1}{2}, j + \frac{1}{2}, k\right) - H_z^{n+\frac{1}{2}}\left(i - \frac{1}{2}, j + \frac{1}{2}, k\right)}{\Delta r_1(i)} \right], \quad (6)$$

其中, $m = (i, j + 1/2, k)$;

$$E_z^{n+1}\left(i, j, k + \frac{1}{2}\right) = CA(m) E_z^n\left(i, j, k + \frac{1}{2}\right) + CB(m) \times \left[\frac{r\left(i + \frac{1}{2}\right) H_\phi^{n+\frac{1}{2}}\left(i + \frac{1}{2}, j, k + \frac{1}{2}\right) - r\left(i - \frac{1}{2}\right) H_\phi^{n+\frac{1}{2}}\left(i - \frac{1}{2}, j, k + \frac{1}{2}\right)}{r(i) \Delta r_1(i)} - \frac{H_r^{n+\frac{1}{2}}\left(i, j + \frac{1}{2}, k + \frac{1}{2}\right) - H_r^{n+\frac{1}{2}}\left(i, j - \frac{1}{2}, k + \frac{1}{2}\right)}{r(i) \Delta \phi} \right], \quad (7)$$

其中, $m = (i, j, k + 1/2)$;

$$H_r^{n+\frac{1}{2}}\left(i, j + \frac{1}{2}, k + \frac{1}{2}\right) =$$

$$CP(m)H_r^{n-\frac{1}{2}}\left(i, j + \frac{1}{2}, k + \frac{1}{2}\right) - CQ(m) \times \left[\frac{E_z^n\left(i, j + 1, k + \frac{1}{2}\right) - E_z^n\left(i, j, k + \frac{1}{2}\right)}{r(i)\Delta\phi} - \frac{E_\phi^n\left(i, j + \frac{1}{2}, k + 1\right) - E_\phi^n\left(i, j + \frac{1}{2}, k\right)}{\Delta z} \right], \quad (8)$$

其中, $m = (i, j + 1/2, k + 1/2)$;

$$H_\phi^{n+\frac{1}{2}}\left(i + \frac{1}{2}, j, k + \frac{1}{2}\right) =$$

$$CP(m)H_\phi^{n-\frac{1}{2}}\left(i + \frac{1}{2}, j, k + \frac{1}{2}\right) - CQ(m) \times \left[\frac{E_r^n\left(i + \frac{1}{2}, j, k + 1\right) - E_r^n\left(i + \frac{1}{2}, j, k\right)}{\Delta z} - \frac{E_z^n\left(i + 1, j, k + \frac{1}{2}\right) - E_z^n\left(i, j, k + \frac{1}{2}\right)}{\Delta r_2(i)} \right], \quad (9)$$

其中, $m = (i + 1/2, j, k + 1/2)$;

$$H_z^{n+\frac{1}{2}}\left(i + \frac{1}{2}, j + \frac{1}{2}, k\right) =$$

$$CP(m)H_z^{n-\frac{1}{2}}\left(i + \frac{1}{2}, j + \frac{1}{2}, k\right) - CQ(m) \times \left[\frac{r(i+1)E_\phi^n\left(i + 1, j + \frac{1}{2}, k\right) - r(i)E_\phi^n\left(i, j + \frac{1}{2}, k\right)}{r\left(i + \frac{1}{2}\right)\Delta r_2(i)} - \frac{H_r^n\left(i + \frac{1}{2}, j + 1, k\right) - E_r^n\left(i + \frac{1}{2}, j, k\right)}{r\left(i + \frac{1}{2}\right)\Delta\phi} \right], \quad (10)$$

