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Research Article

Radial Electrical Resistivity Measurements of Rocks on Laboratory Core Samples Using an Electromagnetic Sensor: Macro and Micro Eddy Currents

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Rocks subjected to weak alternating magnetic fields exhibit a magnetic hysteresis phenomenon due to the magnetic susceptibility and chemical composition of ferromagnetic or ferrimagnetic mineral grains. In order to characterize the physical properties of rocks, magnetic susceptibility and electrical resistivity measurements have been carried out. So a device has been developed in our laboratory as a highly sensitive sensor to measure the magnetic and electrical properties of rocks. This work deals with a nondestructive method to analyze these properties. A ballistic method has been considered by using a search coil in a sensitive alternating current bridge. Usually, the use of the complex ac magnetic susceptibility is convenient to reach the bulk magnetic susceptibility, where the imaginary component is often very weak and neglected. In this paper, we have considered this to determine the electrical resistivity of rocks.

1. Introduction

The modern alternating bridge, with both high and sensitive balances, has almost completely superseded the ballistic galvanometer for determining the magnetic properties of core materials in weak magnetic fields (low flux densities: 0.6 Oe) which are mainly employed in telephone and radio devices. The suitability of the alternating current bridge for this purpose has been known for some time. However, the continuous improvements of nonmagnetic materials and the accuracy requirements of a modern geophysical apparatus have required some refinements in the equipment and the interpretation of the technical measurements. Eddy currents induced in a conductor by an external ac magnetic field are important in the fields of electricity and magnetism and have many applications as accomplished by Sun et al. [1]. Eddy currents usually cause losses in transformers and make it possible to levitate a conducting sample. They create a torque in motors employing rotating magnetic fields and reveal metallic objects such as weapons or mines. It is known that an important application of eddy currents is induction heating. Eddy currents are widely used for contactless measurements of electrical resistivity especially for conductor cores as noted by Íñiguez et al. [2]. The use of this idea in a geophysical context is the subject of this work as described below. The concept of the effective complex magnetic susceptibility of a conductor $k = k' + ik''$ which is very useful in this respect has been developed by Landau and Lifshitz [3]. The effective magnetic susceptibility depends on eddy currents and has no relation with the usual magnetic and electrical properties; it depends on the frequency of the ac magnetic field, the electrical resistivity, and the shape of the sample. The effective magnetic susceptibility is a complex quantity because there is a phase shift between the electrical field induced by the ac magnetic field and the eddy currents in the sample. Several classroom demonstrations by Churchill and Noble [4] and laboratory experiments concerning eddy currents have been published. One of the experiments that have been described consists of two parts: the magnetic shielding by a conducting sheet and the distribution of current flowing through a wire bundle. The frequency-dependent impedance of a round copper wire has been measured by Gosselin et al. [5]. A lock-in amplifier measured the real and imaginary parts of the impedance. A simple method for determining the frequency dependence of the skin depth in a conductor was described by Wiederick and Gauthier [6]. An experiment has been reported, which consisted of conducting tubes with different wall thicknesses placed coaxially between a solenoid and a detecting coil. The amplitude and phase of the voltage induced in the detecting coil were then measured by ZióŁKowska and SzydŁOwski [7]. The determination of the effective magnetic susceptibility of a conductor was read by a differential transformer using a compensation circuit with a lock-in amplifier as the null detector. The real and imaginary parts of the susceptibility were measured versus the frequency of the magnetic field. Some comments can be made regarding the experiment which is reported elsewhere by Juri et al. [8]. First, the effective magnetic susceptibility of a conductor is measured using a much simpler setup consisting of an oscillator, a differential transformer, and an oscilloscope. Both parts of the susceptibility are seen from the shape of the Lissajous pattern on the oscilloscope screen. Second, if a lock-in amplifier is involved in the measurements, there is no need for a compensation of the output voltage of the differential transformer following the proper tuning of the lock-in amplifier that measures this voltage immediately providing dc voltages proportional to the real and imaginary parts of the susceptibility. Lastly, the electrical resistivity of a cylindrical sample is available from a single measurement based on the determination of the phase angle of the effective magnetic susceptibility, instead of using the procedure previously described by Juri et al. [8]. In order to fit the experimental data to the theoretical curves, the data were shifted along the x-axis by adjusting one parameter, the electrical resistivity of the sample. The authors suggested this procedure as a contactless method for determining the electrical resistivity. A simple model of magnetic braking in a metal strip was confirmed by various experimental tests as noted in Wiederick et al. [9]. An experiment on magnetic drag comparing the data to computer simulations was performed by Marcuso et al. [10]. A mutual induction of the apparatus for measuring magnetic susceptibility and electrical resistivity was reported by Edgar and Quilty [11]. A quantitative backing experiment was described by Maclatchy et al. [12]. An analysis of the motion of a conducting plate as it passes through a magnetic field was presented by Cadwell [13]. Magnetic damping was studied by means of an air track and a motion detector. Recently, the damping of a magnet oscillating inside a conducting tube was determined by Hahn et al. [14]. This paper considers the modified technique required to take into account the eddy current shielding and hysteresis effects in petrophysics (geological core) through variations in the inductance and the resistance of the coil winding and the details required for the ac bridge and any associated devices in order to perform the required accurate measurements. Fundamentally, the ac method involves measurements of the inductance and the effective resistance of winding on the test specimen, such measurements being made at low frequencies and in weak magnetic fields and at several current values. From these measurements, the magnetic susceptibility and electrical resistivity of the test core can be computed for the low flux density range and low frequencies. The details of such calculations will be given below, beginning with approximate methods and successively proceeding to more accurate computations.

