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A novel induction-based device for the measurement of the complex magnetic susceptibility

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ABSTRACT

A device named magnetic susceptometer for a complete determination of the magnetic complex susceptibility of materials and minerals has been conceived and manufactured as a complement for the in situ characterization of rocks during high resolution magnetic prospections. In this work a device and its capabilities for susceptibility measurements are described, the calibration performed with artificial samples, and the values of real and imaginary susceptibility of natural samples in a range comprising: $\chi = 10^{-4}$ to 10^{-7} [SI], representative of Earth and also Mars rocks.

1. Introduction

Complex magnetic susceptibility determination of natural and synthetic samples is an important measurement for its complete magnetic characterization. Magnetic losses, eddy currents, accumulated magnetic energy, and changes on these and other properties under variations of amplitude and frequency of an external magnetic field may be of interest in the characterization of synthetic materials for some applications like transformers and superconductivity “Singh et al. [1]”, and basic science like spin glasses, phases transitions and superparamagnetism characterization “Mulder et al. [2], and del Barco el al. [3]”. It also can give relevant information of the conditions of formation (global magnetic fields) or cooling and alteration processes (atmospheric temperature and environmental conditions) in the study of natural rocks, where the remanent magnetization measurement is not enough to extract relevant parameters “Pandarinath [4]”.

The determination of the complex susceptibility implies not only the measurement of initial susceptibility and determination of the hysteresis loop “Singh et al. [1], Mulder et al. [2], and del Barco et al. [3]”, but also the behavior of the material under the action of an alternating magnetic field.

Current magnetic susceptibility measurements are performed in devices “Marcon and Ostanina [5]” based on magnetic induction like Vibrating Sample Magnetometers (VSM) “Foner [6]” or Alternating Force Magnetometers (AFM) as in Vibrating Wire Susceptometer from “Asti et al. [7]” for the real part, and magneto-optical methods “Motta et al. [8]” as well as Superconducting Quantum Interference Devices (SQUID) “Li et al. [9]” can determine the real and imaginary components. Additionally, other techniques using Micro-Electro-Mechanical Systems (MEMS) “Drung et al. [10]” or Nuclear Magnetic Resonance (NMR) “Duyn [11]” have been more recently introduced. These examples of equipment provide high-resolution susceptibility values “Mulder et al. [2]” but have high power consumption, often consist in complex procedures and are limited to medium to large laboratory facilities due to the large dimensions of the devices and maintenance resources. In all cases, very little portable equipment exists, it is considered bulky and often requires liquid nitrogen for its operation “Timofeev et al.

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[12]". This is a limitation to studies, which need the analysis of natural samples because on the one hand a process of sample collection and transportation to the facility is needed, and on the other hand because the exhaustive analysis of the collected sample can lead to non-appropriate conclusions if it lacks representativeness. Furthermore, along the sequence of processes, any gap in the traceability might result in the loss of information regarding the original orientation of the samples, essential for paleomagnetic studies and with implications on the structural anisotropies.

An in situ prospection including susceptibility as well as magnetic field vector measurements is highly recommended because magnetic signatures and properties of outcrops, when measured in the nature, are the result of the contribution not only from surface rocks, but also from the magnetic properties of the subsurface and surroundings "Michelena and Kilian [13]". Therefore, complementary in situ analyses are highly desired and they suppose a very powerful tool from which many scientific and industrial sectors like Paleomagnetism, Geology, Geophysics, Mining, Oil Industry, Arqueology, etc "Clark [14] and Murdock et al. [15]" can be benefited.

The presented device has been conceived as a part of a compact and portable multisensor magnetic instrument, with the capability to measure the magnetic field and therefore an estimation of the vector (three axes): Natural Remanent Magnetization (NRM) + induced magnetization, the Magnetic Susceptibility and the minor hysteresis loops of the minerals "Day [16] and Dunlop [17]". In this work we focus on the capability of the device to measure the magnetic susceptibility, and therefore name the device susceptometer.

2. Methodology

The susceptometer is based on an inductive circuit comprising an autoinduction with an H shaped ferrite core (Fig. 1) and two capacitors connected in series and parallel with the coil (Fig. 2). The circuit is brought to the natural RLC resonance, which minimizes its power consumption. In these circumstances, along the working cycles, the capacitor C_1 (in parallel to the autoinduction) sources a high current to the coil, which generates fields in the gap of the magnetic circuit in the order of 30 mT.

When a magnetic or metallic material is approached to the bottom gap of the ferrite, the magnetic induction (B) in this part of the magnetic circuit changes, as a consequence of the different relative real permittivity (μ') of the material respect to the air (upper gap). Even more, due to the complex nature of the permeability (composed by a real: μ' and an imaginary part: μ''), other dissipation processes might be unchained in the gap, like eddy currents or processes of spin relaxation.