其中, $m = (i + 1/2, j + 1/2, k)$ 。

式(5) ~ (10) 中相应的系数分别为

$$CA(m) = \frac{2\varepsilon(m) - \sigma(m)\Delta t}{2\varepsilon(m) + \sigma(m)\Delta t},$$

$$CB(m) = \frac{2\Delta t}{2\varepsilon(m) + \sigma(m)\Delta t}, \quad (11)$$

$$CP(m) = \frac{2\mu(m) - \sigma_m(m)\Delta t}{2\mu(m) + \sigma_m(m)\Delta t},$$

$$CQ(m) = \frac{2\Delta t}{2\mu(m) + \sigma_m(m)\Delta t}. \quad (12)$$

1.2 非均匀网格剖分

为精确地模拟仪器偏心对随钻电磁波测井响应的影响,并提高计算效率,在径向 r 和纵向 z 上均采用

非均匀网格剖分(图2)。纵向上,在接收线圈位置采用局部加密,以增加接收信号的精度。在径向上,线圈与钻铤之间步长为 $\Delta\rho_1$,线圈与井眼之间为 $\Delta\rho_2$,井眼外侧 $\Delta\rho$ 逐渐增大到最大网格步长($\Delta\rho_{\max} = \delta/5$)。其中 δ 为模型中最大电阻率对应的趋肤深度:

$$\delta = \frac{1}{\omega\sqrt{\mu\varepsilon}} \left\{ \frac{1}{2} \left[\sqrt{1 + \left(\frac{\sigma}{\mu\varepsilon} \right)^2} - 1 \right] \right\}^{-1/2}. \quad (13)$$

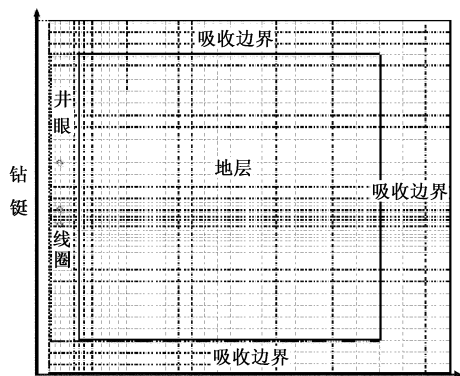


图2 网格剖分示意图

Fig. 2 Schematic drawing of mesh

1.3 UPML 吸收边界条件

为模拟无穷区域的电磁波传播现象,同时避免在截断边界处产生反射现象,需要在模拟区域外侧加入吸收边界,从而将电磁波等效为在无限区域中传播。采用各向异性完全匹配层(UPML)作为吸收边界进行时域有限差分数值模拟^[12-14],在圆柱坐标系下,UPML吸收边界中麦克斯韦方程组微分形式可以表示为

$$\Delta \times H = j\omega\tilde{\varepsilon}E, \quad (14)$$

$$\Delta \times E = -j\omega\tilde{\mu}H. \quad (15)$$

当式(14)、(15) 介质本构参数满足以下条件时,即可以实现吸收边界处无反射:

$$\tilde{\varepsilon} = \left(\varepsilon + \frac{\sigma}{j\omega} \right) \cdot \text{diag} \left(\frac{S_{\tilde{\rho}}}{S_{\rho}}, \frac{S_z S_{\rho} \tilde{\rho}}{\tilde{\rho}}, \frac{S_{\rho} \tilde{\rho}}{S_z \rho} \right), \quad (16)$$

$$\tilde{\mu} = \mu \cdot \text{diag} \left(\frac{S_{\tilde{\rho}}}{S_{\rho}}, \frac{S_z S_{\rho} \tilde{\rho}}{\tilde{\rho}}, \frac{S_{\rho} \tilde{\rho}}{S_z \rho} \right). \quad (17)$$

其中, $\tilde{\rho}$ 为扩展坐标系中 ρ 所对应的变量,其表达式为

$$\tilde{\rho} = \rho_0 + \int_{\rho_0}^{\rho} S_{\rho} d\rho'. \quad (18)$$

S_{ρ} 、 S_z 分别为扩展坐标系中频率域的变量,其表达式分别为

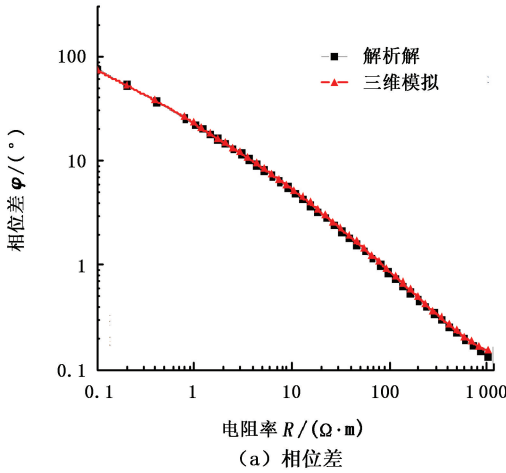
$$S_{\rho} = \kappa_{\rho} + \sigma_{\rho}/(j\omega\varepsilon_0), \quad (19)$$

