The Calibration of an Array Induction Logging Tool in half-space

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Abstract. Array induction logging tools are currently relatively widely used resistivity logging tools. The scale of array induction logging tools includes workshop scale and half-space scale. The main purpose of the workshop scale is to use the ring scale to determine the instrument constant (K value). The half-space scale determines the system error of the instrument coil, that is, the basic value. The longest sub-array of the array induction logging tool MIT has a detection depth of 2.5m in the air. Signals over 14m account for 10%, and signals over 28m account for 5%. The ground conductivity must be considered during the half-space calibration process. Influences. This topic studies the method of eliminating grounding conductivity and coil system errors. The completion of the subject will be of great significance to the accurate calibration of the instrument measurement signal.

Keywords: Half-space, Logging Tool, Calibration Correction.

1. Introduction
The purpose of induction logging is to measure the resistivity of the formation, and resistivity is an important parameter for calculating oil saturation in logging oil and gas evaluation. Array induction logging tool is the most widely used resistivity logging tool at present. In the array induction measurement, the instrument is composed of multiple sub-arrays with different intervals working at multiple frequencies at the same time. After the measurement signals are digitized downhole, they are all transmitted to the ground computer, and the ground software is synthesized and focused to provide the information required by the user. What the instrument directly measures is a voltage signal, which must be converted into a conductivity signal through a scale. Therefore, calibration is an important task before the array induction logging tool is used. Whether the calibration is accurate is related to the standardization of induction logging tools in various mining areas, related to the accuracy of induction logging data, and directly affects the accuracy of semi-quantitative and quantitative interpretation using induction logging data.

The scale of the array induction logging tool includes workshop scale and half-space scale. The main purpose of the workshop scale is to use the scale ring scale to determine the instrument constant (K value). The half-space scale determines the residual signal of the instrument coil system, that is, the base value. The longest sub-array of the array induction logging tool MIT has a detection depth of 2.5m in the air, with 10% signal beyond 14m, and 5% remaining beyond 28m. It is impossible to find an environment without conductive media within a radius of 30m. In the 3m-high half-space calibration process, the influence of the ground conductivity must be considered, and physical measurement and
numerical simulation must be combined to eliminate the influence of the ground, so as to carry out accurate calibration.

This topic will be based on the current domestically produced array induction logging tool MIT, establish a half-space calibration physical and mathematical model, calculate the response characteristics of the array induction tool in a half-space calibration environment through finite element numerical calculation methods, and analyze the calibration environment parameters. For the influence characteristics of the measured data, establish a half-space scale earth influence database to eliminate the influence of the earth conductivity on the instrument calibration and improve the accuracy of the instrument calibration. The completion of the research of the subject will have important practical significance for accurately calibrating the measurement signal of the instrument.

2. Development status of instrument calibration method

Establishing the linear relationship between the measured voltage signal and the formation conductivity signal is the main purpose of the instrument calibration [1]. According to the calibration theory of the array induction logging tool, the calibration coefficient, calibration signal, and calibration position of the array induction logging tool can be calculated, but these are only theoretical values. When the actual instrument is scaled and put into use, there are certain differences between actual environmental conditions and theoretical calculations. Not only long arrays are affected by the earth and surrounding conductive media, but short arrays are affected by machinery, technology, materials, temperature, electronic circuits, etc. Make the instrument calibration inaccurate [2]. We know that the ideal instrument calibration is carried out in a standard uniform formation. The instrument is placed in the uniform formation, the difference between the theoretical calculation value and the actual measurement value is determined, and the theoretical value is corrected. Based on the reality that we have not yet achieved this ideal calibration condition, there are currently three methods for instrument calibration at home and abroad:

(1) The scale ring determines the scale coefficient. We know that the instrument calibration of conventional induction logging is to connect scale rings of different conductivity to a conductive ring with a certain diameter in series, and place them vertically on a specific position of the coil system to simulate a uniform formation with determined conductivity. The electromagnetic field signal measured by the conductive ring on the receiving coil is equal to the electromagnetic field signal in the infinite uniform stratum, which can effectively avoid the skin effect while making the scale coefficient linear to the greatest extent [3][4]. We know that foreign companies Atlas and Halliburton both use wooden houses and scale brackets when calibrating array induction logging tools, that is, workshop scale and half-space scale in the usual sense, and the initial debugging and heating of the instruments are completed in the wooden house. In the experiment, two tall wooden brackets were built next to the wooden house. When scaled, the instrument and the scale ring were hoisted horizontally or vertically, and the conductivity signals of two heights were measured to calibrate and eliminate the influence of earth conductivity to achieve more accuracy. The purpose of the calibration [5].

