Microwave Reflectometry for the Diagnostic of Cultural Heritage Assets

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L. Capineri[1], **P. Falorni**[1], **C. Frosinini**[2], **M. Mannucci**[3], **N. Macchioni**[4], **R. Olmi**[7], **S. Palanti**[4], **S. Penoni**[5], **S. Pieri**[7], **S. Priori**[7], **C. Riminesi**[6], **A. Santacesaria**[2], and **C. Todaro**[5]

[1]Dipartimento Elettronica e delle Telecomunicazioni, Università di Firenze, Firenze 50139, Italy
[2]Opificio delle Pietre Dure, Via degli Alfani 78, Firenze 50100, Italy
[3]LegnoDOC, Via Pier della Francesca, b39, Prato 59100, Italy
[4]CNR, IVALSA, Via Madonna del Piano 10, Sesto Fiorentino 50019, Italy
[5]Faberestauro, piazza Ginori 13, Sesto Fiorentino 50019, Italy
[6]ELab Scientific, 17 Fra' D. Bartolomeo Street, Firenze 50132, Italy
[7]CNR, IFAC, Via Madonna del Piano 10, Sesto Fiorentino 50019, Italy

Abstract— A non destructive diagnostic method for cultural heritage assets based on microwave reflectometry has been studied and developed. This new method is implemented with a ridged antenna operating in the range 1.5–3 GHz for the detection of reflected wave amplitude and phase variation due to the dielectric properties of the materials under investigation. Particular interest has been devoted to wood structures attacked by fungi and insects and to mural paintings with delaminations due to subsurface humidity. A simplified model of the antenna coupled to the material has been implemented in terms of a cascade of transmission lines in order to investigate the response of the system in presence of dielectric discontinuities. A series of laboratory models have been developed to assess the capability of the method to display in real time images of a calculated parameter which includes both amplitude and phase variation respect to a reference response taken from a homogeneous portion of the investigated item. A novel compact easy to use in-situ optical system mounted on the antenna has been developed to correlate the positions of the antenna on the surface with the optical digital picture, avoiding cumbersome wheel optical encoding which need flat surfaces and raster lines for guiding the manual scan.

1. INTRODUCTION

Microwaves can penetrate up to several centimetres in dry wood [1] or plaster and brick or stone walls [2]. In the operating frequency range of the instrument (1.5–3 GHz) there is also a good sensitivity to the moisture content, that can be a source of degradation both in wooden structures and in mural paintings, favouring the development of biotic decay in the former and the development of detachment of the painted layer in the latter [3, 4]. Preliminary experience with the holographic radar have pointed out that using single emitting frequency and two antenna polarizations it is possible to get high resolution images of impedance discontinuities at shallow depth by using the phase variation information. Moreover the investigation of cultural heritage assets like paintings on wood or frescos often implies to work on thickness of the order of a few wavelengths. Then the use of high frequency pulsed radar becomes difficult due to the overlapping of the finite pulse length reflected from the item interfaces [5–7]. This research work is aimed to a new microwave reflectometry system for the investigation for several materials like stone, plaster and wood. The depth analysis is performed thanks to a modulated continuous wave operating in the 1.5–3 GHz frequency range. The electromagnetic wave penetration in a medium depends on the dielectric characteristics of the material: moisture, presence of cavities, and material inhomogeneities can be detected exploiting the dielectric "contrast" among different regions. The specifications of the system should take into account the application requirements in not easy areas, such as restoration sites, including portability (weight and reduced size) and autonomy (battery operation). These features should be added to the responsiveness, reliability and, possibly, the low cost. The implementation of the microwave reflectometer prototype consisted in:

(1) The development of a generator/receiver that complies with electromagnetic compatibility issues. The prototype described in this paper has been based on a commercial Vectorial Network Analyzer.

(2) An optical compact low cost system for tracking the scan head with accuracy better than 1 cm that takes into account different environmental illumination conditions.

(3) The development of models to study the interaction between the electromagnetic signal and the different media — e.g., wood, stone, plaster.

(4) The development of software for signal analysis and imaging of the reflectometric response.

The results of the prototype applied to several case studies will be presented for two areas of interest in the cultural heritage: diagnostics of frescoes and mural paintings, diagnostics of wooden structures and artefacts. In both cases the objective is the detection of material discontinuities (voids, delaminations, knots) and inhomogeneities (in particular, moisture), by analysing images obtained by scanning the head of the microwave reflectometer on the object under investigation.

With regard to the study of wall paintings, the analysis should also give information about the texture of the support layer.

Concerning wooden artefacts, two types of structures are of interest: structural elements (beams) and panel paintings. For both structures, laboratory models have been developed: the presence of fungal decay and pockets of moisture have been simulated in wooden beams, as well as painted woods boards attacked by xylophageous insects.

These activities should hopefully lead to the creation of a database of "signatures" that will later be used to interpret the results of on site diagnostic case studies that will be discussed in the presentation.

