

Qualitative and Quantitative Characterization of Liquids from TDR Measurements

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Abstract- Time-domain Reflectometry (TDR) is a well-established technique for the development of microwave sensors devoted to the dielectric characterization of materials. This renders TDR an appealing method for a variety of monitoring applications. Till now, TDR has been successfully applied to solve hydrological or soil prospecting problems, though its adoption in many other cases is worth an investigation. In this paper, it is demonstrated that TDR is a viable approach for quantitative and qualitative real-time characterization of liquids inside tanks. In fact, in one shot the suitable handling of time-domain reflectometry data allows the determination of the liquid level, as well as the evaluation of dielectric properties, such as dielectric permittivity and electrical conductivity. Some applications to real cases are proposed, referred to petrol-chemical mixtures or water-based liquids, thus validating the approach on a wide range of materials.

I. Introduction

Time domain reflectometry (TDR) technique, originally developed to detect faults along power transmission lines, is widely used in hydrology and soil science for measurement of soil water content. Usually, water content measurements can be performed using three-rod probes and TDR measurements can be made manually or automatically. It is distinguished from other techniques by its accuracy, its non-destructive character and the simplicity of its execution [1]. Since its first applications in soil sciences, the TDR has known several developments [2, 3] mainly consisting in the improvement of the excitation electronics and the development of new TDR probe designs to enhance their sensitivity [4-6]. Other relevant advances pointed out that, for accurate measurements of the reflection coefficient, the effect of cable losses and additional signal dissipations must be taken into account, so that a calibration procedure can clearly discriminate the attenuations due to the sample and to the measurement set-up. This way, accurate measurements in a wide range of conditions, particularly when long coaxial cables are employed for TDR-probe connection are possible [7, 8]. On such bases, in this paper, the Authors propose an application of TDR technique to develop multifunctional microwave sensors, able to detect, in one shot, the liquid level inside industrial tanks, different phases in stratified medium and some quality parameters, such as dielectric constant and electrical conductivity, related to liquids inside tanks. The paper is structured as follows. In Section 2 the foundations for TDR are recalled. In Section 3 the experimental set-up is described. In Section 4 results are proposed and discussed, related to different liquids. Finally, conclusion is drawn.

II. Measurement Technique

Time Domain Reflectometry, or TDR, is a remote-sensing, non-invasive measurement technique that has been used for many years to determine the spatial location and nature of various objects. By measuring the time interval between pulse transmission and its echo, the distance from the reflecting object may be easily calculated, along with other relevant properties of the object. A time domain reflectometer transmits the incident signal through a transmission line and records the travel time and magnitude of all reflected signals (echo) returning from the controlled system. The relative dielectric permittivity ϵ of the medium, which is assumed to be lossless, is related to the TDR signal velocity propagation v , by the following equations [9]:

$$v = \frac{c}{\sqrt{\epsilon}} \quad (1)$$

$$\Delta t = \frac{2L}{c} \sqrt{\varepsilon} \quad (2)$$

where c is the light propagation velocity in vacuum, $c = 3 \times 10^8$ m/s, Δt is the travel time for the TDR signal to travel forth and back in the waveguide of length L . Equation (2) yields the direct dependence between the TDR signal travel time and the medium dielectric properties. In the case of a TDR probe vertically inserted in a stratified medium with different phases the measured total travel time of the TDR pulse is a summation of the travel times in the different phases [10]. Changes in the characteristic impedance (produced by changes in the dielectric constant, for instance) causing electromagnetic discontinuities that reflect voltage can be detected, thus enabling applications to liquid level monitoring. Furthermore, voltage reflection profiles are unique for each type of discontinuity, allowing an easy identification of impedance changes caused by the dielectric constant variation. The dielectric change is related to the reflection coefficient ρ through equation (3), and the length of the transmission system up to the point where the mismatch occurred can be evaluated through equation (4):

$$\varepsilon = \left(\frac{1 - \rho}{1 + \rho} \right)^2 \quad (3)$$

$$D = \frac{D_a}{\sqrt{\varepsilon}} \quad (4)$$

where D is the distance of the signal trip up to the mismatch point in the medium and D_a is the corresponding distance in air.