2. Rock Magnetic Susceptibility and Geological Impact

To characterize the physical properties of common natural materials, the main objective is to determine and check the method procedure used for the measurements based on a nondestructive one. So a simple and inexpensive experiment consisting in the determination of the effective magnetic susceptibility and in the contactless measurement of electrical resistivity is described below. In order to do this, an inductive method was applied using an ac bridge at low frequency and a weak magnetic field as noted by Puranen et al. [15]. The measuring device presented in Figure 1 consists of five units: oscillator, bridge unit, lock-in amplifier, acquisition card associated to a computer, and conveyor belt. The ac bridge is composed of two inductance coils and two resistors. The bridge power feeding comes from a low-frequency generator through a toroidal transformer. The signal voltage from the bridge is taken to a lock-in amplifier, which obtains its reference voltage directly from the transformer. The conveyor belt serves as a support for the test object sample, and it is actuated by the dc motor controlled by a variable speed drive. It is a small dc motor powered at a voltage of 24 V and equipped with a speed reducer, to conduct measurements in the static or in the dynamic position. The principle of measuring operation is as follows. First, the ac bridge is balanced without a sample. Then, a sample is inserted into the measurement coil of the bridge, which becomes unbalanced. Each of the two components of the ac complex magnetic susceptibility of the sample in the direction of the coil axis is proportional to the out voltage in X and Y indicators of the lock-in amplifier, respectively, as in phase and in quadrature signal acquired by synchronous detection which are displayed on the computer screen. In this case, it was necessary and convenient to characterize the two coil parameters: inductance and resistance, by an accuracy method. To do so, the Hewlett Packard HP4192A LF impedance analyzer was used and the results obtained are those shown in Figures 2(a) and 2(b). From these results, it was possible to choose the frequency interval in which the apparatus would be used and made it easy to balance without a sample. The out-of-balance detector of the ac bridge with the sample inserted may have a characteristic influence constant which should be considered when taking measurements over time. The system's response will be described by a convolution operation as defined in theoretical equation (4). The hysteresis loop,

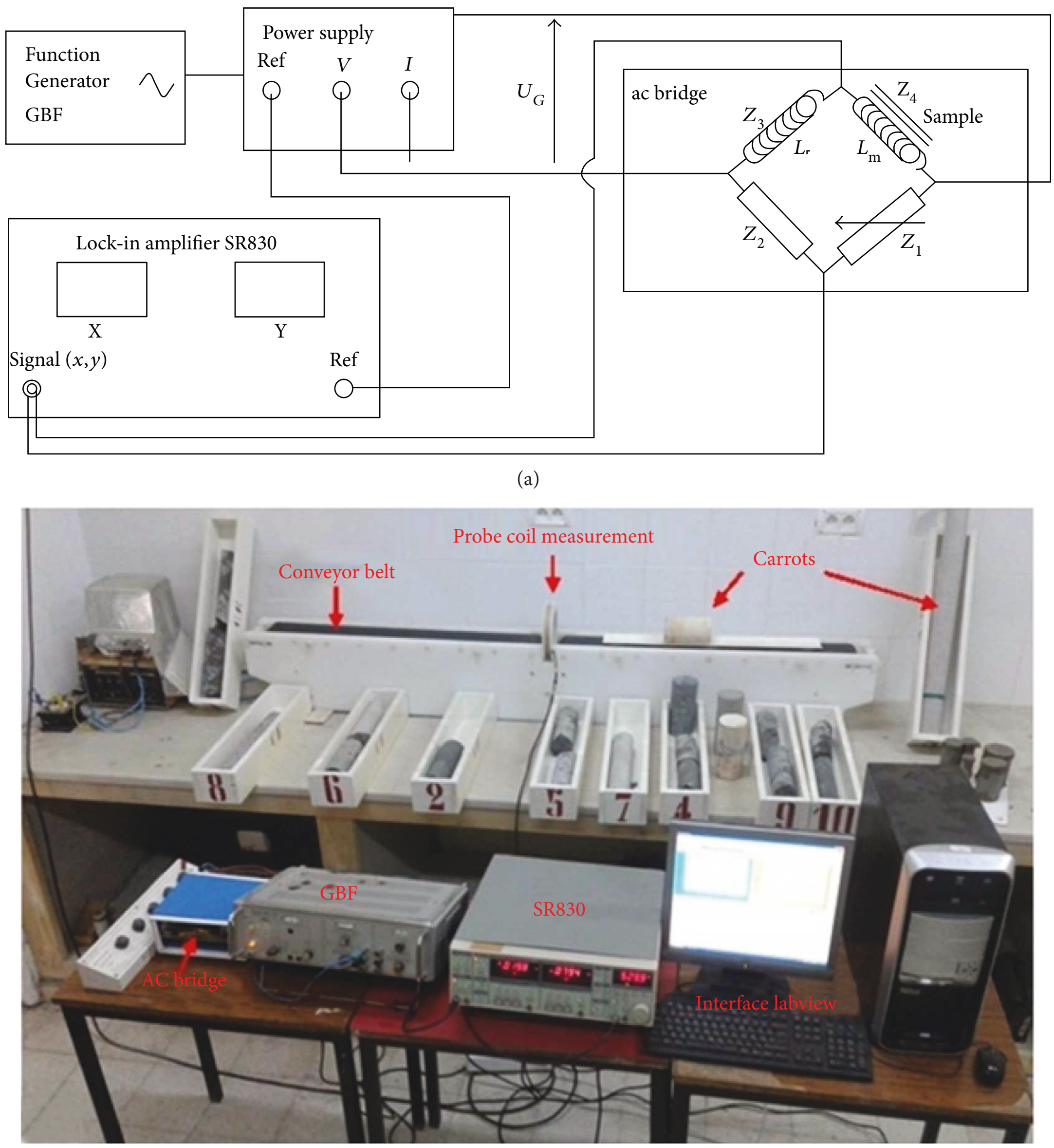

Figure 1: (a) Block diagram of measurement system. (b) Simplest setup for determining magnetic susceptibility and electrical resistivity.