$$S_z = \kappa_z + \sigma_z/(j\omega\varepsilon_0). \quad (20)$$

其中

$$\kappa_{\rho} = 1 + (\kappa_{\max} - 1) \left(\frac{\rho - \rho_0}{\rho_1 - \rho_0} \right)^p,$$
$$\kappa_z = 1 + (\kappa_{\max} - 1) \left(\frac{\rho - \rho_0}{\rho_1 - \rho_0} \right)^p,$$
$$\sigma_{\rho} = \sigma_{\rho\max} \left(\frac{\rho - \rho_0}{\rho_1 - \rho_0} \right)^m, \sigma_z = \sigma_{z\max} \left(\frac{\rho - \rho_0}{\rho_1 - \rho_0} \right)^m.$$

式中, ρ_0 和 ρ_1 分别为 UPML 层的内边界和外边界。通过选择适当的 $\kappa_{\max}$ 、 $\sigma_{\rho\max}$ 、 $\sigma_{z\max}$ 值, 使在 UPML 层内满足 κ_{ρ} 、 κ_z 均大于 1, σ_{ρ} 、 σ_z 均大于 0, 从而使得 UPML 介质中的电磁波迅速衰减。在计算区域内, 则满足 $\kappa_{\rho} = \kappa_z = 1$, $\sigma_{\rho} = \sigma_z = 0$, m 和 p 分别为整数, 本文中 $m = 4$, $p = 2$ 。



2 数值模拟与验证

测井过程中, 通过测量两接收线圈感应电动势的相位差和幅度比, 进而刻度成为相位差电阻率和幅度比电阻率^[15-16], 其定义如下:

$$PD = \arg(V_{R_1}) - \arg(V_{R_2}), \tag{21}$$

$$AR = 20 \log V_{R_2}/V_{R_1}. \tag{22}$$

式中, ϕ 为相位差; A 为幅度比; V 为接收线圈电位; R_1 、 R_2 分别为两接收线圈。

图 3 为均匀地层 FDTD 三维数值模拟结果与解析解结果对比, 两者能很好地吻合, 验证了算法的正确性。

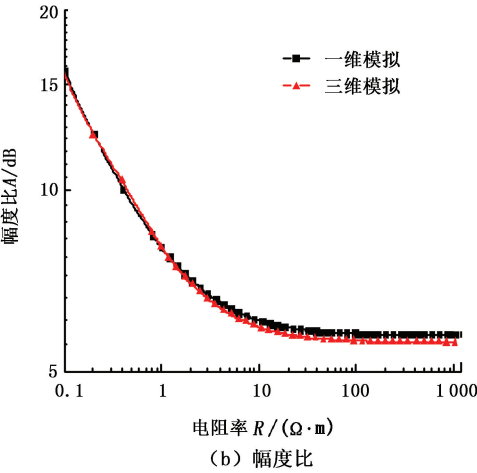


图 3 均匀地层解析解与三维数值模拟结果对比

Fig. 3 Comparison of 3D FDTD simulation results with analytical results in homogeneous formation

仪器偏心模型如图 4, 其中线圈半径(r_{coil})为 11.43 cm, 仪器轴半径(r_{mandrel})为 10.16 cm, r_{borehole} 为井眼半径, r_{offset} 为仪器偏心距, 定义为仪器轴心到井眼中心的距离。本文中采用“阶梯近似”方法对井

