Preliminary Study of Embedded Structural Anomalies in Architectural Structures by Microwave Subsurface Tomography

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Abstract— A non-destructive technique (NDT) based on microwave reflectometry has been applied to perform subsurface tomography images. The localization in depth of anomalies in architectural structures such as, for example, inhomogeneity in the masonry texture (cavity of air, metals, and humidity) or on timber structure by means of NDT approach is crucial not only in the diagnostics of the Cultural Heritage, but in general for all civil industry. The target of our research is the development of a robust and user-friendly system to investigate the materials used in architecture until 20 cm in depth, with a resolution less than 1 cm. The system consists by a vector network analyzer and an wide band antenna (ridged antenna) operating in the range 1.5–6 GHz. The measurement of the reflection coefficient variation (amplitude and phase) due to the dielectric dis-homogeneity into the materials under investigation is acquired. The equivalent time-domain response is reconstructed using an Inverse Fourier Transform of the baseband signal and by a simple model based on TEM approach is determined the constrains on the size of the anomaly (maximum resolution) and on its position into the host medium (maximum non unambiguous range).

The material can be investigated by scanning — step by step — the surface by the probe antenna. For each step is obtained the reflection coefficient in the frequency range, and subsequently transformed in the time-domain by out-line processing.

Thanks to the penetration of the used microwave radiation, it is possible to sectioning the material under test in slices transversal to the surface up to 20 cm in depth. The interdistance between two consecutive slices is related to the distance between the two corresponding scanning lines.

The performance of the proposed technique together with its resolution limits are discussed as regards with other approach proposed in literature. The results on architectural structure are presented. The potentiality of the system as diagnostic tool based on NDT approach for the framework of Cultural Heritage will be discussed together with its limits.

1. INTRODUCTION

Non-destructive testing (NDT) and evaluation techniques for to extract information about the internal structures of the material are of crucial importance in the Cultural Heritage framework [1–3]. The reason for this interest is the possibility to determine and to locate anomalies in architectural structures such as, for example, inhomogeneity in timber structures or in mural structure such as cavity of air, metals and humidity. Thanks to these facilities can be improved the strategies of the restoration and maintenance procedures.

In the past, several approaches to solve these tasks have been suggested for example ultrasound techniques and also microwave techniques ([4–7]). The object of our research is to develop a robust and user friendly system to diagnose the architectural structures until 20 cm in depth, with a resolution less than 1 cm such as a possible alternative to the aforementioned methods. The aim is achieved by a microwave reflectometer system operating in the time domain.

The choice of the probe is important for two reasons: (1) must be able to ensure a good matching with the material to be investigated; (2) the frequency band must be sufficiently larger to allow the detection of interfaces slab embedded in the host medium until 2 cm from $z = 0$.

The paper is organized in sections. The theoretical background is described in Section 2, where by a simple model, an air slab hosted in a medium with low dielectric constant — it is the case of air cavity in a wood on wall in quite-dry condition — will be evaluated the constrains of the technique. In Section 3 is presented the microwave reflectometer measurement system and the approach used to interpret the data collected in the frequency domain. The Section 4 is devoted to present the results obtained on case study: a large vaulted with frescoed ceiling.

2. THEORETICAL BACKGROUND

The issue of detection of anomalies within an architectural structure, in particular an air slab hosted into a homogenous medium, can be mathematically approximated such as the problem concerning the localization of the interface of the air slab embedded in a half-space of dielectric with loss simulating masonry support with approximation of plane wave. We consider a plan wave of unitary amplitude $E_{inc}(z,\omega) = \exp(-j\beta_0 z)$, being β_0 the free space wavenumber that impinge from the first interface stratified medium at the different frequency $f \in [f_{\min}, f_{\max}] = B$.

In Fig. 1 is sketch a possible measurement configuration with the probe no-contacting the surface of the masonry support. In historical building the walls are often frescoed and it is not possible put in contact the probe with the painted surface, so a small gap (0.5 cm) is left from the surface. Known the size and the dielectric characteristics of the first layer the positioning of the interface of the slab 2 and 3 (z_2 and z_3), and the respective size (d_2 and d_3) can be determined. The permittivity of the first layer of the masonry can be determined by truncated coaxial method implemented from the author in [8] when there are no artistic and architectural constraints.