III. Experimental set-up

The typical experimental set-up consists of the TDR miniaturized unit, the processing control software, the coaxial cable (RG-58) and the stainless steel probes, working like closed circuit radar, detecting any mismatch along the measuring lines. The excitation TDR signal is a step electromagnetic impulse, characterised by a very short rise time, around 200 ps. The propagating signal along the probe encounters an impedance break, causing the TDR signal to be reflected. The reflected signal carries the signature of the sample under study. The exploitation and processing of the signal allows the characterisation of some physical properties of the medium where the probe is inserted, such as the dielectric permittivity and the electrical conductivity. Analyzing the signal behaviour along a probe inserted in a sample, we can see a strong voltage drop at the air-liquid interface produced by the difference in dielectric constant between air and liquid. Since reflection travel time reported in equation (2) is converted to distance along the cable through equation (4), the voltage drop can be located on the transmission line. Typical peaks of moderate size can be seen in the measurements plot caused by the small impedance variation introduced by the BNC connector joining the cable with the probe. This mismatch caused by the connector is a useful reference point for distance measurements. The waveform characteristics of three-wire or two-wire probe designs with different wire material and geometrical configurations were proposed by several authors [11-13], especially for measuring soil moisture and water content. In this work we present a family of coaxial probes, differing in length, particularly suitable for liquid monitoring, due to its characteristic impedance Z_0 , easiness of insertion, stability and accuracy in finding reflection points. The probe is made up of a central, cylindrical conductor with a coaxial conductive shield, both stainless steel made. The shield is suitably perforated, in order to allow the fluid circulation. The probe central conductor is centred on the probe head through a teflon made ring, while the lower part of the probe is inserted in a steel plug, which also allows a short circuit at the probe end, useful for the localization of probe-end point. Experimental results showed that the probe configuration design play a crucial role in terms of accuracy of the presented measurement method. In fact, impedance mismatching in the transmission line may seriously affect the evaluation of liquid dielectric properties. In the present paper we demonstrate that the 50 Ω matched probes show very good performance in terms of measurement accuracy, since multiple reflections and dissipative effects are minimized .

IV. Results and discussion

A. Probe configuration and measurement method explanation

Figure 1 shows the TDR measurements of three coaxial probes in air, whose length are 50 cm, 136 cm and 206 cm respectively, including the 6 cm probe head. The designed characteristic impedance is 50 Ω , hence the probe impedance is perfectly matched with the transmission line, since the measured value of the reflection coefficient equals zero. Figure 1 clearly shows the reflection caused by cable-to-

probe interface, the short circuits corresponding to the probe end, as well as the typical waveform of the reflection coefficient of the cable when it is not connected to the probe. Considering the reflection coefficient derivative plot versus the distance, we can easily locate the probe length, due to its clear peaks occurring at significant interface discontinuities. The measuring parameters considered for all the data reported in the present work are: propagation velocity equal to 1, number of points equal to 1,000 and average equal to 10. In the case of probe in air, according to equations (3) and (4), the measured distances are effective, since $v_p = 1$. Figure 2 shows the derivative of the curves reported in Figure 1 versus the distance. The distance differences between the cable-to-probe interface points and the probe end points give the probe length measurement. Table I summarizes the results, for each measured distance the relative error is also reported.

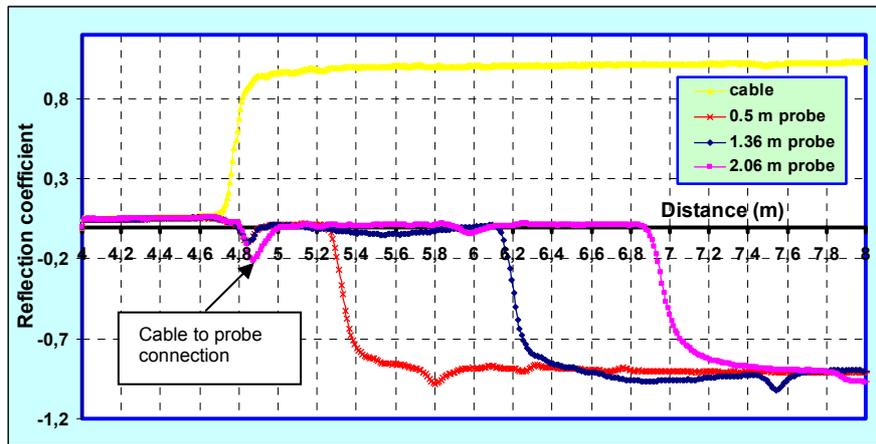


Figure 1. TDR waveform in air for 50 Ω cable and for 50 cm, 136 cm and 206 cm length probes