or any other forms of energy loss, depends on the mineral constituents, the core's geometrical form, and the dimensions. This last factor and the electrical characteristics of the probe coil are related to skin depth and the quality factor of the circuit in the ac bridge. By using laboratory measurements and taking the time response detection of the electrical system in the static or dynamic positions of the core sample cross section across the probe coil (Figure 3), we can directly rise according to the experimental conditions at a low frequency (530 Hz) and in a weak magnetic field (0.6 Oe), simultaneously to the magnetic susceptibility and to the radial electrical resistivity of the sample. When the sample is moved inside the winding of the probe coil, an electromotive force can be detected between the arms of the ac bridge, which must be previously balanced. This phenomenon induced in the winding of the probe coil is caused by the increase of the magnetic energy within the material of the core sample. At the same time, at low frequency, part of the magnetic energy due to the change of the magnetic force with time is lost by eddy currents all over the bulk core. Using a suitable ballistic method in the limit conditions of Rayleigh's theory as noted by Takesi [16], the hysteresis energy and eddy current losses can be separated and measured as discussed by Richard [17]. According to the theory established, to describe this phenomenon, one must consider the complex quantity of magnetic susceptibility: $k = k' + ik''$, in order to take into account the effect of the eddy current influence on the phase shift in relation to the energy losses inside the material constituting the core sample [18].

The search for economically interesting accumulations of oil and gas starts with the recognition of likely geological provinces, progresses with seismic surveying, and the drilling

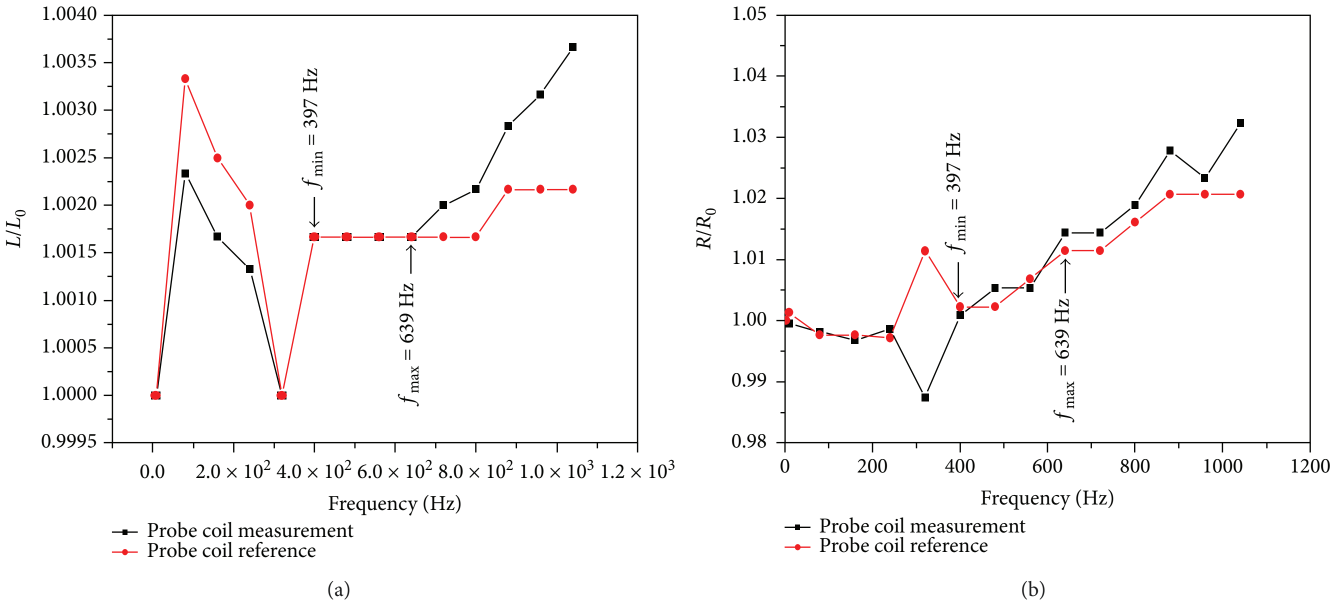

Figure 2: (a) Inductance ratio of two coils. (b) Resistance ratio of two coils as accurately measured with a Hewlett Packard4192A LF impedance analyzer type.

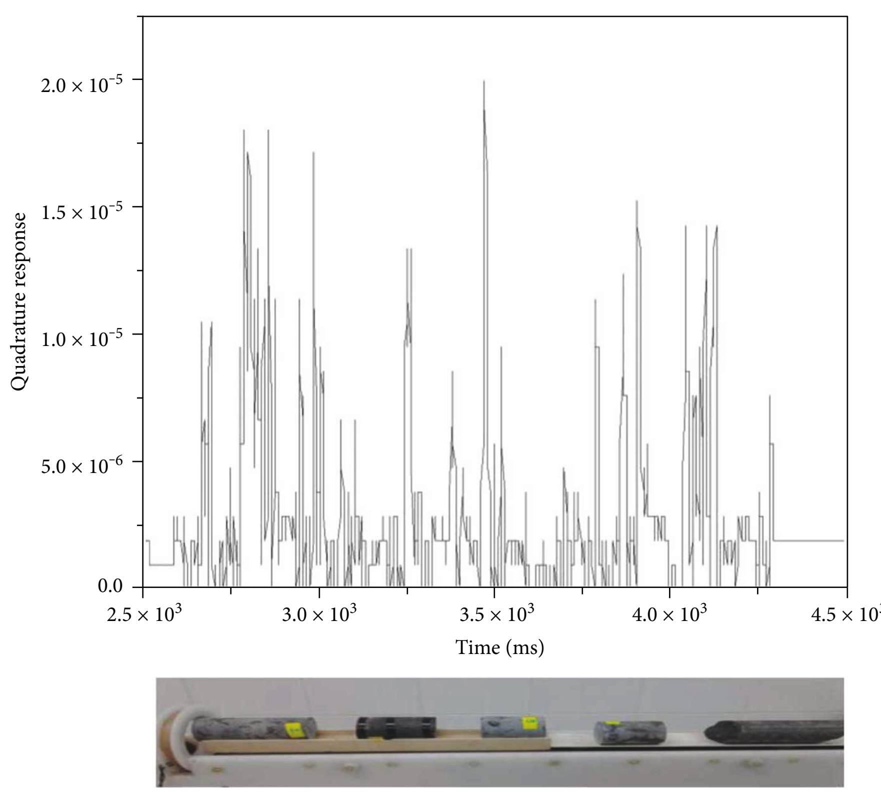

Figure 3: Continuous quadrature response for core sample train.