(2) Research and design automatic calibration processing software for instrument calibration. Because there is no ideal calibration environment, we thought of test wells in various oil fields. Various logging instruments have been tested in this well, and we have basically mastered the geological structure and electrical conductivity distribution of the well. Therefore, we can first establish the test well Physical model, and then use the computer to get the theoretical response value. Put the manufactured instrument in a test well for testing, compare the pre-simulated value with the measured result, and calculate the difference to get the theoretical and actual errors. The computer stores the correction amount and passes it through multiple times in wells with known wellbore conditions. Experiments, measurements, comparisons, and multiple calibrations can establish a more accurate calibration relationship. Therefore, as long as the processing solution software for automatic calibration of instrument calibration is developed, once the calibration relationship is determined, other instruments only need to test in the test well to complete the calibration work [6].
(3) Calculate the scale through the establishment of induction logging physical simulation and numerical calculation. From the perspective of development, physical simulation is low cost and easy to implement, which is a trend for accurate calibration. For example, Keshizhen and Feng Qining, University of Petroleum, etc., in order to study the effect of fractures on the response of dual lateral logging, established a set of dual lateral logging physical scaling simulation system. The electrical and geometric dimensions of the simulation system are both It is reduced by a ratio of 1:20. Considering that the detection depth is affected by the frequency, the transmitted signal frequency is increased accordingly [7]; Kang Guojun of Jilin University and others also used physical simulation methods when completing multi-frequency electromagnetic wave logging experiments. Including a simulation device composed of several parts such as tank formation, module, high-frequency electromagnetic wave logging system and corresponding auxiliary equipment [8]; the foreign Schlumberger company is analyzing and studying the borehole of the new three-component array induction logging tool During the impact, a large water irrigation with a height of 20 inches and a radius of 7 inches and a conductive plastic pipe with a diameter of 13 inches were used to fill the interior with salt water or fresh water as the formation model and the flowing medium in the borehole to make the logging tool vertical Through water irrigation, to simulate the influence of each sub-array by the wellbore conductive mud[16]; Qiao Wenxiao et al. also made physical simulations of reflected wave imaging logging by making reduced-scale aluminum and concrete model wells[9].

3. Problems and solutions

3.1. Array induction logging tool MIT
The instrument consists of 8 three-coil system sub-arrays. One sub-array contains a transmitting coil T, a shielding coil B and a receiving coil R. The 8 sub-arrays share one receiving coil, which is equivalent to 8 sets of coil systems. The shielding coil and the receiving coil are wound in opposite ways, forming a single-shot two-handed sub-array with the transmitting coil. There are three operating frequencies (26325 Hz, 52650 Hz, 105300 Hz). Sub-array 1 and sub-array 2 only receive high-frequency signals, sub-array 3 and sub-array 4 receive high-frequency and intermediate-frequency signals simultaneously, and sub-arrays 5, 6, 7 and 8 simultaneously Receive low-frequency and intermediate-frequency signals, use mathematical methods to perform software focusing and synthesis processing on the measurement signals, and send the waveforms to the surface after digitization. A total of 28 original logging real and imaginary signals are recorded, after borehole correction, true resolution focusing and resolution After rate matching, five detection depth curves and three sets of resolution curves are obtained. After inversion processing, the resistivity of the invasion zone, the true resistivity of the formation and the invasion radius can be obtained [10].

The layout of the coil system is shown in Figure 1.

![Figure 1. Schematic diagram of coil system layout of MIT array induction logging tool](image)

3.2. Source processing
The transmitting coil can be equivalent to the following ways:
The array induction coil is wound on a core rod with a radius less than 0.03m, except for the shortest sub-array, the distance between the remaining coils is much greater than 0.03m. At this time, the limited size of the coil can be ignored, so the transmitting coil can be equivalent to a magnetic dipole source. The magnetic current density of the transmitting coil $J_M$ can be expressed as

$$J_M = I_T A_T N_T$$

where $I_T$ is the current size of the transmitter coil, $N_T$ is the number of turns of the transmitter coil, and $A_T$ is the area of the transmitter coil. By using this equivalent way in the finite element calculation, the grid at the source can be greatly simplified, and the calculation efficiency is greatly improved.

