Innovative Possibilities in Time Domain Reflectometry

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Abstract –In this contribution we describe new possibilities regarding TDR measurements, related to the measurement of the electromagnetic characteristics of lossy and possibly magnetic and dispersive materials. The proposed advancement is related to the introduction of a spatial diversity in TDR measurements, achievable by means of extensible probes or alternatively by means of arrays of probes. The spatial diversity can replace the frequency diversity increasing the information achievable at single frequency, so allowing measurements immune from the effects of a possibly unknown dispersion law. Moreover, measuring the reflection coefficient at fixed frequency we can achieve information about both the propagation velocity of the electromagnetic wave along the line and about the intrinsic impedance of the line, which in its turn allows to discriminate between the dielectric permittivity and the magnetic permeability of the material, meant as complex quantities in order to include lossy cases too. There are several possible fields of application and in particular, with regard to the properties of the soil (of interest for archaeological prospecting), the attenuation of the waves in the soil can be estimated (which is important in relation with GPR prospecting), or the water content or in some cases the possible presence of some pollutant.

I. INTRODUCTION

Time domain reflectometry TDR is a tool widely exploited for diagnostic and monitoring purposes in geophysics, quality control (e.g. of alimentary substances, but also of electric wires), measure of water content, detection of organic pollutants, geotechnical applications and several other applications [1-2]. Moreover, it can be helpful in GPR prospecting [3-5]. A TDR probe provides local results or results along a guided path in any case, but quite accurate and in a relatively easy and cheap way. The quantity more often measured with a TDR probe is the dielectric constant of the material under test or also its conductivity, but also reflections caused by discontinuities along the guided path of the wave are of interest in some applications.

Generally, in radio frequency or microwave reflectometry, an electromagnetic signal propagates into the system under test, and information about the material crossed by the wave is worked out recording and processing the reflected waves. Measurements, as well as data processing, can be performed either in time domain (time domain reflectometry - TDR) or in frequency domain (frequency domain reflectometry - FDR). In general, a TDR instrumentation working in time domain is cheaper, but instruments working in frequency domain can be more precise. In some cases, the two approaches in time and frequency domain can be conveniently joined. In particular we will propose an innovative possibility in this sense. When exploited in time domain, the incident TDR signal usually is a step-like pulse travelling down the transmission line at the velocity of propagation of the waves in the medium. Ideally, the incident signal is described by a Heaviside function of the kind $u\left(t - \dfrac{z}{c}\right)$, where t is the time, z is the abscissa and c the propagation velocity of the electromagnetic waves in the probed medium. However, the recorded signal, being the sum of the incident wave plus several reflected waves propagating backward and forward, presents as a step-like signal, with either ascending and descending case dependent steps. The discontinuity points of these steps (better evidenced considering the derivative of this signal) contain information on the propagation time of the signal along a path of known length, and consequently contain information on the propagation velocity in the probed medium.

When the signal is considered in frequency domain, it is of interest to consider the steady regime conditions were a standing wave propagates along the probe, so that in any point the signal is sinusoidal, but the amplitude

and phase of this sinusoid change vs. the position along the probe, and these variation contain information regarding the characteristics of the crossed medium. In particular, this information is related, through the reflection coefficient, to the dielectric, conductive and also magnetic (if any) properties of the material being probed [6-7]. In this contribution we will show how both the complex dielectric permittivity and the complex magnetic permeability can be in principle retrieved from TDR data in frequency and time domain, translating a theory already well assessed for laboratory measurement in waveguide [6-7] in the framework of the TDR measurements. The practical advantage in doing this is that a TDR probe does not involve the transportation of a sample of material in laboratory (which requires attention in order not to perturb the sample, and requires expensive equipments), because it is the probe that is brought in the field. Moreover, the probe does not perturb the material to be investigated.

II. MATHEMATICAL MODEL

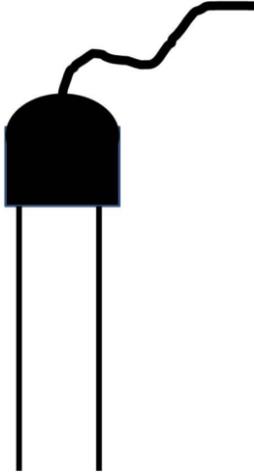A basic scheme of a TDR probe is provided in Fig. 1.