Being β_g the gap free space wavenumber, β_w the host medium wavenumber and β_d the dielectric slab wavenumber, the expression of the reflection coefficient for the considered problem, at the section $z = 0$, is given by the following relation [9]:

$$\Gamma(0,\omega) = \frac{\begin{array}{c}\Gamma_0 + \Gamma_1 e^{-2\mathrm{j}\,\beta_g d_1} + \Gamma_0\Gamma_1\Gamma_2 e^{-2\mathrm{j}\,\beta_w d_2} + \Gamma_2 e^{-2\mathrm{j}\beta_g d_1} e^{-2\mathrm{j}\,\beta_w d_2} \\ +\Gamma_3 e^{-2\mathrm{j}\,\beta_g d_1} e^{-2\mathrm{j}\,\beta_w d_2} e^{-2\mathrm{j}\,\beta_d d_3} + \Gamma_0\Gamma_1\Gamma_2\Gamma_3 e^{-2\mathrm{j}\,\beta_d d_3}\end{array}}{\begin{array}{l}1 + \Gamma_0\Gamma_1 e^{-2\mathrm{j}\beta_g d_1} + \Gamma_1\Gamma_2 e^{-2\mathrm{j}\beta_w d_2} + \Gamma_0\Gamma_2 e^{-2\mathrm{j}\beta_g d_1} e^{-2\mathrm{j}\beta_w d_2} \\ +\Gamma_0\Gamma_2 e^{-2\mathrm{j}\,\beta_g d_1} e^{-2\mathrm{j}\,\beta_w d_2} e^{-2\mathrm{j}\,\beta_d d_3} + \Gamma_1\Gamma_3 e^{-2\mathrm{j}\,\beta_d d_3} e^{-2\mathrm{j}\,\beta_w d_2} + \Gamma_2\Gamma_3 e^{-2\mathrm{j}\,\beta_d d_3}\end{array}} \quad (1)$$

where:

$$\Gamma_i = \frac{\zeta_i - \zeta_{i-1}}{\zeta_i + \zeta_{i-1}} \quad i = 1, \ldots, n \quad (2)$$

is the reflection coefficient at the interfaces located in $z = z_i$, ζ_i is the characteristic impedance of medium, and ζ_0 is the characteristic impedance of the free space. This very simplified model is useful to understand the limits of the approach in terms of maximum resolution and maximum non unambiguous range.

In the proposed method the reflection coefficient is represented by N complex values corresponding to N discrete frequencies separated by Δf. As well know the Fourier Transform of a periodic signal give one discrete spectrum in the frequency domain, equivalently, a periodic signal can be expressed in time domain by the Fourier series where the coefficient of the series are the spectral line (amplitude and phase) in the frequency domain, so the reflection coefficient in the time domain

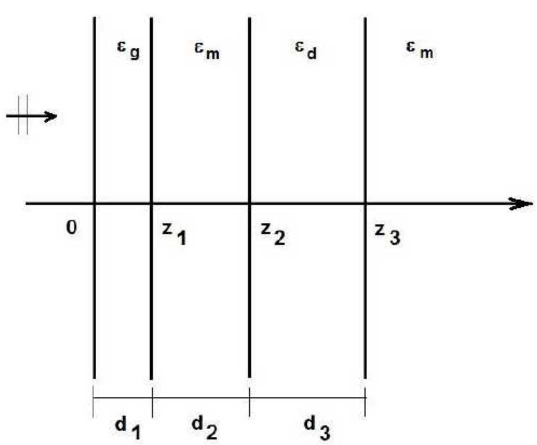


Figure 1: Geometry of the problem. The air gap (d_1, ε_g) and slab (d_3, ε_d) embedded in a homogeneous half-space medium (ε_m).

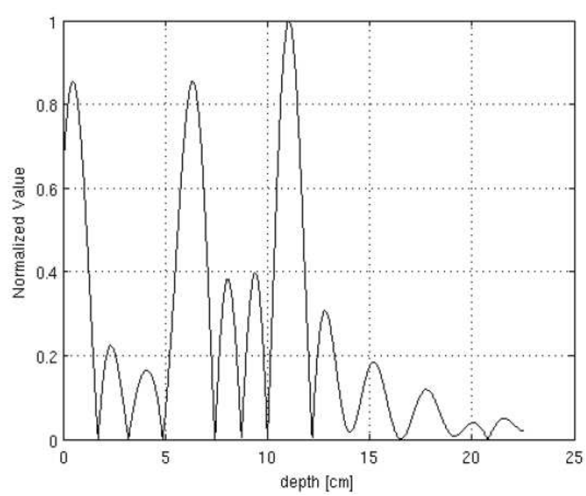


Figure 2: Normalized reflected signal from a host medium ($\varepsilon_m = 2.5 + j0.02$) with embedded a free-space slab at $z_2 = 4.5$ cm and with a thickness of $d_3 = 5$ cm.