2. THE TRANSMISSION LINE MODEL

The interpretation of the reflection measurements requires the development of a model of the interaction between the antenna and the material under investigation. A full-wave model can be implemented using well known numerical approaches, e.g., the finite element method, but the solution is quite time consuming and not very flexible.

An analytical approach is very desirable, as it allows studying the dependence of the response on the geometry and on the dielectric properties. A zero-order approximation is therefore assumed, consisting in representing the material under investigation as a layered medium excited by a plane wave. Such a system is described by an equivalent circuit consisting in a series of transverse electromagnetic (TEM) lines with characteristic impedances depending on the dielectric constant of each layer. As an example, Figure 1 represents a wooden structure with a cavity inside, represented by the line section identified by the characteristic impedance Z_2.

The reflection coefficient Γ at the wood surface is defined in the following equation:

$$\Gamma = (f, d_1, d_2) = \frac{Z_0 - Z_{i1}(f, d_1, d_2)}{Z_0 + Z_{i1}(f, d_1, d_2)} \tag{1}$$

where Z_{i1} is the impedance at the air-material interface, defined by:

$$Z_{i1}(f, d_1, d_2) = Z_1 \frac{Z_{i2}(f, d_2) + iZ_1 \tan(k_1 d_1)}{Z_1 + iZ_{i2}(f, d_2) \tan(k_1 d_1)} \tag{2}$$

d_i is the thickness of the layer i, f is the operating frequency and k_i the wavenumber in the i-th material.

We can observe that the reflection coefficient can be measured at different discrete frequencies in order to get the information about impedance variation (amplitude and phase) into the material.

3. EXPERIMENTAL APPARATUS

The experiments have been done by using a set-up consisting of a portable reflectometer model Anritsu S331E using a double-ridged antenna as a probe head, shown in Figure 2. In our experiments the antenna has been manually scanned over the surface of the investigated item without air gap. This is not a limitation for the investigation of paintings or frescos because a thin (few mm thickness) protective layer can be used to couple the antenna to the surface.

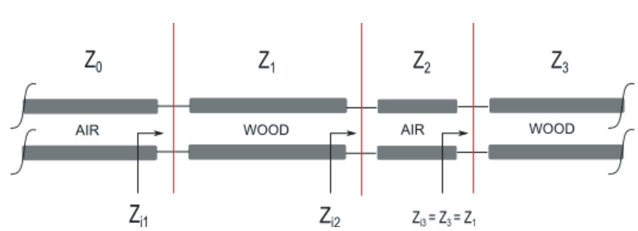
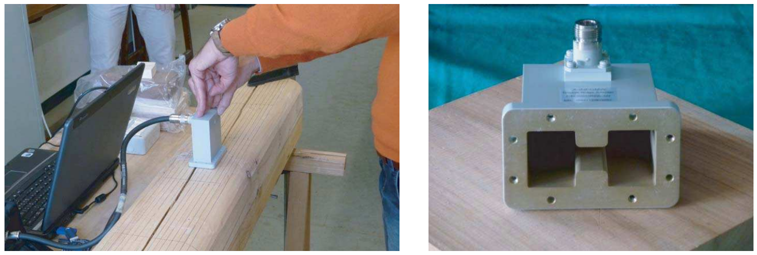


Figure 1: The TEM model of a wooden structure under investigation.



(a) (b)

Figure 2: Measurement setup on (a) a wood beam and (b) a particular of the double-ridged antenna.

Figure 3: Wood beam utilized for measurement, internal cavity in the centre of the beam and image obtained through elaboration of the signals obtained with the double-ridged antenna on wood surface with optical positioning system.

4. IMAGING OF THE PARAMETER $K\varepsilon$

For each antenna position the reflection parameter is acquired together with the antenna position. A parameter called $K\varepsilon$ has been defined (see Equation (3)) to obtain a single display representation of the amplitude and phase variation of the reflection coefficient respect to a homogeneous portion of the material assumed as reference response (Γref).

$$K\varepsilon = \frac{|\Gamma ref|}{|\Gamma|}\cos\left[\arg\left(\Gamma\right) - \arg\left(\Gamma rif\right)\right] \tag{3}$$

where $\Gamma ref = \frac{Z_0 - Z_1}{Z_0 + Z_1}$ is the reference reflection coefficient.

A preliminary experiment has been carried out to test the feasibility of the method on a wood beam where in the central position a cavity was excavated. Different wood blocks, artificially attacked by insect, positioned inside the cavity simulated different grade of biotic decay. (see Figure 3(a)).

On the investigated surface the wood beam shows some knots and vein patterns. On the Figure 3(b) the image of $K\varepsilon$ in false color (yellow and red) where all above features can be described accurately. The position of the ridged antenna has been acquired with an optical system with position accuracy better than 1 cm that is a fraction of the wavelength.

5. CONCLUSION

The developed microwave reflectometry have been tested on laboratory models and has demonstrated sufficient sensitivity to detect dielectric variations inside the material. The imaging of a calculated parameter which includes both amplitude and phase variation is investigated with the perspective of facilitating the interpretation of acquired images by a final user when operating in-situ or in a restoration laboratory.

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