Designing a Current Injection Tool for Logging While Drilling

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Abstract: High-resolution imaging is useful in oil and gas exploration to identify producing fractures that can be in the millimeter thickness range. In principle, high-resolution imaging may be achieved using "current injection" to measure the electrical conductivity of the formation. Two current injection devices are compared for possible use as Logging While Drilling (LWD) imaging: The modified microlaterolog (MMLL) and the "short guard" (SG). Both the MMLL and SG in this work make use of a constant current source surrounded by an array of insulators and focusing current sources. The devices are readily and accurately modeled in three dimensions using Comsol Multiphysics. Geologic layers of various thicknesses and conductivities are simulated using variable (parametric) conductivity in the subdomain. The output voltages of the devices are calculated using integration coupling on points on the voltage monitor.

Keywords: LWD, Resistivity, Current Injection

1. Introduction

When drilling for oil and gas, it is useful to have as much real-time knowledge of the geologic formations as possible to locate the producing layers. In some cases when drilling with conductive drilling fluid, for example Barnett Shale [7], high-resolution electrical imaging is useful to identify layers that have thicknesses of the order a few millimeters.

A method of imaging thin fractures is to inject a constant current into the formation and measure the electric potential near the current source [6]. Since the current is known and the voltage is measured, the resistivity of the formation near the current source can be determined. If the crack is invaded with drilling fluid, the resistivity of the crack is usually different from that of the formation, and voltage of the current source will vary accordingly.

Two current injection devices, the MMLL and the SG, are compared for possible use as LWD imaging. The purpose of this study is to determine which of the two devices produces better resolution of thin cracks and better measurement of the resistivity of the formation. It is important to construct realistic computer models since there are too many parameters (such as formation conductivity, formation thickness, borehole fluid conductivity, and device position) to easily model and test experimentally.

1.1 Modified Microlaterolog (MMLL)

The microlaterolog (MLL) [2,3,4] is a variation of the Laterolog 7 [1] device developed for focused electrical resistivity measurements in oil exploration. The microlaterolog (Figure 1) allows for directional resistivity measurements by focusing current from a central source electrode using an outer focusing bucking ring. The inner electrode is a constant current source, I_c, and the current in the focusing ring, I_f, is adjusted such that the voltages in two monitor rings (M, N) are equal. When the two voltages are balanced, the current from the central button should flow perpendicular to the borehole, injecting a "pencil" of current into the formation. The resistivity of the formation near the source electrode is determined by the ratio of the monitor voltage to the current through the source electrode.

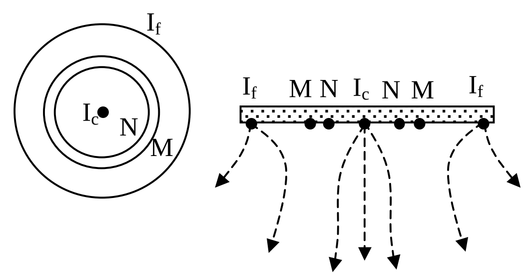

Figure 1. Schematic of a MLL. Dashed lines represent current flow patterns. Adapted from [4].

The modified microlaterolog (MMLL) (Figure 4) utilizes a central disk electrode as the source current, and a bucking ring as the focusing electrode. Rather than balancing the voltage on two monitor electrodes, the MMLL uses a single monitor electrode to measure the voltage. The current through the focusing electrode is set with a current ratio equal to the ratio of the area of the bucking ring to the area of the central disk. In principle, this produces equal current densities in the central disk and bucking ring. The resistivity of the formation near the source electrode is determined by the same method as the MLL.

1.2 Short Guard (SG)

The guard electrode [5] is a system that measures the resistivity of the formation by injecting a thin "disk" of current perpendicular to the borehole (Figure 2). The current disk originates from a "measuring electrode" and is focused by current from upper and lower guard electrodes. Focusing occurs if the voltages of all three electrodes are equal, or if the current density in all three electrodes is equal. In the case of constant voltage, the current through the measuring electrode is the measured quantity. For the case of constant current density, the voltage between the measuring electrode and a distant point (ground) is the measured quantity. The resistivity of the formation near the measuring electrode is proportional to the ratio of the voltage between the electrode and a distant point (ground) to the current from the measuring electrode.