Fig. 1. Scheme of a TDR probe

An electromagnetic generator induces a voltage between the two rods, that propagates along the rods (that constitute a bifilar line). If the medium in which the rods are knocked is homogeneous (which will be always assumed in the paper), the signal is reflected at the end of the probe the reflected contribution back-propagates toward the source after a time, then this signal is reflected again at the beginning of the line and a new foreword propagating contribution is added, and so on.

As well known, in lossless cases the propagation velocity of a TDR signal is given by

$$c = \frac{\grave{c}_o}{\sqrt{\varepsilon_r \mu_r}} \qquad (1)$$

where c_o is the speed of light in free space

($c_o \approx 3 \times 10^8 m/s$), ε_r is the relative dielectric permittivity of the medium, μ_r is the relative magnetic permeability, which at radiofrequencies is equal to 1 for many practical materials but not for all of them. The propagation time of a step-pulse along the probe indicates the time that takes the wave to travel a length equal to twice the length of the rods of the TDR probe. So, when the incident field is a Heaviside function, the received field over the time is a step signal with discontinuities regularly spaced at

$$T = \frac{2L}{c} = \frac{2L}{c_o} \sqrt{\varepsilon_r \mu_r} \qquad (2)$$

This allows to have an estimation of the product $\varepsilon_r \mu_r$ from measurements in time domain in lossless cases. Indeed, in presence of losses both the dielectric permittivity and magnetic permeability are complex, and the return time of the signal is indeed linked both to the real and the imaginary parts of these two parameters. For many media, however, the imaginary parts of the dielectric and magnetic relative constants are lower than their respective real parts, and the return time of the signal can provide a first estimation of the real part of the product of $\sqrt{\varepsilon_r \mu_r}$. Instead, passing to measurements in frequency domain, after some calculations the reflection coefficient at the air-medium interface, on the air side, is given by [5]:

$$\Gamma\left(-L^-\right) =$$

$$= \frac{\left(Z_{lo}\sqrt{\frac{\mu_r}{\varepsilon_r}} - Z_{lA}\right) + \left(Z_{lo}\sqrt{\frac{\mu_r}{\varepsilon_r}} + Z_{lA}\right)\exp\left(-j\frac{4\pi f}{c_o}\sqrt{\varepsilon_r \mu_r}L\right)}{\left(Z_{lo}\sqrt{\frac{\mu_r}{\varepsilon_r}} + Z_{lA}\right) + \left(Z_{lo}\sqrt{\frac{\mu_r}{\varepsilon_r}} - Z_{lA}\right)\exp\left(-j\frac{4\pi f}{c_o}\sqrt{\varepsilon_r \mu_r}L\right)}$$

$$(3)$$

Where Z_{lo} is the intrinsic impedance of the bifilar line provided by the rods of the probe knocked in the material under test, but evaluated in air, i.e. when the probe is not knocked, and Z_{lA} is the intrinsic impedance of the portion of line in air. Possibly $Z_{lo} = Z_{lA}$ but not necessarily: the important fact is that both quantities are a-priori known parameters. As can be seen, the reflection coefficient contains information both on the product $\sqrt{\varepsilon_r \mu_r}$ and on the ratio $\sqrt{\frac{\mu_r}{\varepsilon_r}}$, which allows in principle to retrieve both ε_r and μ_r from the data.

III. RESULTS

We have minimized a least square cost functional given by the discrepancy between the model and the data, where the diversity of data to provide sufficient information is given by different lengths of the rods of the probe, i.e. different values of L:

$$F(\varepsilon_r, \mu_r) = \sum_{k=1}^{M} \left| \Gamma_a(L_m) - \Gamma(\varepsilon_r, \mu_r; L_m) \right|^2 \qquad (4)$$

