ELECTROMAGNETIC RESPONSE OF SOIL

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Abstract − The possibility of measuring both time-domain and frequency-domain response on small soil samples would allow one to predict the influence of such soil on various types of mine detectors without field trial. We have measured the time-domain soil response on standard cylindrical samples. The time response to abruptly removed magnetic field is similar to $1/t^x$, where x is between 1.1 and 1.3. We have also measured frequency-domain response in the 400 Hz to 480 kHz band by various independent methods and compared with values calculated from the time response. This study shows that for soils with high content of nanoparticles the complete frequency characteristics should be measured instead of traditional two-point measurement.

Keywords: paper instructions, layout, references (up to five)

1. INTRODUCTION

Traditional electromagnetic induction metal detectors operate in the band below 100 kHz. At these frequencies, the electromagnetic field is influenced by two material properties: the magnetic susceptibility and the conductivity. In this respect, metal detectors differ from radar sensors operating at frequency above 1 GHz which are influenced by the permittivity (dielectric constant) of the material, a negligible factor for metal detectors. If the susceptibility and/or conductivity of the soil is too large, it may be impossible to raise the detector sensitivity sufficiently to detect minimum metal mines without the detector alarming constantly when near the soil. It should be borne in mind that the volume of soil interacting with the electromagnetic field is essentially a roughly hemispheric region under the head, and is large compared with the objects which it is required to detect. Particularly problematic are soils whose susceptibility is frequency-dependent in the relevant bandwidth. Such soils are referred to as "noisy", "uncooperative" or "difficult" and cause serious problems where there are no good alternatives to the use of metal detectors, as may be the case in e.g. landmine clearance.

Metal detector manufacturers are well aware of this problem and have devoted a great deal of research and development effort to overcoming it. High-quality modern detectors are equipped with soil-compensation circuits which reduce their sensitivity to the soil without reducing the sensitivity to metal very much, if at all; a patent review is given by Gaudin et al [1].

2. SUSCEPTIBILITY

Values of susceptibility for soils range from less than 10^{-5} to up to 10^{-2} SI (some authors and manufacturers use 10^{-5} SI as a basic unit, to give values of the same order of magnitude as with cgs units). Anything above about 10^{-4}, which is by no means unusual, is sufficient to give a signal in a highly sensitive detector circuit. All good detectors today can eliminate the basic effect of soil susceptibility by using phase-sensitive detection for continuous wave detectors or time-domain windowing for pulse induction detectors. Unfortunately, real soils may have frequency-dependent susceptibility (e.g. dropping by 10% or more with each decade of frequency) and give responses which are out of phase with the inducing signal. The best detectors employ advanced techniques to overcome this. The continuous-wave detectors use multiple frequency excitation and phase-sensitive detection at all excitation frequencies. Pulse detectors use multiple pulse lengths and/or multiple time windows. The effectiveness of the soil compensation is a key performance factor of metal detectors.

The physical explanation for frequency-dependent susceptibility is that the soil contains significant numbers of magnetic grains whose size is near the superparamagnetic limit [2]. Grains which retain their magnetisation for a time of the order of 10's of microseconds release their magnetic energy in the detector's bandwidth, giving a signal which is not straightforward to discriminate from that due to a metal object.

It is very important to know the soil conditions in which any demining action is carried out, since these will have a significant effect on the campaign effectiveness. The possibility of measuring both time-domain and/or frequency-domain response on small soil samples allows one to predict the influence of such soil on various types of mine detectors without a time-consuming and expensive field trial.

2.1. Instrumentation

Methods for measuring soil susceptibility are well-established and have a long history. For example, Stephenson [3] measured susceptibility of lunar dust at 1.5

kHz and in the range of 300 kHz to 11 MHz using a marginal oscillator.

West and Bailey [4] used 3 Helmholtz coil pairs, a sigma-delta ADC and digital processing. The frequency range is 100 Hz to 70 kHz, noise 3×10^{-5} SI units. The coil geometry is made so that M_{air} (air coupling between the transmission and detection coil) is compensated and also so that the instrument is insensitive to external fields. Their instrument is unstable due to dimensional changes (including by heating by its own excitation current). In all soil samples they observed linear susceptibility versus logarithm of frequency up to 20 kHz; in some samples having slight non-linearity above 20 kHz.