Table I: Comparison between real probe lengths and TDR measured data

Probe length (cm)	Measured probe end point (cm)	Measured cable-to-probe interface point (cm)	Measured probe length (cm)	Relative error (%)
50.0	532.1	481.9	50.2	+0.4
136.0	619.2	482.1	137.1	+0.8
206.0	693.0	483.5	209.5	+1.7

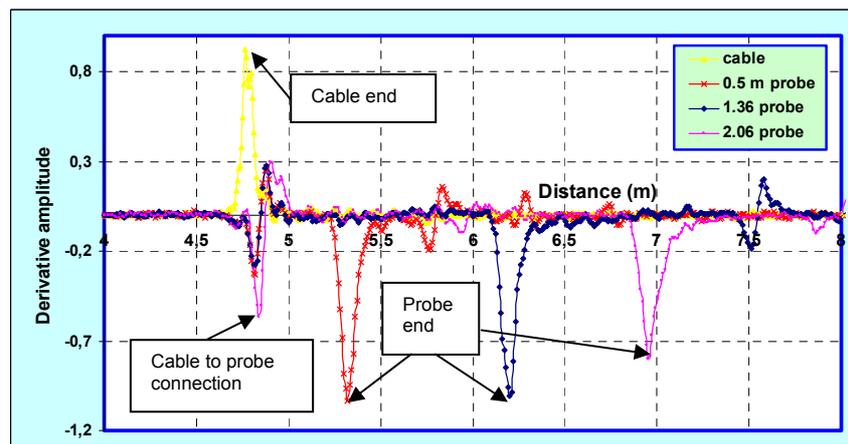


Figure 2. Derivative of data reported in Figure 1

B. Lossless liquids

Several organic liquids were used in order to test the system, and measurements were recorded when the probe was inserted in each of the chosen liquids. As above mentioned, the reflection coefficient associated with each medium is a direct result of the change in propagation velocity along the transmission line caused by the interaction of the electromagnetic wave with the liquid. The use of liquids with different dielectric constants achieved two purposes: 1) testing the method for measurement of reflection coefficient when the liquid has ideal physical properties 2) providing data to

be compared with expected values. The TDR measurements performed on diesel oil, fuel, acetone and ethanol, using the 50 cm probe, are shown in Figure 3. In Figure 4 the derivatives of the curves of Figure 3 are reported. The significant reflections, clearly shown by the derivative curves, correspond to: cable-to-probe connection, air-liquid interface and probe end.

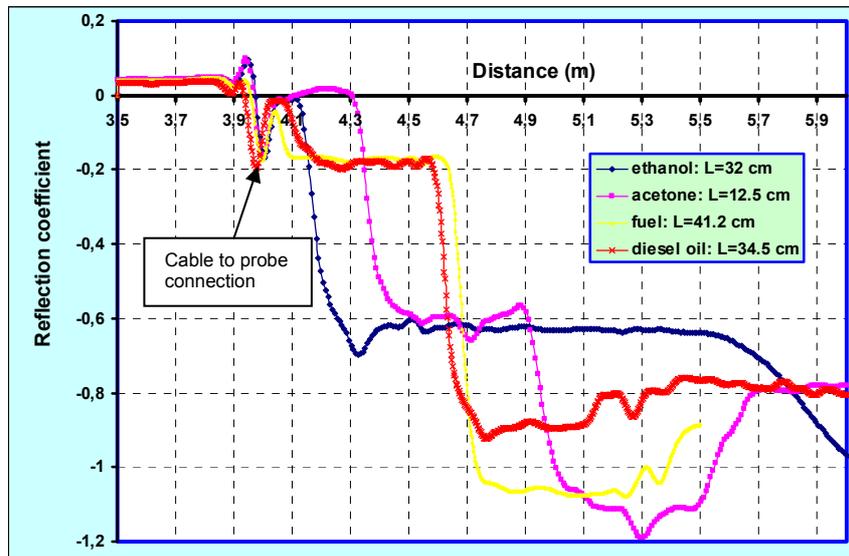


Figure 3. TDR waveforms for ethanol (L=32cm), acetone (L=12.5 cm), fuel (L=41.2 cm) and diesel oil (L=34.5 cm), measured with the 0.5 m coaxial probe

Table II: TDR measured data for levels and dielectric constants of liquids reported in Figure3