Experimentally, the prolongation of the rods can be guaranteed by some screwing mechanism, or just pushing progressively in the material a unique transmission line (in which case $Z_{lo} = Z_{lA}$). To make use of a diversity in length is certainly less fast than making use of frequency diversity, but makes the results immune from the problem of the dispersion of the material and prevents from the risk to excite propagating higher order modes. We have simulated transmission line data, but Gaussian noise has been added to them (SNR=40 dB). The minimization has been exhaustive and has looked for four variable, namely

the real and imaginary part of $\sqrt{\varepsilon_r \mu_r}$ and $\sqrt{\dfrac{\mu_r}{\varepsilon_r}}$. Then,

the unknowns of interest have been retrieved by means of some easy algebra from these two auxiliary quantities. In particular, we have based the minimization on an iterative algorithm, exhaustive at each step, where the new set for the minimization was large one half of the previous one along all the four variables. The cells for the exhaustive minimization were 40 along each direction, so they were $40^4 = 2560000$ all together at each step. The frequency was equal to 200 MHz, where the length of the probe ranged from 25 to 65.375 cm with a step of 2.375 cm. The distance between the rods was 2.5 cm and the diameter of the conductors was 2 mm. These quantities determine the intrinsic impedance of the bifilar line in air, which can be calculated in close form [8]. For the case at hand $Z_{lA} = 50\Omega$.

For the minimization, the initial investigation domain has been chosen as follows:

- $\text{Real}\left\{\sqrt{\varepsilon_r \mu_r}\right\}$ ranging from 1 to 4.52

- $\text{Imag}\left\{\sqrt{\varepsilon_r \mu_r}\right\}$ ranging from -4 to 0

- $\text{Real}\left\{\sqrt{\dfrac{\mu_r}{\varepsilon_r}}\right\}$ ranging from 0.01 to 4

- $\text{Imag}\left\{\sqrt{\dfrac{\mu_r}{\varepsilon_r}}\right\}$ ranging from -2 to 2

The criterion underlying these choices has been to take

into account ranges with amplitude equal to 4 at most, but also accounting for a few physical constraints, namely:

1) $\text{Real}\left\{\sqrt{\varepsilon_r \mu_r}\right\} \geq 1$ because the material media of interests in TDR prospecting are always optically denser than the free space.

2) $\text{Imag}\left\{\sqrt{\varepsilon_r \mu_r}\right\} \leq 0$ because the waves attenuate when propagating far from the sources.

3) $\text{Real}\left\{\sqrt{\dfrac{\mu_r}{\varepsilon_r}}\right\} > 0$ which is linked to the fact that the line is a passive device absorbing power from the generator

The imaginary part of $\sqrt{\dfrac{\mu_r}{\varepsilon_r}}$, instead can be indifferently positive, null or negative.

Moreover, with regard to $\text{Real}\left\{\sqrt{\varepsilon_r \mu_r}\right\}$, we have centered the range for the minimization around the exact value of this quantity distorted with an error of 20%. This because a measurement in time domain can give a fist approximation of the value of this quantity and so we suppose to retrieve in this way this information. However, we have added an error of 20% to account for the possible imprecision of such a preliminary measurement. After achieving the minimum, we have iterated the exhaustive minimization around the solution found at the previous step halving the ranges with respect to all the variables at parity of cells. In this way, we have mitigated the quantization error, that is quite strong because 40 cells per variable provide a quite coarse grid within the initial range. Of course, computational problems prevents the use of a grid with more points.

We have considered a case where $\varepsilon_r = 5 - 0.35j$ and $\mu_r = 2 - 0.2j$. The achieved results are reported in Table 1:

Table 1: results achieved at the subsequent steps of an iterative exhaustive minimization procedure.

Result	ε_r	μ_r
1st step	4.94-0.9j	1.97-0.03j
2nd step	5.19-0.48j	1.95-0.18j
3rd step	5.36-0.69j	1.85-0.07j
4th step	5.28-0.57j	1.90-0.12j
5th step	5.33-0.53j	1.87-0.15j
6th step	5.35-0.56j	1.86-0.13j

As can be seen, we have achieve good results with respect to the real part and less good results with respect to the imaginary part, even if the order of magnitude of

the imaginary parts is correctly identified.

IV. CONCLUSIONS

In this contribution we have presented some results regarding the possibility to measure both dielectric and magnetic characteristics of a medium by means of a TDR probe. The analysis has been performed in frequency domain but also data in time domain are implicitly accounted for in order to properly initialize the procedure of minimization of the relevant cost function. In future, full wave simulations and experimental measurements are in order.

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