General comments on instrumentation:

1. All methods assume operation well below the coil resonance frequency, so that the currents through parasitic capacitances can be neglected.

2. Homogeneity of the magnetic field within the sample volume is generally not required as soil samples are linear. West and Bailey [4] used large Helmholtz coils but they have small sensitivity and they are susceptible to interference. Small solenoid coil with non-homogenous winding density can achieve reasonable field homogeneity.

3. Compensation need not be perfect but must be very stable. A toroidal bucking coil or a transformer are more stable solutions than the air coil system used by West and Bailey [4]. Gain and quality factor Q can be adjusted independently by potentiometers as described by Scott and Malluck [5]. If a ferromagnetic core is used in the bucking coil, it should be designed to work far from saturation to avoid non-linearity.

4. The amplitude of the excitation magnetic field of metal detectors is usually below 10 A/m. The susceptibility of known soils in this field range is independent of the field magnitude. However, the excitation field in some measuring instruments may be higher and this may cause errors in some soils. De Wall and Worm [6] described false "frequency dependence" of some samples containing pyrrhotite or titanomagnetites, caused by the fact that the Bartington instruments do not have the same measuring field at all frequencies.

The results available in literature show that the real (in-phase) part of susceptibility of most soils uniformly decreases with the logarithm of frequency, and the imaginary part is much smaller and frequency independent. However, clear deviations from this rule was observed by Dabas et al. [7,8] and other authors, although the effect was observed mainly on soils containing metal particles. This indicates that it is not always sufficient to measure the soil samples only at two different frequencies.

For the time response measurement, no laboratory instrument is available. In the field, the time-domain response of the soil can be estimated by using pulse-induction metal detector and measuring the Ground Reference Height (GRH). The GRH is an empirical measure of how noisy a soil is for metal detector use. It is the height at which a metal detector without soil compensation, calibrated in an agreed manner, stops sounding as it is slowly raised from the soil surface [8].

3. MEASUREMENTS AND SIMULATIONS

3.1. Time response

In this work, the time-domain soil response on standard 10 ml (approx. 25×25 mm) cylindrical samples was measured using a single 50-turn solenoid coil with 32 mm diameter and 25 mm length. The rectangular current pulses with adjustable amplitude and duration were used. The voltage induced after the energizing pulse decay was amplified by 100 using double stage amplifier with anti-saturation antiserially connected Schottky diodes at the input of each stage. The amplified induced signal was then sampled using a LeCroy WaveJet 300 oscilloscope. The waveforms obtained with and without sample were subtracted. Simultaneously registered was also the energizing current, measured with a Tektronix AM 5030S / TM 5003 dc-coupled current clamp. Table 2 shows the decay slopes and voltage amplitudes obtained for 5A/ 445 µs pulses. Also given are susceptibility values measured with a Bartington MS2B meter (see section 2.2). An example of a raw acquired waveforms is shown in Fig. 1. The same measurement corrected for background signal is shown in Fig. 2.
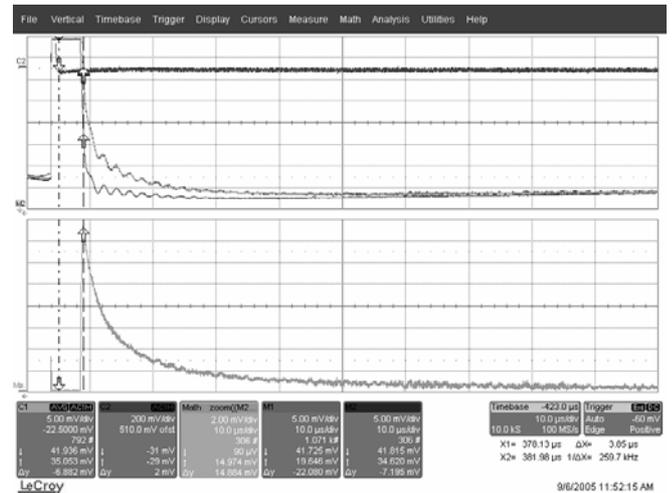

