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Noninvasive Patch Resonator-Based Measurements on Cultural Heritage Materials

Emanuele Piuzzi[1], Erika Pittella[1], Stefano Pisa[1], Andrea Cataldo[2], Egidio De Benedetto[2], Giuseppe Cannazza[2]

[1]*Sapienza University of Rome - Department of Information Engineering, Electronics and Telecommunications, Via Eudossiana 18, 00184 Rome, Italy*
emanuele.piuzzi@uniroma1.it, erika.pittella@uniroma1.it, stefano.pisa@uniroma1.it
[2]*University of Salento-Department of Engineering for Innovation, Complesso Ecotekne - Corpo O, 73100 Lecce, Italy,*
andrea.cataldo@unisalento.it, egidio.debenedetto@unisalento.it, giuseppe.cannazza@unisalento.it

***Abstract* – In this work, a noninvasive microwave-based system for monitoring water content in stone materials used in Cultural Heritage structures is presented. By placing a planar resonator in contact with the considered stone sample, through reflection scattering parameter measurements, it is possible to associate the resonant frequency of the resonator to the moisture content of the stone sample. In this way, an experimental relationship between resonant frequency and moisture content can be obtained. Experimental tests are carried out on two types of materials, namely gentile and carparo stones: which are typically found in Cultural Heritage structures in Southern Italy and they are particularly affected by deterioration and decay phenomena. Measurements were performed for five levels of water content of the stone samples, and the empirical relationship between each considered level of water content and the corresponding measured quantity were derived. The obtained results demonstrate that this solution appears robust.**

I. INTRODUCTION

The monitoring and preservation of Cultural Heritage is a heartfelt issue not only for the Scientific Community, but also for the general population, thanks to the widespread awareness of the importance of preserving the invaluable cultural treasures.

Moisture is one of the major causes of decay of ancient building materials. As a result, a wide range of measurement techniques is applied for detecting moisture presence. Among these techniques, ground penetrating radar (GPR) [1, 2], spectroscopic techniques (colorimetry, FT-IR and μ-Raman) [3] have been extensively used for non-invasive moisture characterization of subsurfaces; however, the use of these techniques requires the operator to possess in-depth technical/scientific knowledge to obtain accurate results. On the other hand, microwave reflectometry-based measurement systems, as those presented in [4], allow a noninvasive approach; additionally, they are also easy to be used in the field, and they can be implemented in low-cost versions. In [4], different microwave-based methods and probes were comparatively used to infer, noninvasively, the relationship between the water content θ of stone materials and the reflection properties at microwave frequency of the material. More specifically, three types of probes (an open-ended coaxial probe; a patch resonator; and an open-ended waveguide) and two different measurement instruments (a vector network analyzer and a time-domain reflectometer) were employed for the characterization of stones used in Cultural Heritage. The obtained results demonstrated that the use of a patch resonator as a probe can provide several advantages over the other considered methods; in particular, by placing the stone sample in contact with the planar resonator, the variation of the resonance frequency of the resonator can be related to the water content of the stone sample.

Starting from these considerations, in this work, experimental tests were carried out on two types of materials, namely *gentile* and *carparo* stones: these materials are typically found in Cultural Heritage structures in Southern Italy and they are particularly affected by deterioration and decay phenomena. Measurements were performed for increasing level of water content of the stone samples, and the empirical relationship between each considered level of water content and the corresponding measured quantity were derived.

II. BACKGROUND

The basic principle is to exploit the fact that the presence of water, whose relative dielectric permittivity is in the order of 78, increases the dielectric permittivity of the considered stone materials (which, in dry conditions, exhibit a relative dielectric permittivity of the order of 5-6).

On the other hand, as well known, the resonant frequency of a patch resonator is related not only to the permittivity of the substrate, but also on the permittivity of the medium in which the resonator radiates [5, 6].

Based on these considerations, the idea is to place the

Table 1. Reference water content levels, θ_{ref}, for gentile and carparo stones

type	reference $\theta_{ref}(\%)$ values				
gentile	12.2	10.4	6.3	4.8	0.0
carparo	28.5	24.4	5.6	3.7	0.0

planar resonator in front of the considered stone sample, and to measure the corresponding resonant frequency (f_r). Thus, obtaining an experimental relationship between resonant frequency of the resonator and moisture content of the sample.

III. MATERIALS AND METHODS

A. *Materials*

As aforementioned, two types of stones were considered: *gentile* stone and *carparo* stone.

The former is a calcarenitic ground stone, and its mineralogical composition is that of calcite [7]. Thanks to its good workability properties, this stone has been widely used in the building sector with several functions, for ashlars and load-bearing elements but also for coatings, decorations and statuary [8].

As for *carparo* stone, this is a limestone from the South of Italy (particularly used in the Salento area). Its rough appearance derives from cementation of sediments of limestone, in the marine environment. This material is commonly used in construction stone, ornamental stone, and architecture. It was especially employed in the Baroque era, for the facades of several churches and historic buildings; an example is the wonderful cathedral of Sant'Agata in Gallipoli (Lecce, Italy). Being a natural material, *carparo* does not have a completely homogeneous appearance and may vary in grain size and color gradation depending on the concentration of chemical components and the different extraction points. Fossils or parts of them are often found in the stone, a feature which gives even more value to the product and guarantees the absolute genuineness and natural origin.

For each type of stone, one sample was cut with the following dimensions:
- 19.8 cm $\times$ 19.9 cm $\times$ 2.3 cm for the *gentile* stone;
- 19.9 cm $\times$ 19.7 cm $\times$ 2.1 cm for the *carparo* stone.

B. *Methods*

The presented measurement system relies on establishing the empirical relationship between the resonant frequency (f_r) of a patch resonator and the water content (θ) of the stone sample, when the planar resonator is placed on the sample [4], as shown in Fig. 1.