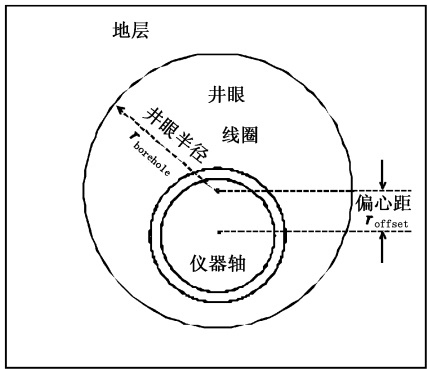


图 4 仪器偏心模型横切面

Fig. 4 Horizontal corss-section of an eccentric borehole problem

眼与地层的边界进行处理, 即首先确定网格中心点所处的介质区域, 并规定该介质区域为整个网格所属的区域, 如图 5 所示。然而正是“阶梯近似”给模

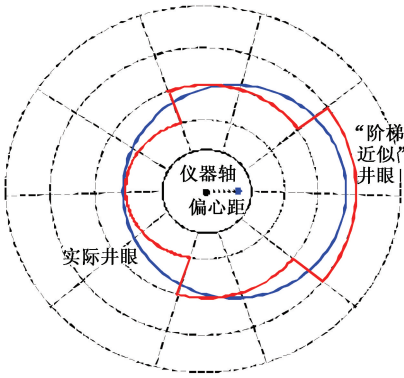


图 5 “阶梯近似”示意图

Fig. 5 Schematic drawing of staircase approximation

拟引进了误差, 为了分析该误差对响应的影响, 本文模拟了井眼半径为 30.48 cm, 钻井液电阻率为 0.1 $\Omega \cdot \text{m}$, 地层电阻率为 10 $\Omega \cdot \text{m}$, 不同偏心距条件下随钻电磁波仪器响应, 并与 Hue^[7] 文献中的半解析解进行对比 (图 6)。由图中可以看出, 两种算法模拟结果基本吻合, 模型偏离柱坐标系中心时所采用的“阶梯近似”对响应的影响较小, 从而验证了算法

的正确性。此时幅度比定义为: $A=V_{R_1}/V_{R_2}$ 。

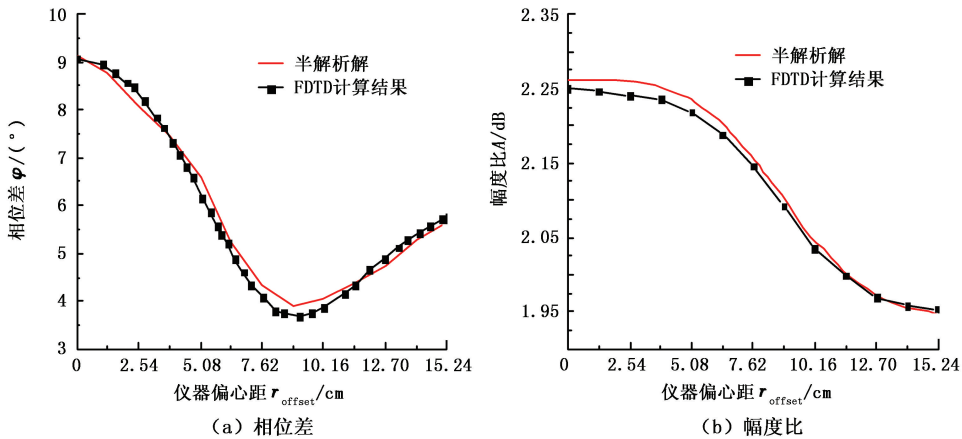


图 6 仪器偏心条件下随钻电磁波测井响应 FDTD 与半解析解模拟结果

Fig. 6 FDTD simulation results and analytical results of electromagnetics LWD response in eccentric borehole

3 仪器偏心条件下随钻电磁波测井响应分析

3.1 钻井液性质的影响

分别对水基钻井液与油基钻井液模拟了不同偏

心距条件下随钻电磁波测井响应(图 7、8)。水基钻井液条件下,钻井液电阻率较低($R_{\text{mud}} \leq 0.1 \Omega \cdot \text{m}$)时,随钻电磁波测井响应受偏心影响较明显,且随偏心距增大呈非线性变化,需要进行偏心校正。油基钻井液条件下(钻井液电阻率取 $2000 \Omega \cdot \text{m}$),当地

