Experiments on Magnetic Diffusion in Metal Sheets

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***Abstract*—Experimental work has been conducted to develop theoretical models for a metallic sheet's response to time domain electromagnetic sounding. This technique offers a method to characterize the size and conductivity of different conducting plates. In addition, this response has been compared to a response of a sphere and potential applications have been discussed.**

I. Introduction

Time Domain Electromagnetic Sounding (TDEM) works on the principle of the formation of eddy currents during a sudden change in applied magnetic field. A receiver will sense the time derivative of the magnetic field produced by eddy current diffusion. The TDEM methods have been thoroughly investigated in the past [1]. The objective is to characterize the magnetic diffusion in objects with known theoretical diffusion curves. The study of magnetic diffusion has immense applications in underground propagation since magnetic diffusion can use the conductivity of the earth as an advantage by generating eddy currents, as opposed to a ground penetrating radar technique (GPR) will use high frequency waves which quickly attenuate while propagating underground.

II. Theory of Operation

A rate of change of magnetic flux in an object of finite conductivity will induce eddy currents and they decay as a function of the geometric shape and the conducting properties of the material. The more the conductivity the higher the rate of decay as the currents dissipate more slowly. For finite conducting objects the late time response of the eddy currents is an exponential response [1]. The general solution for a simpler spherical model has been calculated by Wait [2]. For a sphere, the magnetic field generated by eddy currents during a step response of applied magnetic field is given by:

$$B(t) = X^2 + 1/3 - 2\frac{1}{\sqrt{\pi}}x - \sum_{n=1}^{\infty} 2n\left[\frac{x}{n}\mathrm{erf}'\left(\frac{n}{x}\right) - 2\mathrm{erfc}\left(\frac{n}{x}\right)\right]$$

$$x = \frac{\sqrt{t}}{\sqrt{\mu\sigma R}}$$

(1)

In late time, "t", this equation can be approximated as an exponential decay function with a time constant. Khomenyuk [3] has listed the exponential decay time constant of a sphere as:

$$Ts = \frac{\sigma\mu R^2}{\pi^2} \quad (2)$$

The finite square plate time constant has also been listed as:

$$Tp = \frac{\sigma\mu T L}{\pi^2}. \quad (3)$$

Here the "T" is the thickness of the plate, and "R", the radius of the sphere, and "L", the length of the plate. The experimental response observed from the plate is verified to reproduce the correct time constants listed above in late time. The full solution has been attempted numerically by Annan [4] using the concept of eigencurrents however the equation cannot be easily written in analytical form. It is still, however, worthwhile to determine experimentally how the early time response of a sphere compares to that of a plate. Finally, the parameter, "R", in the theoretical model of a sphere given by equation 1 is adjusted to reproduce the same time constant observed in the plate to determine if the early time response of the plate observed in the experiment can be approximated to that of the sphere.

III. Experimental Setup

The experiment consists of a transmitter (Tx) coil of 6 turns and a current of about one amp is passed through the system. A Keysight 33600 series waveform generator, then triggers the transmitter switch circuit to shut down the current through the Tx Coil. This change of magnetic field induces current flow in the metal (Tin) object which decays at a particular time constant depending on the size.

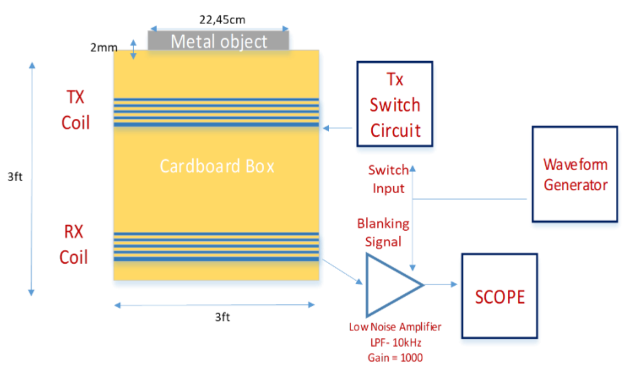

Fig 1. Block Diagram of the System

The receiver (Rx) coil (also consisting of 6 turns) picks up any changes in the magnetic field and feeds it to the SRS 560 low noise amplifier (LNA) whose output is displayed on a Keysight MSO-X 4154A oscilloscope. The SRS amplifier has a high input impedance. The Rx coil is a series inductor and resistor circuit so voltage impulse responses associated with the Tx coil switching off will induce unwanted currents if the input impedance of the LNA is low. The blanking signal stops LNA operation during the turn off of the transmitter. This prevents the

LNA from receiving high voltages that are triggered by the transmitter turning off. The measured response, therefore, is solely due to the environment. The oscilloscope calibrates out the response of the ground by subtracting the signal received with the metal plate from the signal without it, in order to observe solely the response of the metal plate. The process of switching off the current is repeated several times in one second time intervals and averaged to reduce the effects of noise in the system.

