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Electromagnetic Imaging of Dielectric Targets by Using a Tomographic Systems

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***Abstract*—The reconstruction of plastic targets by using an electromagnetic imaging system working at microwave frequencies is considered. A prototype of a tomograph is used to measure field scattered data in a multi-illumination multi-view arrangement. The samples of the field are used to retrieve the two-dimensional distributions of the dielectric parameters of the target under test. Experimental results are provided and the overall reconstruction quality is evaluated.**

I. INTRODUCTION

Recent developments in signal processing and measurement systems have allowed a renewed interest in microwave techniques for imaging, nondestructive testing and material characterization in several applications ranging from civil engineering, security, military and medical noninvasive diagnostics [1–4]. Fast and efficient solver have been also devised in the field of computational electromagnetics, making possible the treatment of problems which have been considered computationally prohibitive just few years ago. Finally, new results in the treatment of ill-posed inverse problems have opened new grounds for the real applications of inversion techniques based on field-scattered waves.

In this framework, this paper discusses the use of a system prototype aimed at illuminating an unknown target and measuring the field it scatters in order to retrieve the distributions of the dielectric parameters of the object under test. In particular, the system works at microwave frequencies under tomographic conditions (the target is successively illuminated by incident waves and the scattered field is measured at several different positions around the object). To this end, the transmitting and receiving antennas rotate around the target in order to collect multi-illumination multiview data.

The adopted prototype has been described in details in [5] and has been tested for the inspection of wood materials in different configurations [6–8]. In this paper, the system is applied to another category of targets, in particular, plastic objects.

In order to retrieve the distributions of the dielectric parameters, an iterative inversion procedure based on an inexact Newton method is used. The integral equations relating the target parameters and the field it scatters are combined in a single equation and discretized in a pixelated form.

The present manuscript is organized as follows. In Sections II and III both the adopted inversion procedure and the measurement system are briefly described. Moreover, in Section IV new results are reported and discussed. They concerns an evaluation of the capabilities of the proposed method in inspecting plastic targets. Some conclusions are drawn in Section V.

II. OUTLINE OF THE INVERSION PROCEDURE

The measured scattered field data are inverted by using an approach based on an inexact-Newton algorithm. A two-dimensional formulation under transverse magnetic (TM) is considered. As it is well known, under such assumptions, the equations relating the space-dependent dielectric properties of the investigated area (e.g., the dielectric permittivity and the electric conductivity) can be written in terms of a couple of Lippmann-Schwinger equation (namely, the data and state equations), which can be combined together in order to obtain a non-linear equation in the form

$$\mathcal{L}(\epsilon_r) = e_{scatt} \tag{1}$$

where ϵ_r is the complex relative dielectric permittivity, e_{scatt} is the z-component (being z the axial direction) of the scattered electric field (i.e., the difference between the electric field measured with and without the target), and $\mathcal{L}$ is a non-linear operator.

Such equation, which turns out to be usually severely ill-posed, is solved by means of an efficient inexact-Newton approach (details can be found in [9], [10]). In particular, equation (1) is iteratively linearized by computing the Frechet derivative of $\mathcal{L}$ at the current estimate of the dielectric permittivity and the obtained linear system is solved in a regularized sense by using a truncated Landweber algorithm. The developed algorithm employs a frequency hopping scheme [11] for exploiting the multi-frequency information, too.

III. PROTOTYPE OF THE IMAGING SYSTEM

In order to prove the accuracy and efficiency of inversion algorithms, it is necessary to feed them with electromagnetic field intensities present in the inspection area surrounding an object to be investigated, when this is illuminated by a microwave source. Very often, such field intensity data are obtained by computer simulations [5].

Alternatively and more interestingly, such data can be obtained experimentally. This requires some microwave generation and reception hardware as well as a mechanical setup that ensures a good positioning repeatability and accuracy for collecting the field strengths at various positions. One such experimental microwave tomograph is described in the following.

The prototype – shown in Fig. 1 – was initially aimed at the inspection of wood samples, but has nevertheless been designed by taking into account the possibility to analyze various kinds of objects with different shapes and other material compositions. The dimensions, flexibility and mechanical strength of this tomograph allow it to extend the analysis to any kind of materials even if heavy and bulky with little modifications.

Fig. 1. Automated experimental tomograph.

The SUT (Scatterer Under Test) is positioned on an independently rotating table made of low scattering material, at the center of the inspection area, therefore allowing a multi-view illumination. The transmitting antenna is fixed and its position is used as the reference (0°) of the polar coordinate system centered on the vertical symmetry axis of the setup, whereas the receiving antenna can rotate independently around the scatterer from 45° to 315° of azimuth. Both vertical antenna's holding arms, made of fiberglass, can provide independent movements on the vertical axis ensuring the possibility to conduct sliced or 3D analysis in the future.