Substance	Liquid length (cm)	Probe end point (cm)	Probe-to-liquid interface point (cm)	Apparent liquid length (cm)	ρ_{meas}	ρ_{corr}	$\sqrt{\epsilon}$	Calculated effective liquid length (cm)	Relative error (%)
Ethanol	32.0	582.0	416.6	165.4	-0.63	-0.67	5.06	32.6	+1.9
Acetone	12.5	494.0	435.8	58.2	-0.61	-0.65	4.71	12.3	+1.6
Fuel	41.2	468.0	407.0	61.0	-0.17	-0.18	1.44	42.3	+2.7
Diesel oil	34.5	463.0	410.4	53.0	-0.19	-0.2	1.50	35.0	+1.4

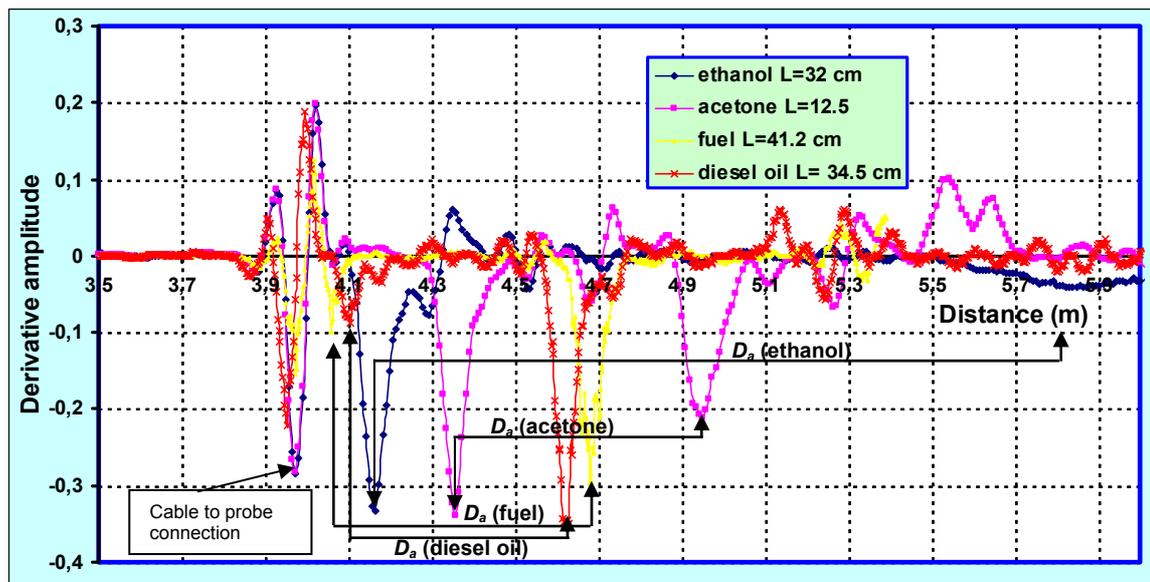


Figure 4. Derivative of data reported in Figure 3

The distance differences between the probe end peaks and the air-liquid interface peaks, clearly located through the analysis of derivative data for each substance, give the apparent liquid lengths. The cable loss attenuation constant A was found through a calibration procedure reported in [8], hence reflection

coefficient values are corrected, according to:

$$A = \exp(2\alpha L) \quad (5)$$

$$\rho_{corrected} = A\rho_{measured} \quad (6)$$

where α is the attenuation coefficient of the line, and L is the cable length. The constant A accounts for signal losses over a path of length $2L$, and equals 1 for ideal cables. For the employed cable of length 3 m, we have measured $A=1.06$. Table II summarizes the results. For each liquid we report the real liquid level, the measured apparent liquid length, the measured reflection coefficient, the corrected reflection coefficient according to (6), the square root of the calculated dielectric constant and, finally, the calculated effective liquid length. Table II also depicts the measurement method procedure adopted in this work: firstly, the apparent liquid level is evaluated from the derivative of the TDR measured data, secondly, using equations (3) and (4), the reflection coefficient value allows to calculate the dielectric constant value of the involved medium, as well as the effective level estimation. In other words, if the medium is unknown, the TDR proposed method can evaluate, in one shot, the liquid dielectric properties together with its quantitative measurement inside a tank. It is worth to note that the experimental results presented in this work show a good agreement between theoretical and estimated dielectric constant values [13]. The system showed also a good performance in locating two different stratified liquids contained in a tank, such as 27.5 cm diesel oil and 9.5 cm tap water. As shown in Figure 5 the measured apparent distance for tap water equals 0.811 m, and the corrected reflection coefficient is -0.8, corresponding to the expected value of dielectric constant ($\epsilon_{water} \cong 80$). The third reflection related to diesel oil-water interface could be also directly read as difference between the total probe length, the probe in air distance and the diesel oil level.