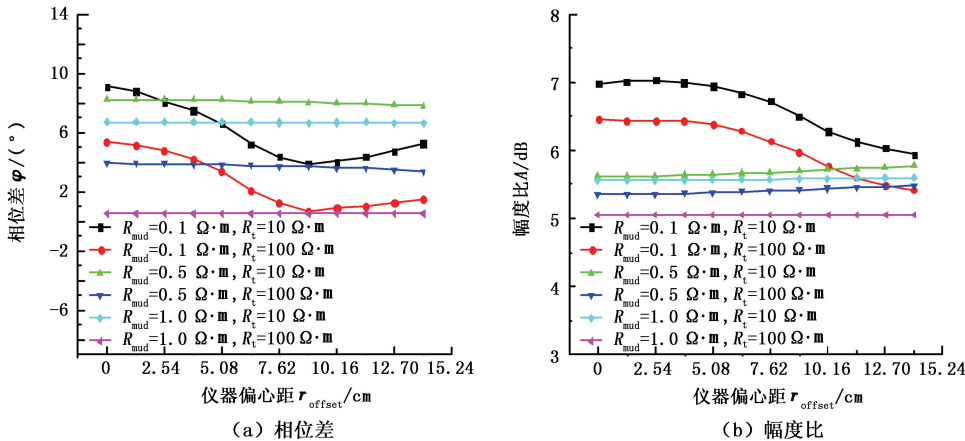


图 7 水基钻井液随钻电磁波测井响应受仪器偏心影响

Fig. 7 FDTD simulation of response of eccentric LWD tool in water-based drilling fluid

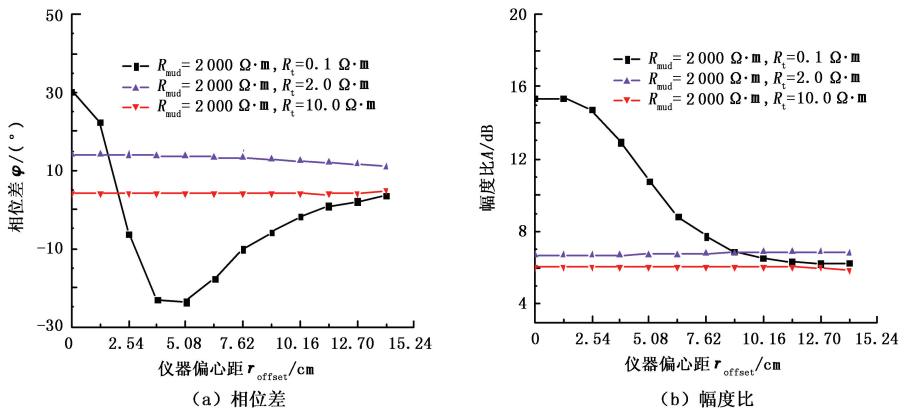


图 8 油基钻井液随钻电磁波测井响应受仪器偏心影响

Fig. 8 FDTD simulation of response of eccentric LWD tool in oil-based drilling fluid

层电阻率小于 $0.1 \Omega \cdot \text{m}$ 时,随钻电磁波响应才受仪器偏心影响,因而对常规砂泥岩地层,不需考虑仪器偏心影响。

3.2 井眼尺寸的影响

钻井过程中经常会出现井壁坍塌、扩径、缩径等现象,导致井眼大小发生变化,为分析不同尺寸井眼条件下仪器偏心对随钻电磁波测井响应的影响,分别建立以下模型进行对比分析(图 9):模型 1 中仪器呈居中测量状态,无偏心;模型 2 为仪器偏心、贴井壁测量状态,设置仪器轴心与井壁之间距离为一定值 $d = 12.7 \text{ cm}$;对不同井眼半径条件下两种模型