of one or more wildcat wells. Clearly, the evaluation of subsurface formations requires the combined efforts of geologists, petrophysicists, drilling engineers, and even geophysicists. However, geologists and petrophysicists would have a greater influence. The geologist is interested in the lithology, the stratigraphy, and the depositional environment of the subsurface strata penetrated by the drilling bit. In the study of Worm et al. [19], an alternative approach was proposed; they suggested that the petrophysicist should use all available information to analyze the physical and chemical properties of the rocks in the subsurface and their mineral components. Initially, the petrophysicist's aim is to differentiate between oil-, gas-, and water-bearing formations and estimate the porosity of the formations as developed by Archie [20]. Ultimately, the geophysicist also uses laboratory data. There is a large database of information available to both geologists and geophysicists, especially information on the characteristic parameters of cores: lithology, hydrocarbon show, heterogeneity and factoring porosity, permeability (Klinkenberg, liquid, and reactive permeability), wettability and capillary pressure, and grain and pore size distributions. In order to determine the porosity and mineralogy of rocks, one can use two physical properties: electrical resistivity and magnetic susceptibility [21, 22]. In this way, a nondestructive method based on the inductive phenomenon will be described.

The coil impedance is a complex quantity written as $Z = R + iL\omega$. One could ask the following question: what happens if we introduce a core with a complex magnetic susceptibility $k = k' + ik''$? The real part k' of the magnetic susceptibility will affect the imaginary part of the impedance (self-induction) by increasing the magnetic energy within the probe coil. Simultaneously, k'' will affect the coil resistance through different energy losses. At the equilibrium, the coil without a core and the electromotive force detected by the null detector in an alternating current bridge are equal to zero. The use of a nondestructive method for eddy currents for the purpose of material characterization and inspection has been studied by Yin et al. [23]. Eddy current signals consist of a spectrum of frequencies and therefore contain far more information about a specific test sample that could be gained from a single-frequency excitation. This alternating voltage excitation has been used conjointly with a probe coil to measure the perturbed magnetic field. The method is very versatile and especially convenient for measurements on samples containing subsurface flaws. Hardware has been developed to generate the alternating voltage excitation signals and record the response of the probe coil, the induced force (emf) when the sample is moved inside its winding. The hardware is under the control of a computer which allows experimental parameters to be varied and the signals to be recorded. The measurements have been achieved using an induction probe coil with various different sample diameters of geological specimens above a subsurface cross section; the results are consistent with theoretical predictions.

3. Contactless Measurements of Rock Resistivity and Background Theory

Let us look at the interaction between the core materials of the probe coil compared with the reference one; these two components of the ac bridge are mainly characterized by these two parameters: the change in the resistance of the wire in the probe coil and the inductance variation of the wire in the probe coil as presented by García-Martín et al. [24]. These variations induced by the core material and introduced in the probe coil were detected and easily measured in dynamic prospection. The inductance bridge, for measuring resistance (energy loss), and inductance variation (energy increase), of a winding surrounding rock specimen, were used to take accurate simultaneous measurements of the two parameters: the magnetic susceptibility and the electrical resistivity with a high sensitivity. The main use of the ac testing method is to determine both the permeability and the energy loss of cylindrical rock samples at low frequency and with a weak magnetic field. The main aim of this study is to find an agreement between the background theory and the experimental results to confirm the contactless method in geophysical tests as performed by Yang et al. [25].

When the specimen is inserted or moved through the search coil cross section, the induced emf can be detected and measured and expressed by the following relationship:

$$U_D = \frac{\Delta L}{4L} U_G + i \frac{\Delta R}{4L\omega} U_G, \quad \Delta L \ll L, \Delta R \ll L\omega, \tag{1}$$

where U_D is the emf detected by a ballistic galvanometer after reaching equilibrium (null detector on the ac bridge arms), U_G is the sinusoidal oscillator excitation tension of the inductance ac bridge at low frequency, and ΔL and ΔR are, respectively, the inductance and resistance variation of the search probe coil impedance with the specimen inserted.

The use of the complex magnetic susceptibility

$$k = k' + ik'' \tag{2}$$

proved that

$$\begin{aligned} \Delta L &= F(z) * k'(z), \\ \Delta R &= \omega F(z) * k''(z). \end{aligned} \tag{3}$$

Then,

$$U_D = \frac{F(z) * k'(z) U_G}{4L} + i \frac{F(z) * k''(z) U_G}{4L}, \tag{4}$$

where the term $(F(z) * k'(z))/4L$ is in phase with the U_G excitation, while the term $(F(z) * k''(z) U_G)/4L$ is in quadrature with the U_G excitation, where z is the coordinate of the point on the principal axis, ω is the angular frequency of the alternating current feeding the ac bridge, $F(z)$ is the geometry function which depends on the search coil shape, and L is the search coil inductance.

By synchronous detection with a reference, the two terms are separated and accurately measured and amplified. The problem is the deduction of the radial electrical resistivity ρ of the specimen from the measured quantities.

$$\begin{aligned} M'(z) &= \frac{F(z) * k'(z) U_G}{4L} G, \\ M''(z) &= \frac{F(z) * k''(z) U_G}{4L} G, \end{aligned} \tag{5}$$

where $M'(z)$ is linked to the magnetic energy thus increases the permeability, $M''(z)$ is linked to the energy loss by eddy current in the specimen like the core in the detector coil, and G is the gain.

Thus, under the two conditions, we concluded that a weak magnetic field was applied and a low-frequency excitation, where $M'(z)$ is proportional to

$$\frac{U_G}{4L}G\left[k'(z)*A(z)\right] \tag{6}$$

and $M''(z)$ is proportional to

$$\frac{U_G}{4L}G\left[k''(z)*A(z)\right], \tag{7}$$

where $A(z)$ is the apparatus function.