Fig. 1. Raw voltage response of a 10 ml soil sample (upper figure, middle trace), background (upper figure, lower trace), subtracted waveforms (lower figure), excitation pulse (upper figure top trace).
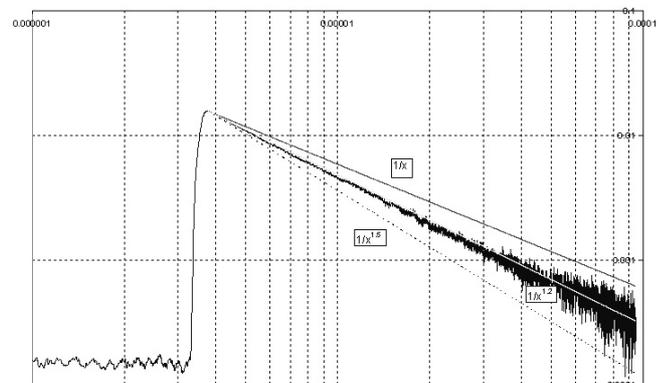

Fig. 2. Voltage response of LK-1 soil (10 ml sample) in loglin scale

We measured 18 samples of noisy soils (all these samples were gathered by JRC staff during various metal detector test campaigns such as [9]). The time response was always similar to $1/t^x$, where x was between 1.1 and 1.3. We have found that using such small samples the time-domain measurements are possible but they are poorly reproducible, as parasitic capacitances, which are hard to define, play too important a role.

Interestingly, no significant difference in the slope x was observed when the length of the magnetization pulse was changed from 445 μs to 100 μs. This is not in agreement with a theoretical description given by Dabas and Skinner [7]. According to this paper, a 1/t response is obtained for long rectangular energizing pulse. For finite energizing time t_e they derived the formula:

$$\frac{\partial J_r}{\partial t} = \frac{k}{t} - \frac{k}{t + t_e}$$

For given time interval we can approximate this dependence by $1/t^x$ where x is a slope in log-log scale. For time between 12 μs and 136 μs Dabas and Skinner numerically calculated the slope x as a function of t_e. The results of their calculations, together with our measurements, are shown in Table 1. It is clear that our experimental results did not confirm the theory.

Table 1. Slopes x of the time response $V = V_0 / t^x$ derived by Dabas and measured

t	x [Dabas]	x our measurements
$t \rightarrow 0$	2	
100 μs	1.6	1.25
450 μs	1.25	1.25
$t \rightarrow \infty$	1	

Soils with susceptibility lower than 100 gave low signal amplitude, which does not allow one to reliably identify the slope.

3.2. Frequency response

For the frequency-domain measurements in the 400 Hz to 480 kHz band we have used the same 50-turn coil as for the time-domain measurements. The susceptibility values were calculated from the inductance measured by an HP 4284A LRC meter. Each time the inductance L_{air} of the empty coil and L_{soil}, that with the sample inside the coil, were measured. Susceptibility was then calculated as $\kappa = (L_{air}/L_{soil}-1)/F$, where F is the correction "filling factor" whose value would be 1 if the coil was deeply buried, so all the field generated was inside the soil. Examples of F factors numerically calculated by Finite Element Method for our coil and different soil volumes are in Table 4. Note that F is not linearly dependent on volume, because the coil field is not homogenous.

Table 1. Calculated filling factors for partly filled coils

Fill	FF
Inside and outside	1
100% of inside volume	0.7
56% vol (0.75×0.75 in)	0.28
12.5% vol (0.5×0.5)	0.09

56% volume of the measuring coil was an estimate for 10 ml standard sample. The calculated F = 0.28 is in good agreement with value of F = 0.32 found experimentally by calibration measurements. Susceptibility of all samples was also measured at 465 Hz and 4.65 kHz by a Bartington MS2-B.

The measurement current was 100 mA, the corresponding field amplitude was about 100 A/m, which is larger value then the field used by the Bartington (80 A/m). Also the field homogeneity was poor: the field at the end of solenoid is only 50% of the maximum field in its centre. However, the measured values usually fitted well with those from the Bartington and it was experimentally verified that at this field value the susceptibility of measured soils is not amplitude dependent. Each value was measured 10-times and averages and standard deviations were calculated. The characteristics is shown in Fig. 3.
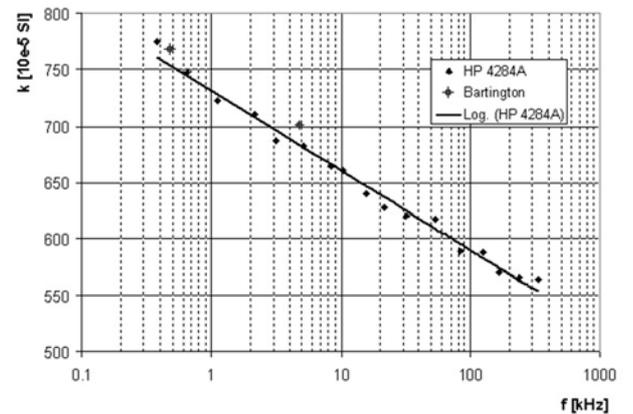

