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Environmental corrections of a dual-induction logging while drilling tool in vertical wells

Zhengming Kang [a,b], Shizhen Ke [a,b,*], Ming Jiang [a,b], Chengfang Yin [a,b], Anzong Li [c], Junjian Li [a,b]

[a] *College of Geophysics and Information Engineering, China University of Petroleum, Beijing, China*
[b] *State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing, China*
[c] *China Petroleum Logging CO. LTD., Xi'an, Shaanxi, China*

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ABSTRACT

With the development of Logging While Drilling (LWD) technology, dual-induction LWD logging is not only widely applied in deviated wells and horizontal wells, but it is used commonly in vertical wells. Accordingly, it is necessary to simulate the response of LWD tools in vertical wells for logging interpretation. In this paper, the investigation characteristics, the effects of the tool structure, skin effect and drilling environment of a dual-induction LWD tool are simulated by the three-dimensional (3D) finite element method (FEM). In order to closely simulate the actual situation, real structure of the tool is taking into account. The results demonstrate that the influence of the background value of the tool structure can be eliminated. The values of deducting the background of a tool structure and analytical solution have a quantitative agreement in homogeneous formations. The effect of measurement frequency could be effectively eliminated by chart of skin effect correction. In addition, the measurement environment, borehole size, mud resistivity, shoulder bed, layer thickness and invasion, have an effect on the true resistivity. To eliminate these effects, borehole correction charts, shoulder bed correction charts and tornado charts are computed based on real tool structure. Based on correction charts, well logging data can be corrected automatically by a suitable interpolation method, which is convenient and fast. Verified with actual logging data in vertical wells, this method could obtain the true resistivity of formation.

1. Introduction

Logging While Drilling (LWD) resistivity tools have been in commercial service since the mid-1980s and have unique advantages in deviated wells, horizontal wells and geosteering applications (Allan et al., 2004). Currently, most wireline well logging jobs can be carried out in LWD mode. Conventional electrical resistivity logging methods of LWD include electromagnetic wave propagation resistivity LWD and lateral resistivity LWD. With the development of technology, electromagnetic wave resistivity LWD has become the main method of LWD resistivity measurement, but it cannot catch up with wireline logging in the depth of investigation (Barnett and Meyer, 1991). In recent years, the dual-induction LWD tool which has better investigation performance and more accurate responses is developed to solve this problem. In addition, the frequency of the tool used is low (about 20 kHz), and it is not affected by the dielectric effect. Besides, the exchangeable and modularized coil array can be easily calibrated and maintained on the offshore platform and remote areas (Allan et al., 2004).

Studies of the responses of dual-induction LWD have been presented by many people, most of whom focus on the influence of single tool structure and calibration of the dual-induction LWD tool. Allan et al. (2004) had a detailed introduction to the design and response characteristics of the dual-induction LWD tool, verifying its feasibility and superiority in theory and practice. Wu et al. (2015) reported on the influence of background values, including drill collar, reflector, magnetic core etc., and revealed the response principle. Xu et al. (2014a, 2014b) studied the tool calibration using water tank and calibration loop, and optimized calibration parameters. However, the response of the total tool structure, the skin effect and the influence of the measurement environment have not been studied yet, although many articles have discussed the environment effect on electromagnetic wave propagation resistivity LWD, lateral logging resistivity LWD and induction logging (Chemali et al., 1983; Jan and Campbell, 1984; Hagiwara et al., 2005; Hou et al., 2013).

Numerical simulation is the basis of tool design and logging interpretation (Xu et al., 2014a). There are various methods which are usually used in the numerical simulation of induction logging, including the Finite Difference method (Graciet and Shen, 2000; Wang and Signorelli, 2004), the Finite Element method (Lovell, 1993), the Integration method (Anderson, 1979; Gao et al., 2013; Dyatlov et al., 2015), and the Numerical Mode-matching method (Zhang and Wang, 1996; Chew et al., 1984). The dual-induction LWD tool is asymmetrical and complicated in geometry, thus the 3D formation model is needed for the

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[*] Corresponding author at: No. 18, Fuxue Road, Changping District, Beijing, China.
E-mail address: wksz@cup.edu.cn (S. Ke).

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simulation. The mesh of 3D FEM method is flexible and suitable for complicated structures and large-scale models. So we used 3D FEM to simulate the responses of the dual-induction LWD tool taking the actual tool structure into account.

First, the influence of the tool structure is eliminated and the skin effect of homogeneous formation is corrected. Then, the investigation characteristics are studied to compare with conventional wireline logging. Finally, borehole correction charts, shoulder bed correction charts and tornado charts are computed and applied to the correction software based on the real tool structure. Verified with actual logging data in vertical wells, this method could eliminate the environmental effects.

2. The tool structures and measurement principles

The structure of the dual-induction LWD tool is different from that of conventional induction tools as shown in Fig. 1. All structure mentioned are considered in the simulation. The arrangement of coils is shown in Fig. 2.The medium induction (MI) consists of a T-B1-R1 array and the deep induction (DI) consists of a T-B2-R2 array. Every subarray has three coils. The measurement frequency is about 20 kHz and current is 1 A. Neglecting the complex tool structure, the measurement principle of the dual-induction LWD and wireline induction logging are the same, and both are based on the electromagnetic induction principle to measure formation conductivity. For homogeneous formations, the relationship between induced electromotive force (EMF) V and apparent conductivity is expressed as follows (Zhang et al., 1994):

$$V = \frac{i\omega\mu I_T A_T N_T A_R N_R}{2\pi L^3}(1-ikL)e^{ikL}, \tag{1}$$

$$\sigma_a = \frac{V-V_m}{K}, \tag{2}$$

$$K = \frac{\omega^2\mu^2 A^T A_R N_T N_R I_T}{4\pi L}, \tag{3}$$

where ω is the angular frequency, μ is the magnetic permeability, I_T is the current of the transmitter coil, A^T andA_R are respectively areas of the transmitter coil and the receiver coil, N_T andN_R are respectively the turns of the transmitter coil and the receiver coil and L is the spacing of the transmitter coil and the receive coil. k is the propagation constant, $k^2 = i\omega\mu\sigma$, σ is the conductivity of formation. K is the apparatus constant, V_m is the signal that the receiver coils get from the transmitter coils directly.