Our method is potentially better as it only requires the knowledge of the diameter, d, of the cylindrical sample, while the standard bulk transport method requires the measurement of the sample cross section as well as the separation of the voltage leads. It seems that by digitalization and deconvolution we can find the k' and k'' values and deduce the radial resistivity value, ρ, for the geological sediment on the cylindrical shape by using the relation established:

$$k''(z)=\frac{\mu_0\omega}{32\rho}d^2,\quad \mu_0=4\pi 10^{-7}. \tag{8}$$

However, in this study, we try to solve this problem by using an analytical method without a deconvolution procedure, and we then define the eddy current parameter as

$$\theta=\pi d\sqrt{2\mu\frac{f}{\rho}}\ll 1, \tag{9}$$

where μ is the magnetic permeability of the specimen, ρ is the radial electrical resistivity of the specimen material looks as the medium value, and d is the diameter of the core sample.

The following is the range of values of θ for

$$\begin{aligned} d&=7510^{-3}\ \text{m},\\ f&=530\ \text{Hz},\\ \mu\approx\mu_0&=4\pi 10^{-7},\\ \rho&\approx 10^2\ \text{to}\ 10^8\ \Omega\cdot\text{cm}\\ \theta&\approx 610^{-6}\ll 1 \end{aligned} \tag{10}$$

where $\theta\ll 1$.

The quality factor for the cylindrical core sample is given by

$$Q=\frac{2\pi fL}{\Delta R}=\frac{8}{\theta^2}\left(1+\frac{\theta^4}{128}+\cdots\right), \tag{11}$$

where L is the inductance of the search coil and $\Delta R=R-R_0$, where R_0 is the direct current resistance measured (at low frequency) of the search coil, R is the alternative current resistance measured (at low frequency) of the search coil with the specimen inserted, and ΔR is the eddy current contribution to the resistance component of the search coil impedance.

On the other hand, the power dissipation by the eddy current for the cylindrical shape is expressed as

$$P=W_e f=\frac{\pi^2 d^2 B^2 f^2}{16\rho}, \tag{12}$$

where B is the magnetic field strength and W_e is the energy dissipation per cycle.

The inductance of material of effective permeability μ', cross-sectional area A, and length of magnetic path l, closely wound with N turns of wire connected to the bridge, is

$$L=\frac{4\pi N^2 A\mu'}{l}. \tag{13}$$

The magnetic field strength on the material surface, caused by the sinusoidal varying current of rms value I_{rms}, is linked to H by

$$H=4\pi N I_{\text{rms}}\frac{\sqrt{2}}{l}. \tag{14}$$

The power loss is

$$W_e f S l=\Delta R I^2{}_{\text{rms}}, \tag{15}$$

where S is the cross section of the sample.

Thus, [17]

$$\frac{\Delta R}{L}=\frac{8\pi W f}{\mu' H^2}. \tag{16}$$

This is applicable to materials in the form of sheets, wires, and so on and to losses due to any cause. It can be expressed in terms of the effective induction, B', which is equal to $\mu' H$.

$$\frac{\Delta R}{L}=\frac{8\pi\mu' W f}{B^2}, \tag{17}$$

where B' is the effective induction inside the specimen, $B'\approx B$, where B is the induction strength at the surface of the specimen.

The effective permeability μ' is taken to be equal to $\mu'\approx\mu_0$, this due to the porosity ratio in the rock bulk.

Then, (12) and (17) lead to

$$\rho=\frac{\pi^3\mu_0 d^2 f^2 L}{2}\frac{1}{\Delta R}. \tag{18}$$

We can reach (18) from substituting (9) into (11) in the background theory.

$$\begin{aligned} \Delta R&=2\pi f\left(k''*F\right),\\ M''(z)&=\alpha\frac{k''*F}{4L}U_G, \end{aligned} \tag{19}$$

where α is a constant.

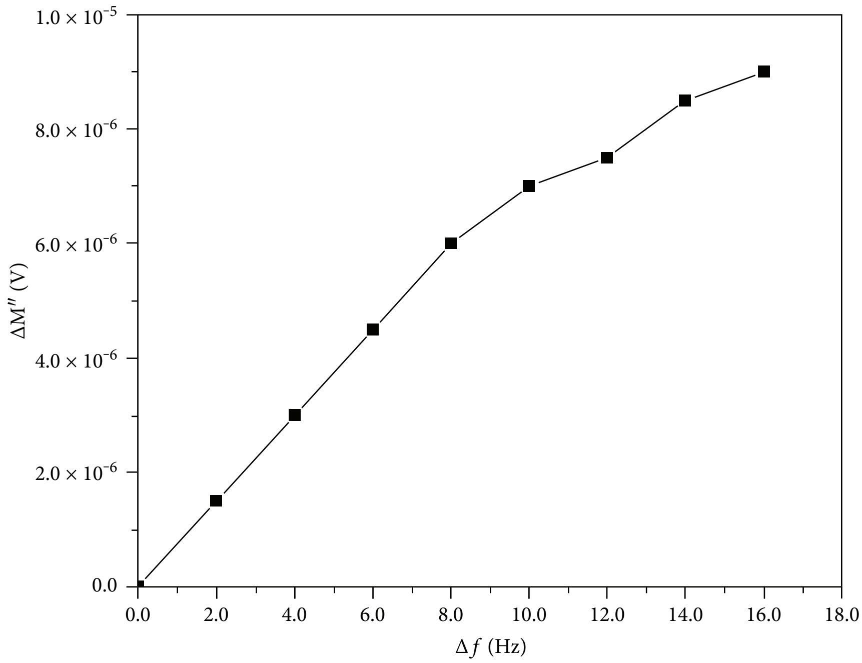

FIGURE 4: Quadrature response variation $\Delta M''$ plotted versus the frequency variation.