The tomograph can accommodate various types of antennas in function of the application needs. The antenna supports of the prototype have sufficient mechanical strength to hold any kind of antennas, regardless of their dimension and weight.

Since the entire structure was conceived so that it can support heavy SUT objects without compromising its transportability, the lower structural elements of the tomograph are mainly made of aluminum. Microwave scattering out of this body structure is avoided with the use of absorber panels, so that the lower part is actually hidden from the microwave point of view.

All the moving parts can be servo-controlled independently with specifically developed software running on an external PC. The microwave signal is generated and again measured by a vector network analyzer (VNA) connected to the PC for the measurement setup, synchronization and data download.

IV. EXPERIMENTAL SETUP AND RESULTS

As mentioned in the previous section, the tomograph prototype can quite easily be converted for various applications with simple hardware modifications. The specific configuration, aimed at the analysis of the object presented in this paper, is illustrated in Fig. 2. The SUT to be imaged is shown in Fig. 3. It consists of a cylindrical construction composed by two coaxial pipes made of polypropylene (characterized by a relative dielectric constant ϵ_r of 1.5). Both pipes are filled with air. The structure dimensions are also shown in Fig. 3.

Both transmitting and receiving antennas are positioned at a physical distance of 700 mm from the axis of the plastic SUT and at 150 mm height. Both are log periodic with a gain of 8.5 dBi, a beam width of 60° and a vertical polarization (parallel to the z axis). The fixed TX antenna completely illuminates the SUT while the RX one gathers the electromagnetic field scattered around the object at various angles. This operation is repeated for every rotation (view) of the SUT. The distance between the antennas and the SUT cannot be considered as constant since the log periodic antennas present a phase center that varies in function of the frequency. A correction to compensate for this phenomenon is therefore implemented in the parsing software and in the reconstruction algorithm.

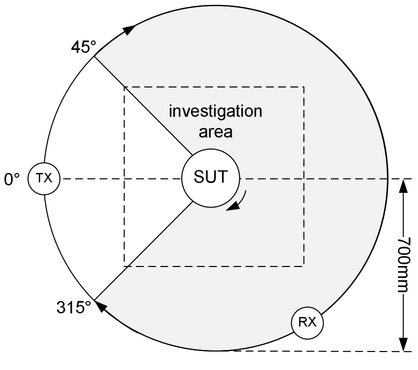


Fig. 2. Tomograph setup.

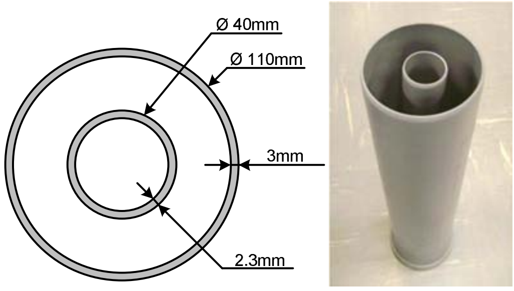
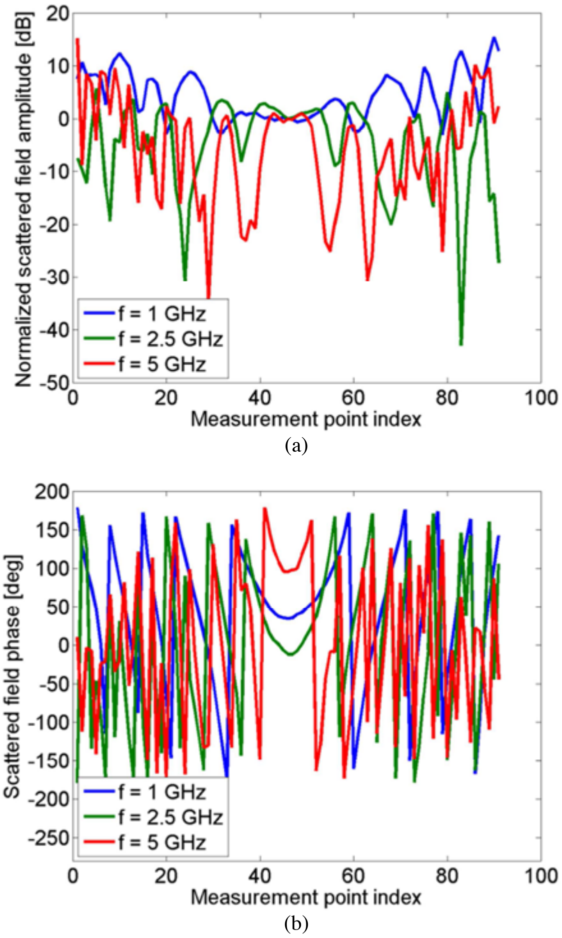


Fig. 3. Scatter under test. (Polypropylene pipes).