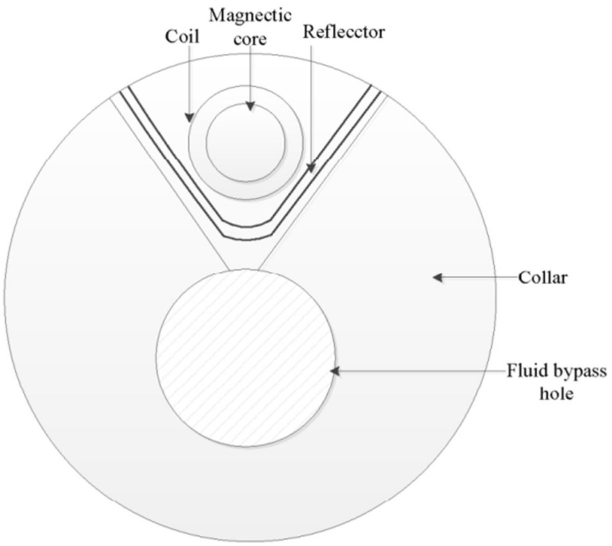

Fig. 1. Cross section of dual-induction LWD tool. For wear prevention, the coil array is encased in the V-shaped slot, which is at open angle of π/3. Coils are wound around the magnetic core to improve signal intensity. There is a reflector with high conductivity between the slot and the drill collar to minimize the influence of the collar. The fluid bypass hole is designed behind the slot, where the drilling fluid can pass by, and has little impact on the mechanical strength of the collar.

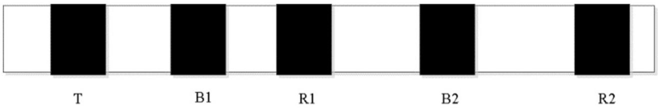

Fig. 2. The coils system of dual-induction tool. T is the transmitter coil; B1 and B2 are bucking coils and R1 and R2 are receiver coils.

3. The model building with 3D FEM

For induction logging, the equation (Eq.), about the electric field strength E, can be derived from Maxwell equations as in the following expression:

$$\nabla \times \left[\frac{1}{\mu_r}\nabla \times \boldsymbol{E}\right] - k_0^2\varepsilon_r\boldsymbol{E} = -i\omega\mu_0\boldsymbol{J}_s, \tag{4}$$

where k_0 is the wave number, ε_r is the relative dielectric constant, μ_0 and μ_r are the magnetic permeability of free space and the relative magnetic permeability. $\boldsymbol{J}_s$ is the current density of source, and ω is the angular frequency.

The boundary condition applied to the surface of the drill collar and finite element model is expressed as the following Eq.:

$$\boldsymbol{n} \times \boldsymbol{E} = 0, \tag{5}$$

Using the variational method and functional analysis, the functional expression of $\boldsymbol{E}$ can be expressed as follows (Sun et al., 2008):

$$F(\boldsymbol{E}) = \frac{1}{2}\iiint_\Omega \left[\frac{1}{\mu_r}(\nabla \times \boldsymbol{E}) \cdot (\nabla \times \boldsymbol{E}) - k_0^2\varepsilon_r\boldsymbol{E} \cdot \boldsymbol{E}\right] \mathrm{d}\Omega + j\omega\mu_0\iiint_\Omega \boldsymbol{J} \cdot \boldsymbol{E}\,\mathrm{d}\Omega, \tag{6}$$

where Ω is the solution domain of the FEM.

In the local coordinate system, the vector equation of the solution field is derived with the shape function for each unit, and then all nodes are combined to form the matrix equation as follows

$$\boldsymbol{A}x = \boldsymbol{B}, \tag{7}$$

where $\boldsymbol{A}$ is the general stiffness matrix, $\boldsymbol{B}$ is the imposed condition and x is the unknown variable.

What needs to be solved is a large sparse matrix and the flexible generalized minimum residual method (FGMRES) is adopted. The induced EMF of the receiver coils and the bucking coils can be obtained from the line integrals to $\boldsymbol{E}$ and then is converted to the apparent formation resistivity.

The solution can be obtained only under 3D conditions due to the asymmetrical structure of the tool. The mesh of the tool structure is finely divided. The size of the mesh gets bigger from the center to the boundary. The accuracy can be satisfied and the computer memory can be minimized by reasonably controlling the maximal and minimal mesh size. The mesh is small enough at the transmitter and receiver coils to guarantee that coils are on the nodes. The boundary layer treatment is adopted at the surface of the collar and the borehole to reduce the loss of energy when the electric field passes through the interfaces.

The electromagnetic wave can be regarded as the spherical wave in an infinite homogeneous medium, so the spherical model is built. To reduce the amount of computation cost, the size of the model should be restricted to a finite scale and the artificial across-section must be