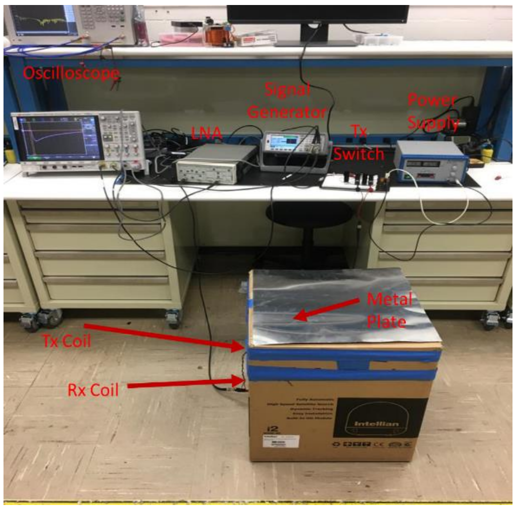

Fig 3. Experimental Setup

IV. Results

The measured data with two different plates has been plotted for a small square plate and a large plate with twice the length. From equation 3, the time constant has been calculated and that of the larger plate should be twice as much as the time constant for the smaller plate. The best fit exponential decay functions have been fitted in both measurements and the results in figure 4 show that the time constant of the large plate is as predicted about twice as much as the small plate.

However, as it is clearly seen, the best fit exponential models only match the data well at the late time and the model is quite different from measurements in early time. The early time response of a sphere has been computed.. Using Equation 1 and differentiating with time (since the Rx coil captures the time derivative of the magnetic field) and adjusting the radius "R" to obtain the same time constant as seen with the metal plates in late, the early time response of the theoretical sphere closely matches the early time response of the plates as shown in figure 5. This experiment has been done for both plates to demonstrate early time response similarities

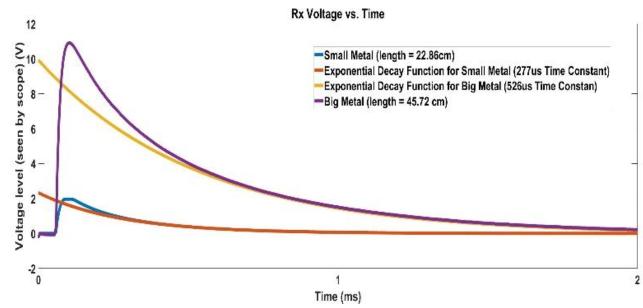

Fig 4. Transient Response of Metal Plates

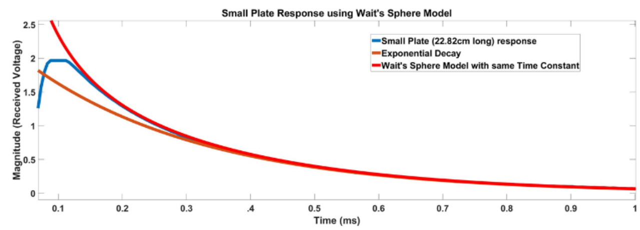

Fig 5. Response of Plate Compared to Sphere

Conclusion

The experimental data showed that it is possible to determine the geometrical and conducting properties of the metallic plates using magnetic diffusion. It was shown that late time response of plates matched exponential curves with a time constant dependent on the properties of the plates. It is also well noted through the experiments that early time response of a sphere matches very closely with that of the plate. Future work would include developing theoretical approximation models for early time response of small metal plates to show that they do resemble that of metallic spheres. These models can be of great value to understand early time responses of finite conductors without numerically solving them. TDEM sounding has been used in the past for underground scanning, and currently TDEM techniques are being developed for underground water detection on Mars and these experiments were for preliminary proof of concept.

Acknowledgment

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