3.3. The establishment of geometric model

Combined with the actual instrument calibration environment, it is established that the air and the earth are cubes, the transmitter coil of the instrument is equivalent to a point magnetic dipole source, and the receiving and shielding coils are equivalent to points at different positions. According to the skin depth formula:

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}}$$

It is known that the size of the solution area required for different earth conductivity is different. The smaller the earth conductivity, the larger the solution area, so the solution area must meet the solution area size required for the minimum earth conductivity.

3.4. Meshing

The gradual division from the center of the source to the surrounding area not only meets the accuracy requirements, but also greatly reduces the time and space complexity of the program.

1. Deal with near the source. The magnetic dipole source is a point source, and the nearby field changes very sharply. Therefore, a dense enough grid is required to ensure the calculation accuracy. We add a radial "distribution" to control the minimum and maximum sizes within a certain range of the point source. Make the calculation accurate enough;

2. The interface between the earth and the air is treated. Air conductivity is 0, earth conductivity is between 0.01S/m ~ 0.25S/m, the contrast is very large, the current suddenly changes at the interface, and the magnetic field changes drastically, so add a thin layer within a certain range of the interface directly below the source. The area makes the interface in it, and the range and thickness of the thin layer are obtained by testing. This reasonable layer processing method can minimize the energy loss when the magnetic field crosses the boundary layer;

3. Receiving point processing. Add auxiliary lines and points to the position of each point of the receiving coil, so that each measurement point is located on the grid division node, eliminating the error caused by the difference;

4. The entire model adopts a gradual subdivision method, and the meshes are gradually sparse from the source to the outside, reducing the number of overall meshes and improving computational efficiency.
4. Calculation and analysis of instrument half-space response

4.1. Analysis of MIT half-space response characteristics of horizontally placed array induction logging tool

When the earth conductivity is 0.2 S/m, the apparent conductivity of array 5 is 5.2 mS/m, the apparent conductivity of array 6 is 6.1 mS/m, the apparent conductivity of array 7 is 7.5 mS/m, and the apparent conductivity of array 8. The apparent conductivity reaches 8.6 mS/m, which also shows that the influence of geodetic conductivity on the half-space scale of the array induction logging tool MIT cannot be ignored and must be corrected.

Calculate the measurement response of the instrument at different heights, set the air conductivity to S/m, the earth conductivity to 0.01 S/m, 0.1 S/m, 0.25 S/m, and the relative permeability and relative permeability of air and stratum. The electrical constants are all set to 1. The frequency is low frequency 26325Hz, and the height of the instrument from the ground varies between 0.2m and 5m. Figure 5 is a graph showing the variation of apparent conductivity with the height of the instrument from the ground.
From the data in figure 5, we can see that the apparent conductivity of each sub-array first increases and then decreases with the increase in the height of the instrument from the ground, and gradually approaches zero. The sub-array curve has a peak.

4.2. Analysis of MIT half-space response characteristics of vertically placed array induction logging tool

Compared with a uniform formation, the eddy current formed when the instrument is placed vertically attenuates in the formation, but the direction of the eddy current does not change, because the current of the instrument placed vertically only has a tangential direction, and there is no normal direction, and the direction of the current will not change. Compared with the uniform space, the strength of the stratum will be reduced.

When the instrument is placed vertically, it is more affected by the electrical conductivity of the ground than when placed horizontally, especially for sub-array 6, at a height of 0.8m, when the ground conductivity is 0.01S/m, the apparent conductivity when placed horizontally is 0.652mS/m, and the apparent conductivity can reach 2.75mS/m when placed vertically.

![Figure 6. Low frequency, earth conductivity=0.01S/m, high impact analysis](image)

4.3. Error Correction Method of Coil System Based on Database

(1) Select the sub-array and reference height as the scale reference. In order to eliminate the coil system error, it is necessary to select two reference heights with a larger difference in apparent conductivity. From the three-dimensional graph, we can see that when the instrument is placed horizontally, the four sub-arrays A5 to A8 all have a maximum peak in apparent conductivity as the height of the instrument increases from the ground, and the corresponding heights are 0.3m, 0.4m, and 0.5m and 1.0m, 0.4m corresponding to the peak height of the sub-array 6 can be selected as the first reference height, and the second reference height can be selected arbitrarily, for example, 3.6m when the difference between the two heights is greater than the measurement error.