Because the SG is azimuthally symmetric, it is useful only for measuring the average resistivity around the borehole. It is not capable of producing detailed directional images of the formation while drilling. To break this symmetry, the SG is modified so that it consists of a small circular measuring electrode surrounded by concentric guard and current return electrodes. Insulators are used to separate the three electrodes (Figure 5). The modified short guard operates on the same principle as the short guard: The measuring and guard electrodes are given the same electric potential or the same current density. This produces a "pencil" of current, perpendicular to the borehole, which is used to determine the resistivity of the formation.

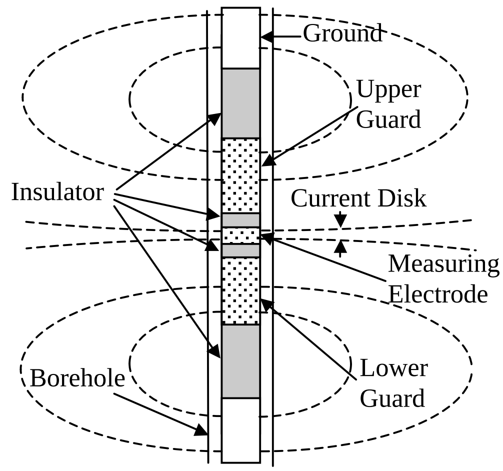

Figure 2. SG device mounted on a mandrel for LWD. Dashed lines represent current flow patterns. The gray shaded regions are insulators, and the dotted regions are the current sources.

2. Governing Equations

Both devices utilize AC currents operated at low frequency (64 kHz). Since there is no expected coupling between the electric and magnetic fields, the quasistatic solution with small induction currents is adequate. Therefore, the time-harmonic equation associated with sinusoidal time variations is the equation that governs these models:

$$-\nabla\cdot\left(\left(\sigma + j\omega\varepsilon_o\right)\nabla V - \left(\mathbf{J}^e + j\omega\mathbf{P}\right)\right) = 0$$

In our model, the external current, $\mathbf{J^e}$, is zero.

3. Numerical Model

Both the MMLL and SG make use of a constant AC current source surrounded by an array of insulators and focusing current sources. These designs are modeled in three dimensions using *Quasi-Statics, Electric → Electric Currents*, in the AC/DC module of Comsol Multiphysics.

The large-scale features of both models are the same because a common experimental model (see section 4 of this paper) is used to test both devices. The overall model consists of a box with dimensions 0.9 m x 0.3 m x 0.4 m. All of the faces of the box are given the boundary condition of electric insulation ($\mathbf{n}\cdot\mathbf{J}=0$).

Inside the box is a single subdomain that represents the water in the tank and the stone block used in the experimental model to simulate a formation with a crack (Figure 3). The block with a single slot (or crack) is simulated in the numerical model using a variable conductivity in the subdomain parameters. The equation used to simulate the block and cracks is:

$$\sigma_w+(\sigma_r-\sigma_w)\cdot\left(x>\left(x_c-\frac{x_b}{2}\right)\right)\cdot\left(x<\left(x_c+\frac{x_b}{2}\right)\right)\cdots_{y,z}$$
$$-(\sigma_r-\sigma_w)\cdot\left(x>\left(x_c+x_{slc}-\frac{x_{sl}}{2}\right)\right)\cdot$$
$$\left(x<\left(x_c+x_{slc}+\frac{x_{sl}}{2}\right)\right)\cdots_{y,z}$$

Where, σ_r = 0.25 Ωm^{-1} and σ_w = 1 Ωm^{-1} are the conductivities of the rock and water, $\left(x_c,y_c,z_c\right)$ is the location of the center of the block, x_b,y_b,z_b are the dimensions of the block, $\left(x_{slc},y_{slc},z_{slc}\right)$ is the location of the center of the slot (crack) in the block, x_{sl},y_{sl},z_{sl} are the dimensions of the slot (crack) in the block, and $\cdots_{y,z}$ indicates that the same terms exist in the equation for the y and z dimensions.