Fig. 3 Frequency response of LK-1 10 ml sample measured by HP 4284A. Also shown are the two values measured by the Bartington MS2B

Most of the samples have susceptibility with a logarithmic dependence on frequency $\chi = \chi_0 \log (f/f_0)$, as predicted from soil models and also observed by West and Bailey [4]. However, some noisy soil samples show small deviations from loglinearity, which may indicate uneven volume distribution of superparamagnetic grains or the presence of conducting or ferromagnetic particles [2]. This would also cause deviation from the ideal 1/t time response.

3.2. Relation between the time and frequency response

In general signal theory the relation between time and frequency response of a linear system is given by Laplace transform. If the time response is 1/t, the corresponding frequency response is loglinear. Generally, for time response of $1/t^x$, the corresponding frequency response is proportional to f(1-x). The simulated frequency response for the very rare case of $1/t^{1.4}$ and common case of $1/t^{1.1}$ is shown in Figs. 4 and 5 respectively.
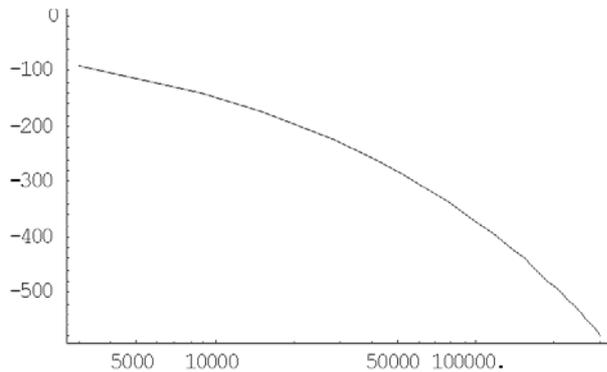
Fig. 4 Simulated frequency response corresponding to very rare time response of 1/t1.4 (x-axis units are Hz, y-axis units are arbitrary)

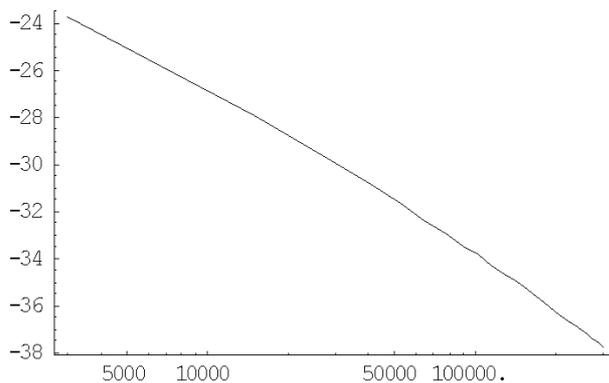Fig. 5 Simulated frequency response corresponding to typical time response of 1/t1.1 (x-axis units are Hz, y-axis units are arbitrary)

These two arbitrary examples show that the slope of the time response theoretically corresponds to curvature in the frequency characteristics. However, this curvature is not necessarily observable in the low frequency region.

CONCLUSIONS

In order to predict the behavior of the pulsed induction-time domain metal detectors in different soils it is desirable to measure the frequency dependence of the soil susceptibility at over all the bandwidth of the detector. It is not easy to perform these measurements because the only two available instruments available on the market specifically for soil susceptibility measurements have only 10 kHz frequency range and their precision is not verified.

We discussed the possibility of making these measurements using a precision LCR meter. The advantage of this method is its simplicity, the disadvantage being large measurement uncertainty and need for calibration at higher frequencies. We have also shown a possibility to use for these measurements a simple bridge and a lock-in amplifier. This instrument gives low uncertainty, but requires calibration at each frequency, which can be made automatically.

Time-domain measurements on a 10 ml soil samples are possible, but the results are not well reproducible due to the high influence of the coil self-capacitance and other effects. From is that point of view, the measurement in the frequency domain would be preferred. The suggested frequency range is up to 100 kHz.

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