的模拟结果见图 10。

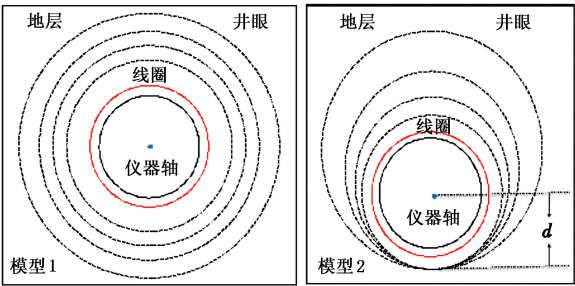


图 9 井眼模型

Fig. 9 Borehole models with different size

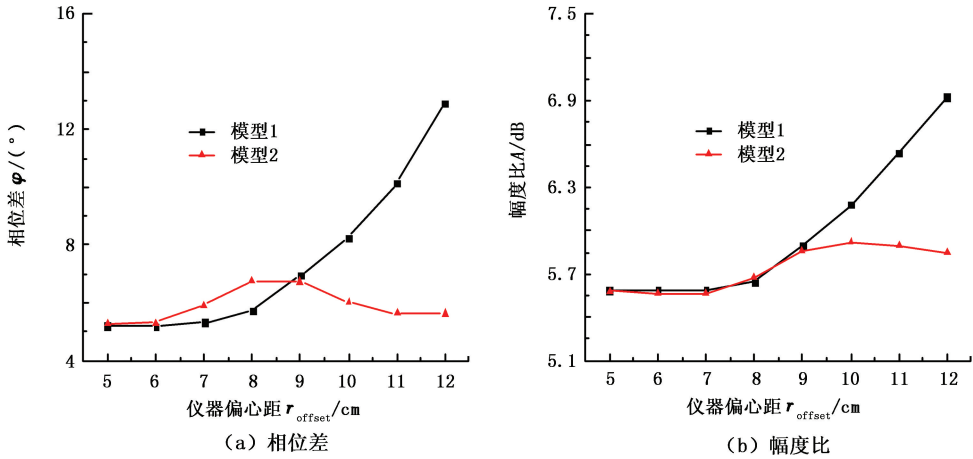


图 10 不同井眼大小随钻电磁波测井响应

Fig. 10 FDTD simulation of response of eccentric LWD tool with different borehole sizes

仪器居中时,相位差曲线和幅度比曲线均随井眼半径的增大而单调增大,而仪器存在偏心时,随井眼半径的增大,随钻电磁波响应呈现非单调变化趋势。当井眼较小时(井眼半径约小于 17.78 cm),仪器偏心对响应的影响较小,两种模型中仪器响应相近;当井眼较大或出现扩径时,二者出现明显偏差,

仪器响应受偏心影响。

3.3 工作频率的影响

传统随钻电磁波测井仪器工作频率为 $0.1 \sim 10 \text{ MHz}$,其中以 2 MHz 的工作频率最为常见,图 11 为不同工作频率偏心条件下随钻电磁波测井响应。

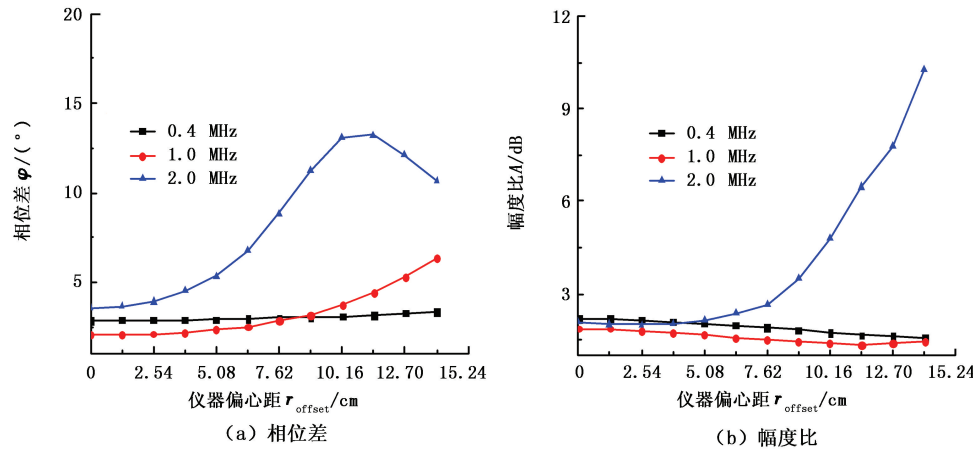


图 11 仪器偏心时不同频率随钻电磁波测井响应

Fig. 11 FDTD simulation of response of eccentric LWD tool with different frequencies

