Introduction

When studying geological sections, the reconstruction of electrical resistivity spatial distribution plays a large part. A conventional way to solve this problem is to register responses from eddy currents excited in the medium by a monochromatic inductive source. Along with that, the investigation of the electrical properties is possible by means of toroidal coils, but their application in petroleum geophysics turns out not to be sufficiently developed.

So far, toroidal coils have been employed in lateral and at-bit logging while drilling of vertical and horizontal wells to evaluate reservoir properties and the borehole environment parameters (Gianzero et al., 1990; Bonner et al., 1993). Azimuthal measurements with toroidal coils formed the basis for creating reservoir resistivity images (Bonner et al., 1996). As a consequence, various tasks are tackled: dip angle and fracture orientation determination, geological and structural analysis, lithological differentiation, thin bed analysis, borehole erosion identification (Bratton et al., 1999; Prammer et al., 2009). Studies have been performed to increase the resolutions of tools with toroidal coils to effectively estimate the properties of thin layers in highly deviated wells (Li et al., 2019).

Oil production from complex hydrocarbon accumulations is ever increasing. Electrically macroanisotropic reservoirs consisting of thin layering of sandstones and shales are considered one of the most topical issues in today’s petroleum geophysics. A reliable assessment of the saturation type is conducted by determining the values of horizontal ($\rho_h$) and vertical resistivity ($\rho_v$) or the resistivity anisotropy coefficient $\lambda^2=\rho_v/\rho_h$. Customarily, these parameters of a macroanisotropic reservoir are obtained through measurements with multicomponent induction logging tools, whose distinguishing feature is complicated data processing and inversion. At that, it was not until the second half of the 1990s that a theoretical and numerical analysis of the capabilities of logging tools with toroidal coils in relation to resistivity anisotropy study began to be carried out (Hagiwara, 1996; Karinski and Mousatov, 2001; Bittar and Hu, 2004). Quite recently, a wireline electromagnetic tool with toroidal transmitters and receivers, aimed at resistivity anisotropy examination, has been introduced and successfully field-tested (Epov et al., 2018a, b; Epov et al., 2019a, b).

At the same time, these few research results are not exhaustive. We believe it is necessary to continue investigating the potential of the unconventional electromagnetic source – toroidal coil. It can be effectively performed via utilizing the results of comprehensive numerical simulation in vertical and deviated oil wells penetrated geological environments of different complexity.

Numerical simulation algorithms

As known, a toroidal source can be approximated by a circular magnetic current. First, we obtained a numerical-analytic solution to the direct problem of electromagnetic sounding upon excitation of the electromagnetic field by a circular magnetic current in cylindrically and horizontally layered earth models. It allows for scrutinizing radial and vertical spatial resolutions of sounding systems with toroids. The current in the source varies in the harmonic law, so the solution is sought in the frequency domain by using the Fourier method. We represent the total field as the sum of normal and anomalous fields. A distinctive feature of the algorithm is the implementation of high-performance calculations necessary for large-scale simulation and analysis of the results. Moreover, it is a basis for creating fast inversion procedures that enable real-time processing of the electromagnetic responses.

At the second stage, to simulate the signals in more realistic earth models, we found a solution to the problem of electromagnetic sounding in a full mathematical statement. A conservative difference scheme is used, which allows one to solve the problem in a spatially inhomogeneous axisymmetric earth model and that with a deviated well. As a result of discretization, the boundary-value problem reduces to a system of linear algebraic equations. For its solution, we use a direct solution method by means of the PARDISO program from the INTEL MKL library, and the iterative method of conjugate orthogonal conjugate residuals with a preconditioner. The developed finite-difference algorithms and their software implementation provide high accuracy and computing performance with the application of graphics processing units.
Multidimensional finite-difference numerical simulation results

Using the developed software-implemented algorithms, we conducted a large-scale finite-difference simulation of the signals of two-coil sounding systems with a toroidal source and receiver in geoelectric models of terrigenous macroanisotropic reservoirs. The lengths of the two-coil probes were taken in the range from the first tens of centimetres to the first metres, which is typical of induction logging systems. The operating frequencies are considered in the range from the first hundreds of kHz to the first MHz. The range is selected for reasons of the optimal combination of locality and depth of investigation.