The change in the magnetic circuit gap induction results in a variation of the autoinductance, which can be easily measured by the corresponding change of resonance frequency of the electrical circuit. Additionally, the dissipation effects are reflected in the fields involved in the magnetic circuit as well as in a change of the voltage drop in the input resistance (R_{in}). The ferrite core has a coupled pair of secondary coils that measure the variation of the magnetic field on the two edges, when a sample is presented to one of them. The variation in the amplitude and phase of the field measured with this secondary coils corresponds with the difference between relative real and imaginary components of the susceptibility of the air and the sample.

Therefore measuring these parameters experimentally, it is possible to obtain a value of the magnetic complex relative permeability. ($\mu = \mu' + i\,\mu''$) i.e. susceptibility ($\chi = \chi' + i\,\chi'' = \mu - 1$ in the International System).

Also, the system is provided with several sets of capacitors to perform complex susceptibility measurements as a function of the frequency in the range between 10 and 100 kHz.

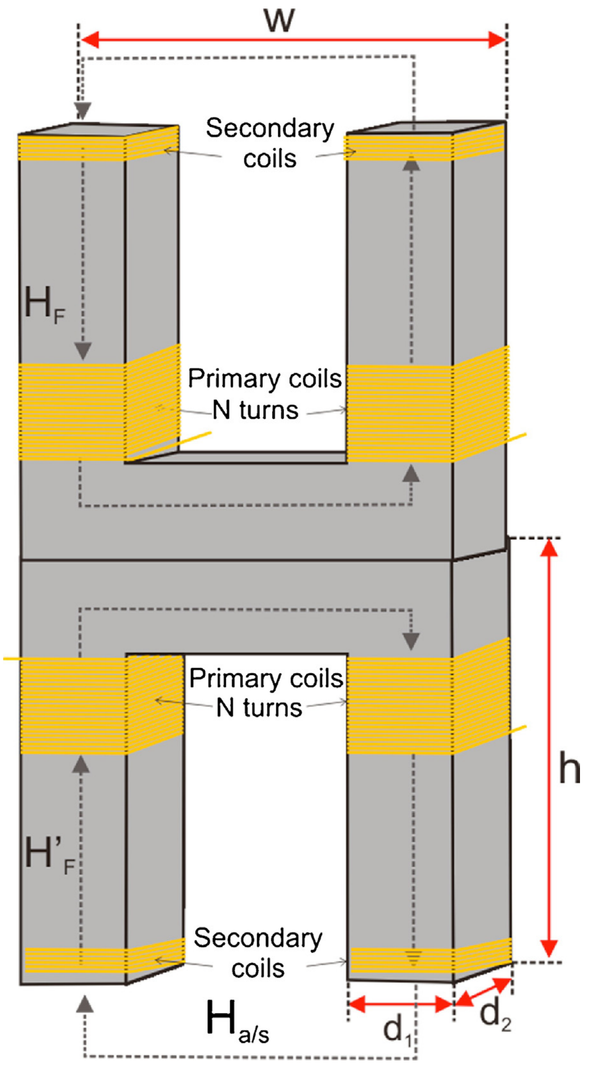

Fig. 1. Scheme of the autoinductance based on a U-shaped ferrite core. Primary coils are connected in series. Secondary coils are connected in series within every U but in opposition between the upper and lower parts of the H.

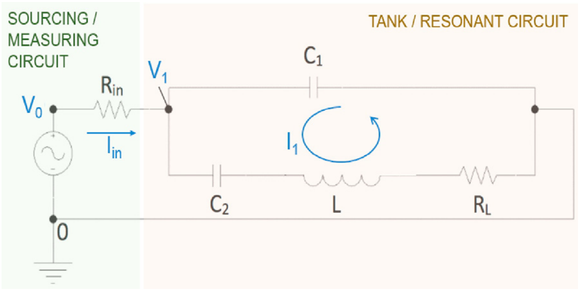

Fig. 2. Scheme of the electrical circuit. A modified tank circuit.

2.1. Mathematics

In this section we introduce the expressions to derive the real and imaginary parts of the permeability as a function of the indirect measurements performed in the electrical circuit.

The total impedance of circuit in Fig. 1 is:

$$Z_T = R_{in} + \left[(Z_{C_1})^{-1} + (Z_L + Z_{C_2} + R_L)^{-1} \right]^{-1} \quad (1)$$

where $Z_{C_1} = \frac{1}{i\omega C_1}$, $Z_{C_2} = \frac{1}{i\omega C_2}$ and $Z_L = R_L + i\omega L$.