(2) Determine the equivalent height. A lot of calculations show that the highest point position of the sub-array has nothing to do with the earth conductivity. This means that the maximum apparent conductivity measurement value of A6 is found by continuously sliding the instrument. The corresponding height is the equivalent height corresponding to the reference height 0.4m, which is the benchmark is raised to the second equivalent height, that is, the first equivalent height is used as the benchmark and 3.6-0.4=3.2m, and 3.2m is the second equivalent height.

(3) Determine the ground conductivity. Measure the apparent conductance of these two equivalent heights separately:

\[ \sigma'_1 = \sigma + \sigma_1 \] (3)
\[ \sigma_2' = \sigma + \sigma_2 \]  

(4)

Where represents the error of the coil system, and represents the contribution of the earth conductivity at the first and second equivalent heights respectively. Since it is the same instrument, the error of the coil system of the instrument at different heights remains unchanged, and the calculation is relatively different.

\[ \Delta \sigma = \sigma_1' - \sigma_2' = \sigma_1 - \sigma_2 \]  

(5)

Check the half-space response database of the sub-array 6 at low frequency to find the ground conductivity at 0.4m and 3.6m. The difference in apparent conductivity is the relative difference, so that the ground conductivity can be determined.

(4) Calculate the coil system error. The error of the coil system is equal to the difference between the experimental measurement value and the theoretical value. The difference between the measured value corresponding to the first or second reference height and the theoretical calculation value is calculated through the equivalent height determined in steps (2) and (3) and the ground conductivity. Then the coil system error of the sub-array 6 can be calculated.

5. Experimental verification

Through actual measurement of apparent conductivity at various heights, the experimental measurement data of MIT sub-array 7 and sub-array 8 are given below:

| height | A7L | A7M | A8L | A8M |
|--------|-----|-----|-----|-----|
| 0.21   | 1.13041 | 1.15095 | -1.38327 | -1.46938 |
| 0.28   | 1.24803 | 1.19311 | -1.17228 | -1.16142 |
| 0.4    | 1.28641 | 1.13888 | -0.83019 | -0.79096 |
| 0.5    | 1.05238 | 0.917804 | -0.73934 | -0.68163 |
| 0.595  | 0.816196 | 0.651944 | -0.72076 | -0.77025 |
| 0.69   | 0.585687 | 0.510775 | -0.76915 | -0.7032 |
| 0.79   | 0.477688 | 0.332963 | -0.81211 | -0.74353 |
| 0.895  | 0.241047 | 0.137448 | -0.84873 | -0.84937 |
| 1.01   | 0.118658 | -0.05756 | -0.91373 | -1.00877 |
| 1.1    | -0.01829 | -0.12798 | -1.03371 | -1.03956 |
| 1.19   | -0.15005 | -0.17936 | -1.18611 | -1.08264 |
| 1.3    | -0.25847 | -0.34624 | -1.19882 | -1.1138 |
| 1.405  | -0.3162 | -0.44815 | -1.3312 | -1.25862 |
| 1.495  | -0.43163 | -0.50597 | -1.34088 | -1.26865 |
| 1.595  | -0.52306 | -0.59733 | -1.45455 | -1.44079 |
| 1.695  | -0.56761 | -0.70909 | -1.55638 | -1.55165 |
| 1.805  | -0.6337 | -0.80325 | -1.57324 | -1.52659 |
| 1.91   | -0.59832 | -0.82541 | -1.65642 | -1.61781 |
| 2.01   | -0.84275 | -0.88127 | -1.78514 | -1.70496 |
| 3.6    | -1.48642 | -1.59048 | -2.55151 | -2.34179 |

From the results, we can see that the measured curve is the same as the result calculated. The apparent conductivity of each sub-array has a peak at different heights, that is, as the height of the instrument from the ground increases, the apparent conductivity has a Peaks, each array peak appears at different heights.
6. Conclusions
In this paper, finite element software is used to calculate the half-space response of the array induction logging tool MIT, analyze the response characteristics of the instrument horizontally, vertically and obliquely, and establish a half-space response database when the instrument is placed horizontally. Based on this database, according to the changing laws and characteristics of the data, a database-based calibration method for instrument half-space calibration is proposed.

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