Then, the convolution operation can be omitted and ΔR can be expressed by the following expression:

$$\Delta R = \alpha 2\pi f \frac{4L}{U_G} M''(z), \tag{20}$$

where $M''(z)$ is the analogy response of the device.

From (18) and (20), we conclude that

$$\rho(z) = \alpha \frac{\pi^2 \mu_0 d^2 f U_G}{16} \frac{1}{M''(z)}. \tag{21}$$

Equation (21) is homogenous with the following relation: $\bar{k''} = (\mu_0 \omega / 32\rho) d^2$. This is the average value of the quadrature component of the complex magnetic susceptibility. We note that the analogy response $M''(z)$ of the apparatus without its digitalization can be used and reach the deep purpose and radial electrical resistivity value of the specimen material by using the complex magnetic susceptibility in an inductive contactless method.

4. Experiment Results

In the second part, we search the relationship between the wire parameters of the probe coil and the physical properties of the core-like sample in the coil axis. Our aim is to check the agreement between these results and the background theory.

Then, from (21), we find $\rho(z) = \alpha(\pi^2 \mu_0 d^2 f / 16) U_G (1/M''(z))$, where $\rho(z)$ is the effective local and radial electrical resistivity of a cylindrical specimen in an axial ac magnetic field. The procedure is to measure one parameter and fix the other ones; hence, we plotted the device response $M''(z)$ versus various parameters. The plot of $\Delta M''$ (V) versus Δf (Hz) in order to extract the eddy current effect from the energy lost (hysteresis and residual energy); then the curve is a straight line at low frequency which intercepts the zero point thus agreeing with the theory prediction when the voltage excitation U_G and diameter d are fixed (Figure 4). The operation consists of plotting $\Delta M''$ (V) versus ΔU_G, and with the current feeding of the probe coil, which is proportional to the magnetic field, the magnitude is close to 0.6 Oe (Figure 5). A linear response of the device M'' (V) versus the square diameter of the specimen on the cylindrical shape as measured when the excitation voltage $U_G = 1.25$ V and frequency $f = 530$ Hz are fixed (Figure 6). This therefore confirms the linearity of the response of the device M'' (V) versus all the different parameters when the resistivity value of the specimen cross section confined by the field lines is considered fixed and homogenous, and then the average value of the radial electrical resistivity is obtained. With these results and discussion, it is interesting to continue with the determination of the constant α as a function of the parameters U_G, f, and d, from the standard measurements made on homogenous core samples from a wide range of geological families. A comparison of our predictions was made with those obtained by contact methods. Various geological samples from different areas of the country were taken. It is important to confirm their sedimentary nature (clay, sandstone, salt, marl and marble). To reach a good agreement with the developed background theory, the samples were cut in a cylindrical shape with the same diameter and a length of over 80 mm as shown in Figure 7. Some samples were prepared in natural conditions, and many inductive measurements were taken and saved in order to be compared with those obtained by contact methods by using an HP4192A

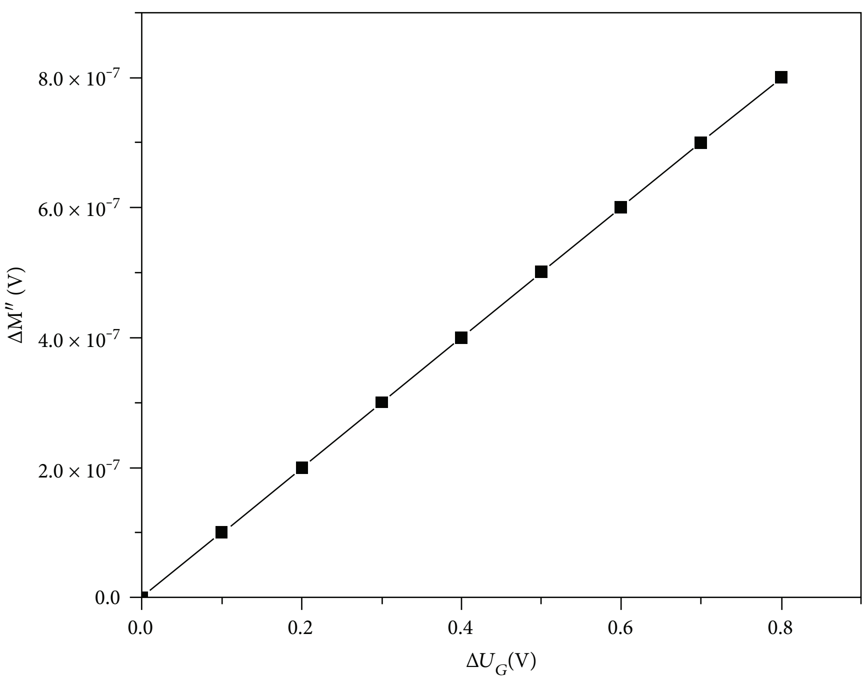

Figure 5: Quadrature response variation $\Delta M''$ plotted versus the voltage excitation variation.