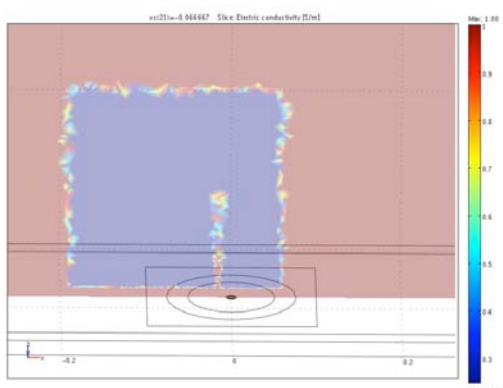

Figure 3. A slice of the x-z plane through y=0 of the SG model. Pink region represents water, and the blue region is the ceramic stone. The rough edges show the grid elements in the model.

The location of the crack and the block are varied using the parametric solver, and the output voltages of the devices are calculated using integration coupling on a point on the voltage monitor. Integrating over a point on the monitor is equivalent to measuring the monitor voltage. When comparing the COMSOL MMLL and SG models, the bottom of the block is 1 cm above the sensors. When comparing each model to the experimental model, the bottom of the block is 3.175 mm (1/8”) above the sensors.

3.1 MMLL Numerical Model

The MMLL (Figure 4) has a central 1 mA current source that has a diameter of $1/4''$ (6.35 mm) with a COMSOL boundary condition of *current flow* $\left(\mathbf{n}\cdot\mathbf{J}=\mathbf{n}\cdot\mathbf{J_o}\right)$. A monitor electrode with a boundary condition of *floating potential* $\left(\int-\mathbf{n}\cdot\mathbf{J}=I_o\right)$ used for measuring voltage is separated from the central current source by an insulator $\left(\mathbf{n}\cdot\mathbf{J}=0\right)$. Three more insulators separate two more monitor electrodes (M and N electrodes in the original MLL model) from each other, the inner monitor, and an outer focusing

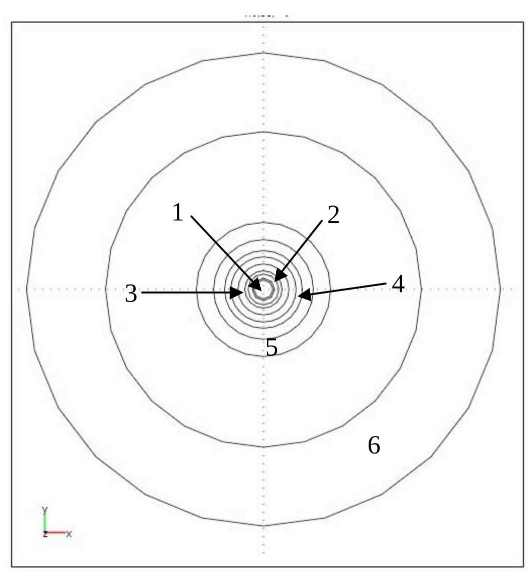

Figure 4. Face view of the MMLL, which lies on the bottom of the box. 1. Central current source. 2. Monitor electrode. 3. N electrode. 4. M electrode. 5. Focusing electrode (bucking ring). 6. Ground. All electrodes are separated by electric insulation.

electrode (bucking ring). The focusing ring is another current source (*current flow boundary condition)*, with a current 240 times larger than the central source. Finally, the outer ring of the array is *ground* (V=0).

3.2 SG Numerical Model

The SG (Figure 5) is somewhat simpler than the MMLL. It consists of a 1 mA central current source with *current flow* boundary condition and a radius of 1/4". It is separated from a monitor electrode by an insulator. The monitor electrode is used to measure the voltage near the central electrode. An insulator separates the monitor electrode from a wide guard electrode that is responsible for focusing the current from the central current source. The focusing guard electrode has the *current flow* boundary condition, with the current along the z-axis equal to 240 times the current from the central source. The x and y components of the current are equal to zero. The guard electrode is separated from ground by a thick insulator.

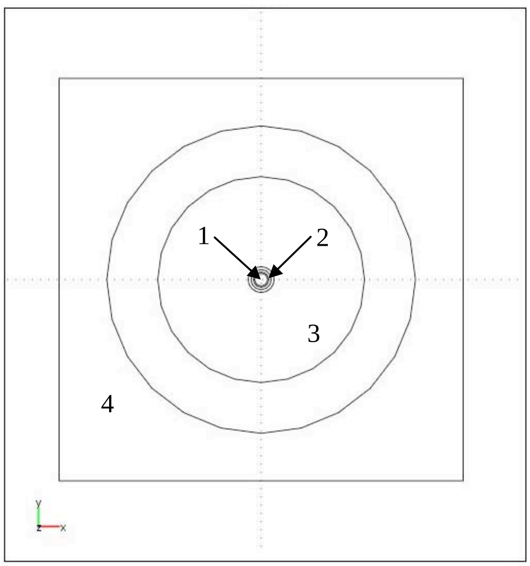

Figure 5. Face view of the SG, which lies on the bottom of the box. 1. Central current source. 2. Monitor electrode. 3. Focusing (guard) electrode. 4. Ground. All electrodes are separated by electric insulation.