can be determined by the following relation:

$$\Gamma(0,\omega)=\Sigma_{n=1}^{N}2\left|\Gamma(0,\omega_n)\right|\cos\left(\omega_n t+\arg\left(\Gamma(0,\omega_n)\right)\right)\operatorname{sinc}\left[\pi B\frac{\left(t-\arg\left(\Gamma(0,B/2)\right)\right)}{2\pi B/2}\right] \tag{3}$$

Let us to define, by the Nyquist sampling criterion, the maximum unambiguous distance:

$$R_{\max}=\frac{c_0}{4\Delta f\sqrt{\varepsilon}} \tag{4}$$

moreover we define, by the Rayleigh's criterion, the maximum resolution distance, i.e., the minimum distance between two interface for their unique positioning:

$$R_{\min}=\frac{c_0}{2B\sqrt{\varepsilon}} \tag{5}$$

Let us consider the dielectric permittivity of the dielectric slab more large then the host medium. In this case the propagation velocity of the electromagnetic wave in the host medium is more great then the velocity inside the slab, consequently we have an in-depth delocalization of the second interface of the dielectric slab and this make more easy the discrimination the interfaces. Otherwise, when the dielectric permittivity of the host medium is more large then the slab is more difficult discriminate the presence of the second interface in fact, we have a reconstructed peak located backwards respect at actual location of the second interface and this make difficult to discriminate the second interface.

For evaluation of the ability of the model let us consider, in addition to the free-space gap $\varepsilon_0 = 1$, an anomaly in the masonry support consisting on a free-space slab with $\varepsilon_d = 1$ embedded in host media with $\varepsilon_m = 2.5 + j0.02$ (this can be the case of masonry quite near dry condition [4]), and the frequency ranging from $f_{\min} = 1.5\,\text{GHz}$ to $f_{\max} = 6\,\text{GHz}$. The anomaly have the first interface located at $z_2 = 4.5\,\text{cm}$ and thickness 5 cm ($d_3 = 5\,\text{cm}$). The Fig. 2 shows the normalized reflected signal resulting from the proposed model. The x-axis labelled with "depth" explains the penetration profile of the electromagnetic wave this distance is normalized to the permittivity of the host medium (ε_m). The first peak in Fig. 2 refers to the interface air/medium (air gap), the second and the third refer to the interface slab/host medium.

3. EXPERIMENTAL RESULTS

The microwave reflectometer system consist of a portable vector network analyser (VNA Anritsu S331E Site Master), a double ridged antenna with unimodal waveguide propagation in the 1.5–6 GHz band, and a notebook with dedicated software to remote control of the instrument and data acquisition. The data are elaborated offline by a Matlab code implementing the IFFT algorithm and the graphical elaboration of data.

The double ridged antenna (DRG) is the best commercial solution as antenna probe, because it has a width band for unimodal propagation more large than other commercial rectangular waveguide such as, for example, the type WR430 or WR229. Furthermore, the double ridge antenna shows a better matching with the impedance of the material constituting the masonry. In Fig. 3 are plotted the waveguide impedance, for double ridged waveguide and for rectangular waveguide (WR229), respect to the typical impedance of a plaster.

The investigation of the material is performed by a step frequency continuous-wave in the 2–6 GHz band with step $\Delta f = 50\,\text{MHz}$. The sub-surface investigation is possible thanks to ability of the electromagnetic wave to penetrating dielectric materials. The penetration depth depends on the electromagnetic characteristics of the material under test, mainly it affected from moisture content and in second order from the field polarization if the medium is anisotropic (this issue must be well considered on timber structures because wood is an anisotropic dielectric [10]).

The investigation of the surface is performed with scans step by step in order to obtain a vector with N elements (complex value of the reflection coefficient) corresponding to N frequencies for each step (M total number of steps). The overall data are collected in $N \times M$ matrix for each scanning line. Each vector of reflection coefficient is replaced in the time-domain by Equation (3).

In Fig. 5 are presented the results obtained from scans along the principle axes on a vaulted ceiling frescoed in a historic building (Fig. 4). In both tomograms the deep red color indicates an hard discontinuity in the masonry structure due to the detachment of the first layer of the plaster. The deeper anomalies (at about 4–5 cm) are due to the interface brick/air on the top of the vault.