(a)

(b)

Fig. 4. (a) Amplitude [dB] and (b) phase [deg] of the scattered electric field for the first view and for three frequencies. The amplitude is normalized to the value in correspondence to the points opposite to the transmitter.

Scattered fields are often very weak, therefore a concern could arise about the immunity of such an experimental setup against the background noise present in a laboratory similar to the one used to carry out these tests. This question has been addressed by an earlier study of the authors [12] and it was demonstrated that such noise does not significantly affect the quality of the reconstructed image.

The analysis is performed using microwave signals over a range of frequencies between 1 to 6 GHz with $M = 31$ discrete steps of about 166MHz each, with a power level of -5 dBm. The measurement points (RX) are distributed over the circumference from 45° to 315° in $N = 91$ steps of 3°. The multi-view acquisition is performed rotating the SUT by 360° in $R = 16$ steps of 22.5° each. An example of the scattered data provided by the system is shown in Fig. 4.

The distribution of the relative dielectric permittivity reconstructed by the inversion algorithm is shown in Fig. 5. As can be seen from this figure, the system is able to correctly identify the two concentric pipes. Moreover, the value of the relative dielectric permittivity of the plastic material is quite similar to the correct value, especially for the inner pipe. This fact is also confirmed by Fig. 6, which reports a cut of the distribution of Fig. 5 for $y = 0$.

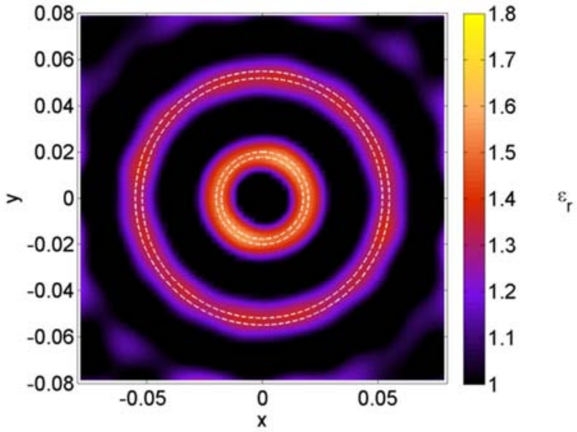


Fig. 5. Final image of the reconstructed distribution of the relative dielectric permittivity. Real data.

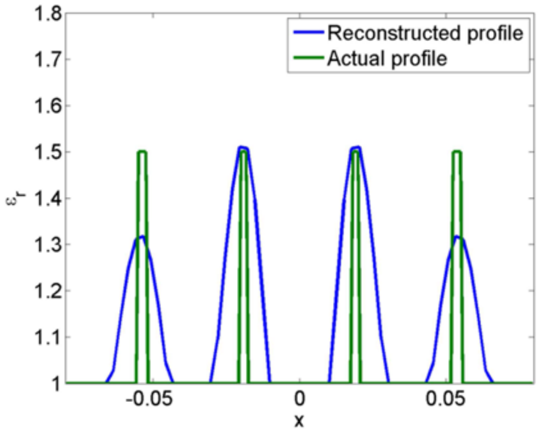


Fig. 6. Horizontal cut (for $y = 0$) of the reconstructed distribution of the relative dielectric permittivity.

V. CONCLUSION

In this paper, the dielectric reconstruction of plastic cylindrical objects by using a microwave imaging systems has been discussed. In particular, a prototype of an illuminating/measuring system, previously developed for the inspection of wood materials, has been adopted. Starting by the measured values of the scattered electric field (under transverse magnetic illumination conditions), the distribution of the dielectric permittivity of the target is obtained by an inversion procedure based on an inexact Newton method, which is quite efficient in dealing with the ill-posedness of the electromagnetic inverse scattering problem. An example of the obtained results is discussed in details. In particular, a plastic pipe is inspected with a good accuracy. Further developments of the proposed approach will consider the integration of the experimental apparatus with a new solving procedure developed in the Banach space, which has been recently proposed and is still in a test phase. The new procedure is potentially able to further improve the reconstruction quality, in particular by reducing the over-smoothing effect usually present in the reconstructed distributions and the artifacts in the background.

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