The simulated signals are the real and imaginary parts of the vertical component of the electric field (ReEϕ and ImEϕ) and of the tangential component of the magnetic field (ReHϕ and ImHϕ). Below are some results of the numerical simulation for the magnetic field component Hϕ, which reflects the main features of the signals of the toroidal source.

The first geoelectric model (Figure 1, on the left) describes the case of a 3 m thick macroanisotropic sandstone-shale oil reservoir (top coordinate -1.5 m, bottom coordinate 1.5 m) in enclosing isotropic shales. The section is exposed by a vertical well with fresh drilling mud (radius 0.108 m, resistivity 2 ohm·m). The horizontal resistivity of the reservoir is 12 ohm·m; the resistivity anisotropy coefficient (λ) variation corresponds to a change in the vertical resistivity from 12 to 96 ohm·m. The host shales are characterized by the same horizontal and vertical resistivity equal to 4 ohm·m.

![Figure 1](image)

**Figure 1** Geoelectric models: a macroanisotropic oil reservoir exposed by a vertical well (on the left) and an isotropic oil reservoir penetrated by a deviated well (on the right). Shales are host rocks in both cases.

An analysis of the finite-difference simulation results for the two-coil probes (Figure 2) allows us to point out the following. The reservoir is distinguished by the maximum Hϕ values, the signals are characterized by a high locality, reach maximum values in the region of crossing the reservoir boundaries, and the smoothest transition across the boundaries is observed for the ReHϕ signal. All the signals unambiguously depend on the resistivity anisotropy coefficient, their shape is symmetric, asymptotic values are achieved in the host rocks. With increasing resistivity contrast, the signal features associated with the transition of the boundaries are smoothed. The differing nature of the signals of the two-coil probes at different lengths and operating frequencies makes it possible to state the mutual informational complement of the signals.

The second geoelectric model (Figure 1, on the right) reflects the presence of a 3 m thick isotropic sandstone oil reservoir (top at -1.5 m, bottom at 1.5 m) in surrounding isotropic shales. The section is penetrated by a deviated well with fresh drilling mud, α being the deviation angle. The reservoir resistivity equals 10 ohm·m, whereas the host shales have the resistivity of 1 ohm·m. The finite-difference simulation results (Figure 3) indicate a symmetric form of the logs at all the deviation angles under the question. Beyond that, at the high angles there appear ‘horns’ near or at the boundaries, which can be applicable for estimating the angle of incidence with the target formation in electromagnetic geosteering problems.
Figure 2 Finite-difference simulation results for the macroanisotropic oil reservoir exposed by a vertical well: two-coil 0.8 m probe at a frequency of 1 MHz. Key – resistivity anisotropy coefficient.

Figure 3 Finite-difference simulation results for the isotropic oil reservoir penetrated by a deviated well: two-coil 0.5 m probe at a frequency of 100 kHz. Key – deviation angle.

Ultimately, the numerical simulation made it possible to select the optimal parameters of the sounding systems with toroids: the ranges of the probe lengths from 0.4 to 2 m and frequencies from 100 kHz to 1 MHz provide a sufficient level of the measured signals, high sensitivity to the reservoir boundaries and deviation angle, and an unambiguous relationship with the resistivity anisotropy coefficient.

Conclusions

Summing up, we carried out an extensive multidimensional numerical simulation of the signals of two-coil sounding systems with toroidal transmitters and receivers in earth models of different complexity. It was shown that the measurements of the various electromagnetic field components are independent and complement each other informationally. Following the simulation results, we established the features of the signals for potential use in the key issues of petroleum geophysics and selected the optimal ranges of the lengths and operating frequencies of the two-coil systems. At the subsequent research stage, it is intended to study multi-coil sounding systems with a toroidal source. They are likely to have an increased spatial resolution due to the focusing of the signals. Another aspect is the development of high-performance algorithms for fast inversion of electromagnetic sounding data obtained with a toroidal source in oil wells. In this case, it is necessary to confirm and clarify the optimal parameters of the sounding systems, based on the results of both large-scale numerical simulation and inversion. It is fair to assume that a toroidal source may find application in other branches of geophysics, such as marine and engineering, which is the subject of further studies.
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References