随着仪器工作频率的增大,测井响应受偏心影响越大,且相位电阻率较幅度比电阻率更易受偏心影响,对偏心距大于 5.08 cm 的 2 MHz 信号,需要考虑偏心校正,而 0.4 MHz 曲线基本不受偏心影响,测井过程中,当出现严重偏心时可参考低频测井曲线确定地层真实电阻率。

3.4 线圈距的影响

图 12 为不同线圈距仪器偏心条件下随钻电磁

波测井响应,由图可以看出:线圈距较大时(如 [60.96,76.2] cm、[91.44,106.68] cm)随钻电磁波测井响应受仪器偏心的影响较明显,且相位差电阻率较幅度比电阻率更易受偏心影响,当偏心距较小时($r_{\text{offset}} \leq 7.62$ cm),幅度比响应几乎不受偏心的影响;线圈距较小时(如 [15.24,30.48] cm、[30.48,45.72] cm)仪器响应均可不考虑偏心影响。

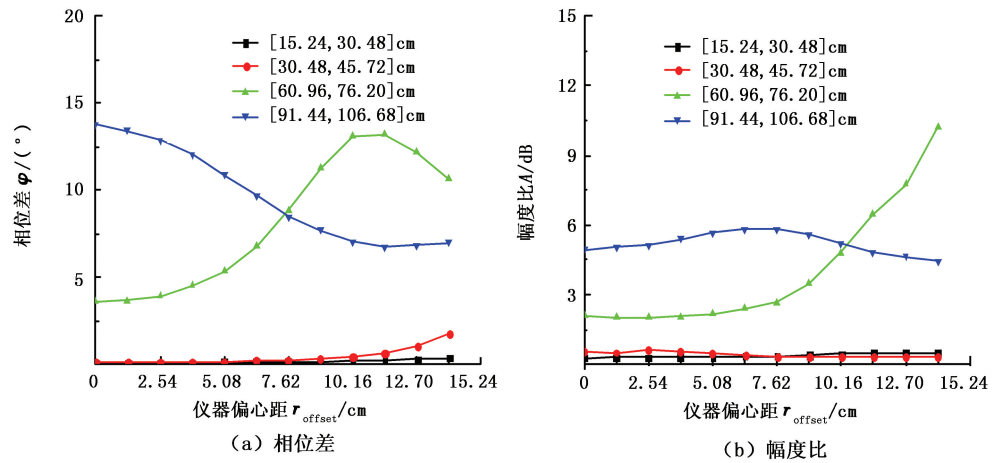


图 12 仪器偏心时不同线圈距随钻电磁波测井响应

Fig. 12 FDTD simulation of response of eccentric LWD tool with different coil spacing

4 结束语

采用柱坐标系时域有限差分方法对偏心条件下随钻电磁波仪器响应进行了模拟与分析,利用各向异性吸收边界避免了反射场的影响,减小了模型计算规模。将三维模拟结果分别与均匀空间解析解和偏心条件下半解析解进行对比,验证了算法的正确性。对常规砂泥岩地层,当钻井液电阻率小于 $0.1 \Omega \cdot \text{m}$ 时,随钻电磁波仪器响应明显受仪器偏心影响,需要进行偏心校正;对油基钻井液基本不需考虑仪器偏心影响;仪器发射频率越高、线圈距越大、井眼越大,随钻电磁波测井响应受偏心影响越大,针对哈里伯顿 EWR-Phase4 随钻电磁波测井仪以及文中所定义的测井环境,当井径大于 17.78 cm,发射频率为 2 MHz 时,需对中源距与深源距探测响应进行偏心校正。

本文主要针对钻井过程中仪器偏心对随钻电磁波测井响应的影响进行了正演模拟与规律分析,随钻测井过程中,应首先确定钻井液性质、井眼几何形状与仪器位置,针对具体情况进行偏心校正,对实际资料的处理校正仍需进一步研究探讨。

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