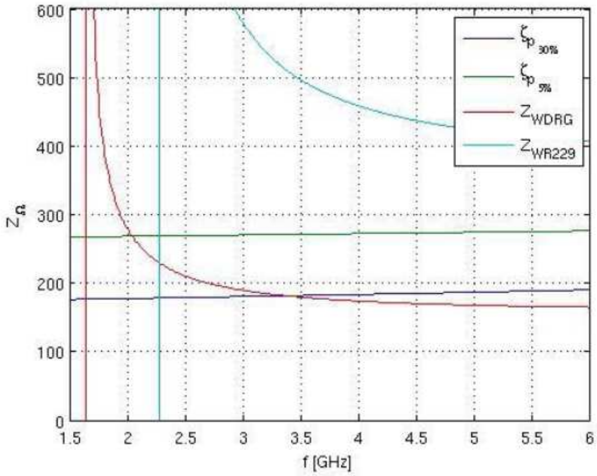


Figure 3: Impedance comparison between characteristics impedance of plaster at different moisture content (5% and 30%), and waveguide impedance for WR229 and DRG.

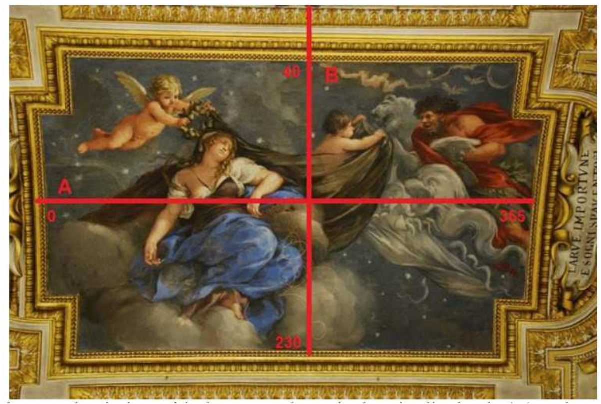
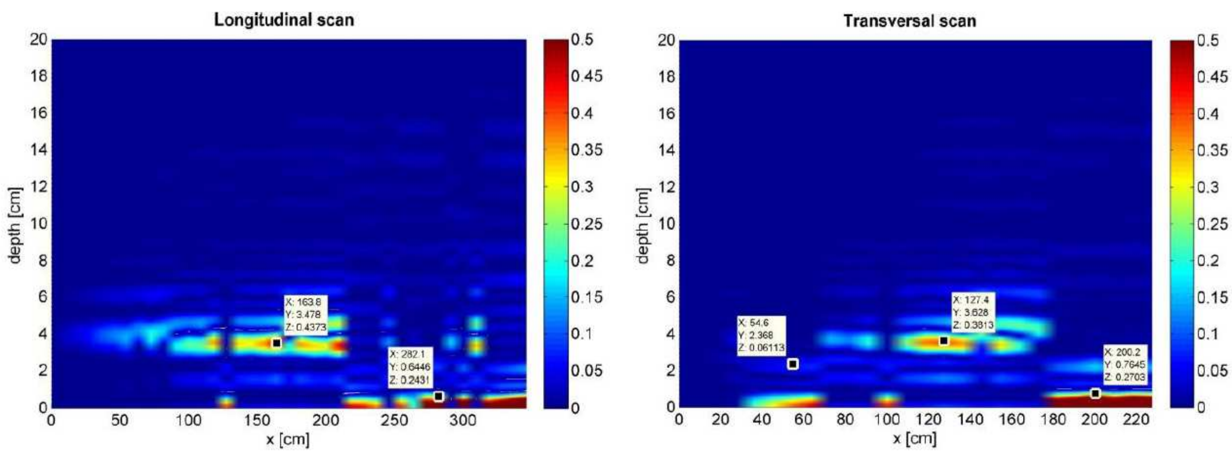


Figure 4: Photo of the mural painting with the scans along the longitudinal axis (A) and transversal axis (B).



(a) (b)

Figure 5: (a) Tomogram of the longitudinal scan; (b) tomogram of the transversal scan.

It is correct to underline that where are located the detachment the discontinuity due the interface brick/air is masked.

4. CONCLUSION

The proposed system based on microwave reflectometric method allows to perform tomography by non-contacting way until to 20 cm in depth with a resolution no more than 1 cm. The system is fully portable and robust and it has been tested on a vaulted ceiling to highlight anomalies in the masonry structure (detachment and air cavity). These preliminary results can be considered promising; the future research activities will be focused on the identification of operative limits in terms of maximum resolution and maximum unambiguous distance respect to the characteristic of the material under test.

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