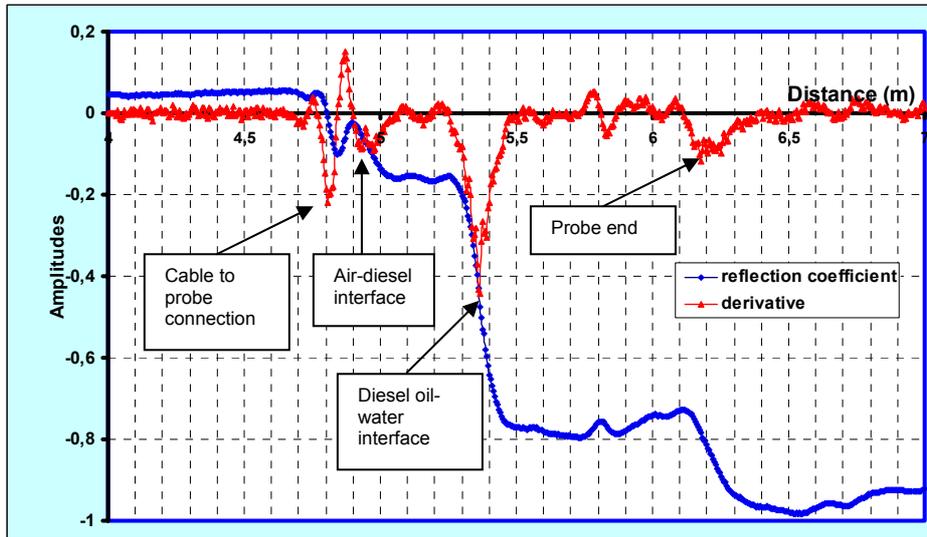


Figure 5. TDR data for a diesel oil-tap water stratified sample (reflection coefficient and derivative)

C. A note on dissipative liquids

When dealing with dissipative liquids, the previously proposed technique can suffer from some limitations. Several TDR measurements, performed on different electrolytic solutions, showed a strong variation of the reflection coefficient with time (related to the apparent distance), because of ohmic and polarization losses. The problem can be circumvented thanks to the estimation of the electrical conductivity (EC). In fact, the reflection coefficient measurement at long time (ρ_{∞}), using the presented coaxial probe in an open-ended configuration, permits to consider the sample impedance as purely resistive. This condition, associated with the ρ scaling procedure reported in [8], allowed us to accurately measure the fluid's EC . Experimental results (not reported in the present paper) demonstrated that the conductivity σ [$dS\ m^{-1}$] is linearly dependent on the sample resistance R_s , through the probe constant K_p [m^{-1}]. That constant value can be determined from calibration with standard EC solutions [7, 13], and it is related to the TDR measurement at long time trough the equation:

$$\sigma = \frac{K_p}{R_s} = \frac{K_p}{Z_0} \frac{1 - \rho_{\infty}}{1 + \rho_{\infty}} \quad (7)$$

This renders the approach amenable to the characterization of dissipative liquids as well.

V. Conclusion

In this paper we demonstrated that TDR can be successfully used for automated detection of liquid and fluid levels. By virtue of continuous remote monitoring, it is possible to observe level variations in tanks, as well as to investigate some physical properties of the involved materials, such as relative permittivity and *EC*. Several advantages of the presented TDR method include spatial resolution in the millimetre-scale, high accuracy and multiplexing capability. Furthermore, the designed coaxial probes have shown a good flexibility and an excellent performance in terms of spatial resolution, characteristic impedance and stability. The liability of the proposed procedure has been proved testing it on several liquids, with different reference relative permittivity, demonstrating its suitability to detect both liquid levels and liquid dielectric properties. The proposed instrumentation was also tested for *EC* measurements. By using a suitable calibration procedure, the effect due to cable losses and additional dissipations can be considered in order to accurately perform *EC* measurements and to evaluate the dielectric constant values, also when long coaxial cables are employed. Based on this evaluation, we conclude that the described system is an excellent candidate for quantitative and qualitative liquid monitoring applications, especially for industrial and environmental control purposes.

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