4. Experimental Model

The experimental model consists of a 0.9 m x 0.3 m x 0.6 m glass tank filled with $1\,(\Omega m)^{-1}$ conductivity water to a depth of 0.4 m. A 10″ (25.4 cm) cubic block of 50% porosity ceramic (σ_r = 0.25 $(\Omega\text{m})^{-1}$) with 1 mm and 5 mm slots cut halfway through is suspended in the water above the bottom of the tank. The tank is placed on a milling machine to allow precise motion in all three directions (figure 6).

The MLL and SG are placed on the bottom of the tank. The two devices consist of conducting layers on a clear plastic sheet (Figure 7). The current source supplies constant current where needed, and the oscilloscope is used to measure the voltage of the monitor electrode.

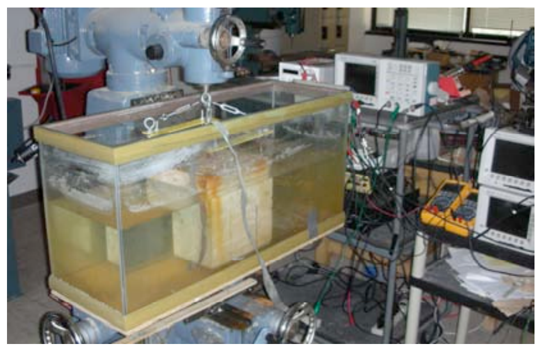

Figure 6. Photograph of the experimental model including the tank, milling machine, and electronics.

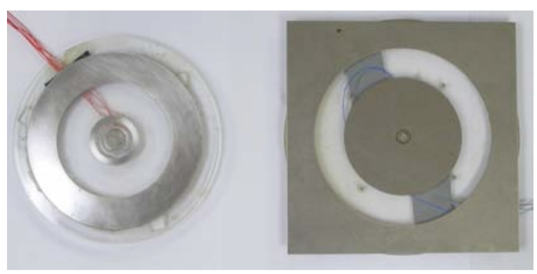

Figure 7. Photographs of the MMLL (left) and SG (right). The dark areas at 11 o'clock and 5 o'clock on the SG are adhesive securing the wire behind the clear plastic.

5. Results

5.1 Comparing COMSOL and Laboratory Models

Before proceeding with optimizing the devices, it is necessary to establish that the COMSOL models produce realistic results compared to experiment. This is done using COMSOL models with the same parameters as the experiment. The center of the block is placed a distance of 1/8" directly above the center of the sensor and then the block is moved in 1 cm increments until the edge of the block passes the outer grounding ring. The monitor voltage is measured at each 1 cm interval.

Figures 8 and 9 show that there is close agreement between the results of the COMSOL models and laboratory models. One difference between the two is apparent when the block is centered 1/8" above the sensor. In both cases the laboratory model gives a higher voltage. This higher voltage may be a result of slight tilting, and therefore greater uncertainty in measurement of the gap between the block and sensor. Another possibility is uncertainty in the value of the conductivity of the stone block used in the laboratory model.

5.2 Using COMSOL Models to Calculate Resolution and Contrast of MMLL and SG

Figure 10 is a plot of the monitor voltage versus the position of the stone block for both the MMLL and SG COMSOL models. This plot represents 61 parametric solutions for the location of the center of the block between –0.2 m and 0.2 m, with the block offset 1 cm above the sensor.

The resolution of the device is calculated by measuring the distance from the 10% signal location to the 90% signal location across the "step function" at the edge of the block. Using this definition of resolution gives 6 cm for the MMLL and 9 cm for the SG. Qualitatively, one can see that the MMLL is better able to resolve the 1/4" crack by the more pronounced dip in Figure 10.