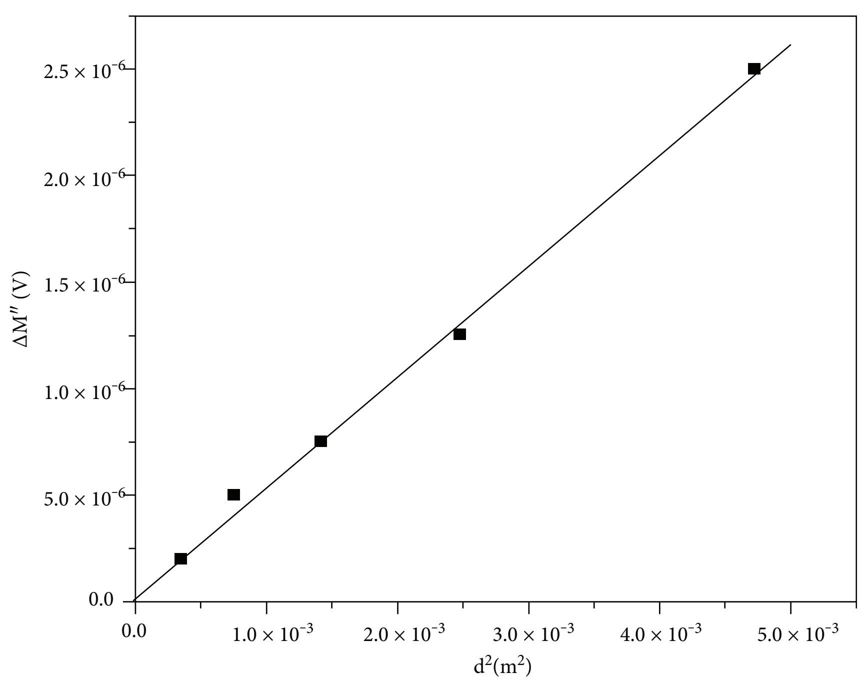

Figure 6: Quadrature response of M'' plotted versus the diameter squared.

impedance analyzer at a suitable frequency and a low alternating excitation voltage. The accuracy resistivity value was deduced from the resistance value by using Ohm's law, taking into account the geometry factor (Figure 8) and considering the homogenous and isotropic assumptions in the cross section of the rock specimen. The main purpose of this is to calibrate and standardize the device responses, so a careful operation to calculate the constant from the linear curve (Figure 9) was established for this goal. In this case, the formula to determine the resistivity expression was deduced (21). The results are summarized in Table 1 confirming the good agreement between the two methods: the inductive and the contact one.

5. Direct Read Out of the Rock Resistivity

The main effect was caused by the eddy current in the core which will be considered the section area energy losses. For

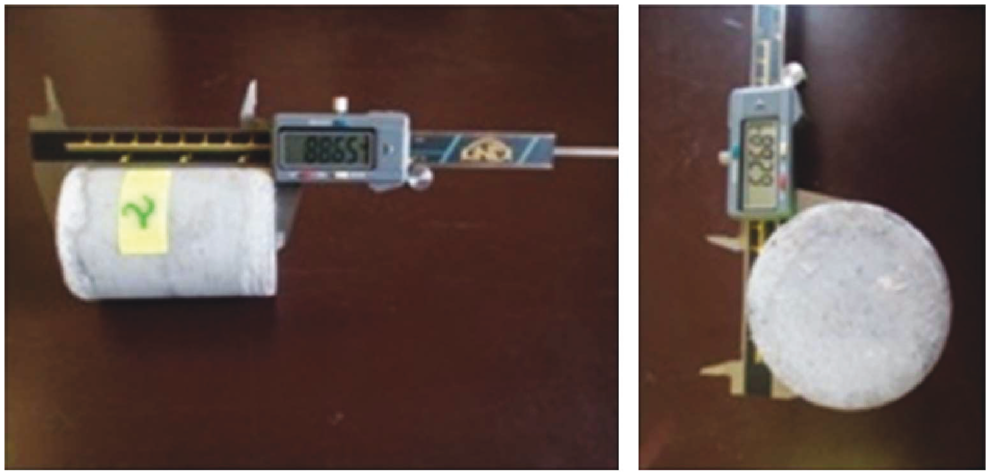

Figure 7: Rock dimensions.

Figure 8: Setup of resistivity measurements using an HP4192A: contact method.

a given diameter of the sample, it depends on the frequency and the ratio $U_G/(M''(z))$ without dimensions. This gives the possibility of expressing the resistivity through the frequency of the magnetic field and the excitation voltage of the ac bridge arm, which should be fixed. Besides, the proportional constant α could be determined by using standard measurements and thus immediately obtain the resistivity of the rock from the inverse value of the detected component in the quadrature (Y: component) by using a differential transformer.

6. Comparison and Check of the Inductive Method Resistivity Measurements

Quarries, granite and marble factories, and natural outcrops in the Bizerte, Beja, Zagouan, and Ben Arous areas of Tunisia were visited, and rock blocks were collected with a total of fifteen different rock types sampled, all of which were sedimentary. Each sample was inspected for macroscopic defects so that it would provide test specimens free from fractures and partings of alteration zones. The locations of the rocks and the result tests are listed in Tables 1 and 2. An impedance analyzer was used for the resistivity measurements: the samples were fixed between electrodes using a screw press. Circular stainless copper electrodes were used in the test in which the two-electrode technique was employed. To ensure a good contact between the electrodes and the samples, a pad of filter paper soaked in brine solution was placed between the core and the steel electrodes. At least, three samples were tested for each rock type and three different voltage table levels were applied for each sample. Using the resistance reading in the geometry of the samples, the resistivity values were calculated from the following:

$$\rho = R\frac{A}{L}, \tag{22}$$

where ρ is the electrical resistivity, R is the resistance, A is the cross section of the specimen, and L is the length of the specimen. The resistivity measurements were performed on cylindrical samples 63.82 mm in diameter and 88.65 mm in length.

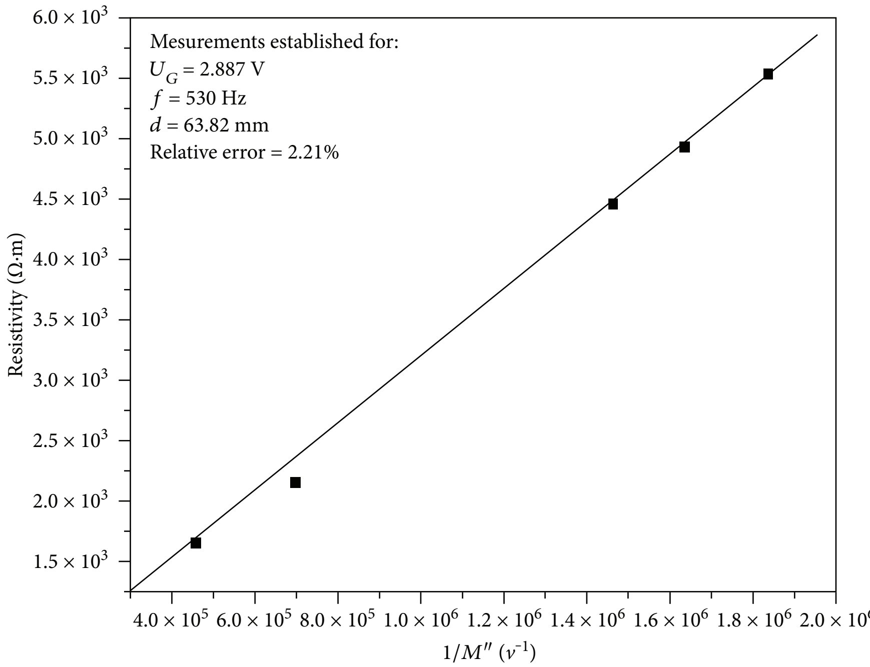

Figure 9: Calibration curve for resistivity measurements.