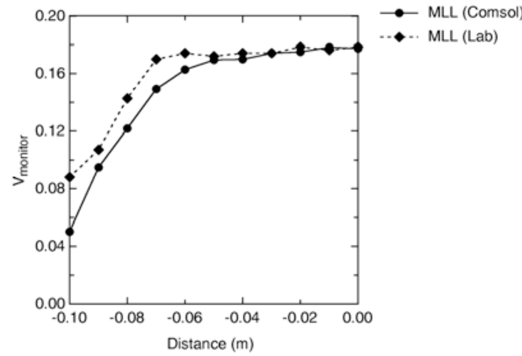

Figure 8. Comparison of COMSOL MMLL and laboratory MMLL models. Plots show monitor voltage for various positions of stone block. Units of monitor voltage are arbitrary.

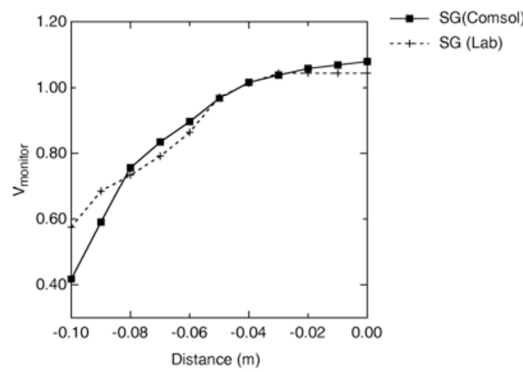

Figure 9. Comparison of COMSOL SG and laboratory SG models. Plots show monitor voltage for various positions of stone block. Units of monitor voltage are arbitrary

Another important function of the MMLL and SG is their ability to measure the contrast in conductivity between the rock and water. An ideal device would measure a contrast of 4, corresponding to the ratio of the conductivity of the water to the conductivity of the rock. In the COMSOL models the contrast may be defined as the ratio of the voltage measurement at the peak of the curve (when the rock is directly over the sensor) to the voltage measurement when the rock is off to the side of the sensor. The contrast of the MMLL is 1.68 and the contrast of the SG is 1.90.

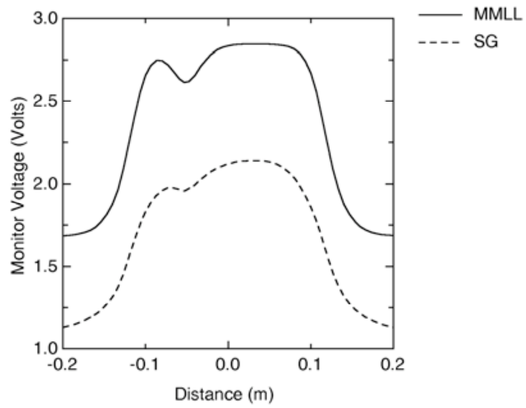

Figure 10. Comparing COMSOL MMLL and SG models. Plots show monitor voltage for various positions of stone block with 1/4" slot.

6. Discussion

The similarity between the results of the COMSOL and laboratory models demonstrates that the COMSOL models are an accurate representation of the MMLL and SG. The agreement between the lab and computational models provides confidence in the utility of the COMSOL models for optimizing and comparing the two devices.

The MMLL provides better resolution of the edge of the block and the crack in the block than the SG. On the other hand the SG provides a better measurement of the contrast ratio between the conductivity of the rock and water.

Neither device is ideal for detecting cracks with thickness in the mm range. Ideally, one prefers to have a device that is capable of accurately measuring the conductivities of the materials while providing resolution at least equal to the size of the central current source.

7. Conclusions

Comsol Multiphysics produces accurate simulations of current injection tools: the MMLL and SG. Since the results of the laboratory experiments agree with the Comsol Multiphysics model, the designer has confidence in the accuracy of the Comsol Multiphysics simulations. These simulations are used to compare the MMLL and SG designs in terms of image resolution and measurement of conductivity. Operating as constant sources of current, neither device is capable of high resolution imaging as defined as resolving fractures with thickness in the mm range. Furthermore, neither device adequately measures the resistivity of the formation. However, coupled with laboratory experiments, COMSOL Multiphysics models will allow us to optimize these devices quickly and efficiently. Further refinements of both devices are more easily done with Comsol simulations, possibly bringing us closer to developing an ideal device for measuring the resistivities of thin cracks in geologic formations.

8. References

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