Table 1: Test results.

Rock code	Electrical resistivity $\times 10^3$ (Ω·m) Contact method	Electrical resistivity $\times 10^3$ (Ω·m) Inductive method
1	2.821	3.012
2	1.706	1.098
3	9.038	9.624
4	11.222	12.064
5	5.906	9.275
6	9.997	8.451
7	1.411	1.852
8	9.338	9.171
9	1.098	0.783
10	0.840	0.957
11	14.835	9.797
12	9.035	9.757
13	48.989	9.704
14	4.378	4.585
15	13.807	6.411

Table 2: Location and name of the rocks sampled.

Rock code	Location	Rock type	Rock class
1	Béja/Tubersouk	Schist	Metamorphic
2	Béja/Djebaldouaznia	Limestone	Metamorphic
3	Béja/Tastour	Limestone	Metamorphic
4	Zagouan/Djebal el oust	Limestone	Metamorphic
5	Ben Arous/Jbalrsas	Limestone	Metamorphic
6	Bizerte/Tahent	Limestone	Metamorphic
7	Bizerte/Tahent	Limestone	Metamorphic
8	Béja/Djebaldouaznia	Limestone	Metamorphic
9	Ben Arous/Jbalrsas	Marl	Sedimentary
10	Béja/Tubersouk	Marl	Sedimentary
11	Bizerte/Tahent	Marl	Sedimentary
12	Ben Arous/Jbalrsas	Sandstone	Sedimentary
13	Bizerte/Sejnane	Sandstone	Sedimentary
14	Bizerte/Boujrir	Salt	Sedimentary
15	Bizerte/Tamra	Sandstone	Sedimentary

7. Conclusion

The experiments conducted in this work show an important application of eddy currents, the contactless measurements of rock electrical resistivity. The measurements were performed in a simple and straightforward manner. The determination of the effective magnetic susceptibility yielded results that are in good agreement with the theory. The contactless rock electrical resistivity on bulk samples demonstrates the capabilities of this technique which may not be widely known. The experiments are inexpensive and may be of interest for possible future works in the geophysical laboratory research field. Besides, the method described should be considered appropriate to perform accurate, fast, and local measurements of rock resistivity in very weak ac magnetic fields and low frequencies on laboratory core samples. In order to obtain successful results, different loggings need to be established, for petrophysics and mineralogy research, from the simultaneous measurements of the two physical parameters:

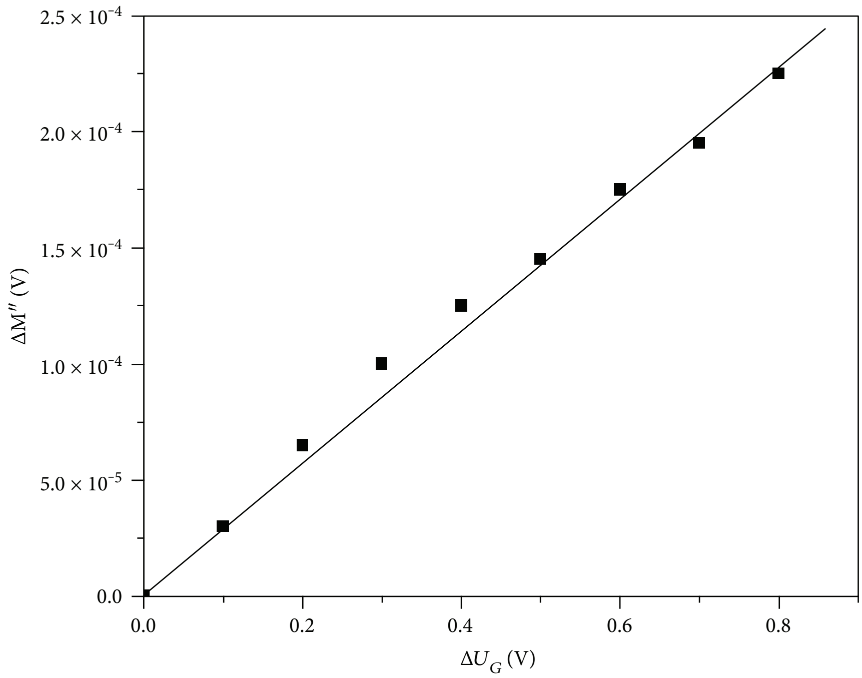

Figure 10: Phase response variation $\Delta M'$ plotted versus the voltage excitation variation.

magnetic susceptibility and electrical resistivity. The apparatus is used like an electromagnetic sensor to measure simultaneously the susceptibility and the resistivity of rocks by contactless technique (Figure 10).

All the results shown should be considered the average values of the measurement of the resistivity taken in natural conditions at room temperature and read as the rock matrix intrinsic resistivity. The comparison between the two methods shows an agreement, but the inductive one is very interesting because it takes into account the local physical properties of the sample. Further studies are in progress, mainly using contactless measurements for various scientific activities. In this way, the petrophysics field is involved in the design of sensors with a faithful response that are reliable for their accurate use. This paper gives an overview of the subject and some insight of the work done in this respect. In our laboratory, we approached the challenge of creating the finest eddy current geological sensors which are in full development.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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