For this purpose, a patch resonator was designed and fabricated [9]. The reflection scattering parameter of the resonator, $S_{11}(f)$, was measured by placing the resonator

Fig. 1. Picture of the experimental setup used for S_{11} measurements.

in contact with the stone samples (moistened at different reference values of θ_{ref}). For each value of θ_{ref}, the $S_{11}(f)$ was measured through a vector network analyzer (VNA, model Agilent E8363C). From the magnitude of the $S_{11}(f)$, the corresponding f_r value was inferred. In this way, the measured f_r values were associated to the corresponding θ_{ref} values.

For each stone sample, to bring the considered samples to reference (known) water content values, θ_{ref}, to be used for testing the measurement systems, the following moistening procedure was carried out:
1) drying of the sample in a microwave oven;
2) weighing of the dry sample, W_{dry};
3) bath in deionized water until saturation (which, for the considered samples, took less than two hours);
4) weighing of the sample, W_i;
5) assessment of the volumetric water content, θ_{ref}:

$$\theta_{ref} = \frac{(W_i - W_{dry})}{V_{stone} \cdot \rho_w} \times 100 \qquad (1)$$

where V_{stone} is the volume of the stone sample, and $\rho_w \cong 0.996$ g/cm^3 is the density of water.
6) measurement on the sample through each of the considered measurement methods;
7) oven drying for a limited amount of time, in order to remove part of the moisture.
Steps 4-7 were repeated for each drying step, until complete dry up of the sample.
Table 1 summarizes the reference values of θ_{ref} for the two stone samples.

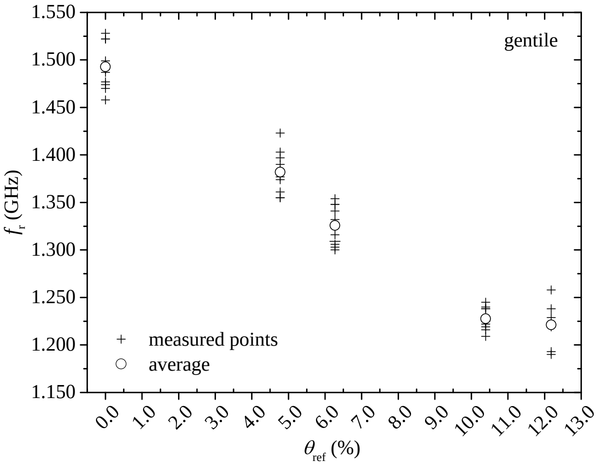

Fig. 2. Measured $\theta_{ref} - f_r$ values for gentile stone. For each considered θ_{ref} value, the results of the ten repeated f_r measurements are reported. The circle markers indicate the average value of f_r.

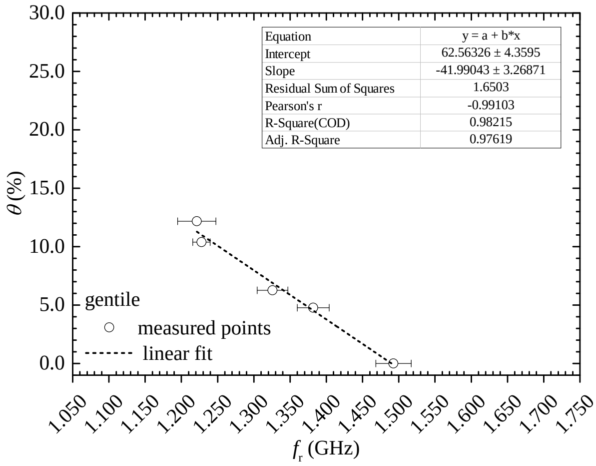

Fig. 3. Calibration curve for gentile stone.

IV. EXPERIMENTAL RESULTS

For each θ_{ref} value, ten repeated $S_{11}(f)$ measurements were carried out. From each of the ten $S_{11}(f)$ curves, the value of the first resonance frequency was evaluated ($f_{r,i}$, where i = 1, ..., 10). Then, the average resonant frequency (f_r) and the standard deviation was evaluated. The f_r value was finally associated to the known reference water content value, θ_{ref}. Fig. 2 shows the measurement results obtained for *gentile* stone: in particular, for each θ_{ref} value, the ten resonant frequency values ($f_{r,i}$) and the average resonant frequency f_r value are shown.

The measurement points were then fitted through a linear regression method, as shown Fig. 3, which also reports the uncertainty bar for each moistening condition.

The line in Fig. 3 represents a calibration curve: in practical applications, for measuring the unknown water content of constructions made of the same type of stone, it suffices to measure the resonant frequency of the resonator, and the unknown water content is retrieved from the calibration line.

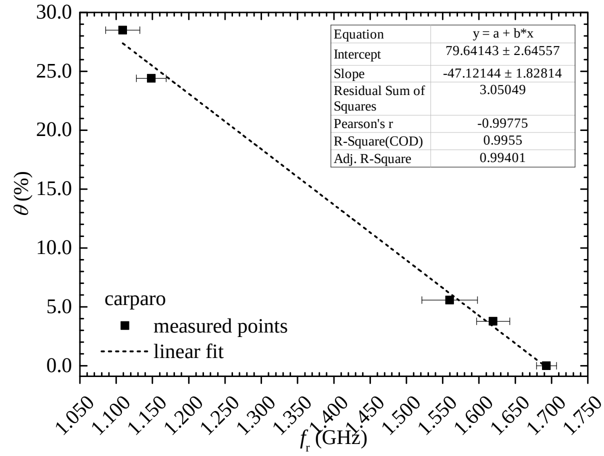

Fig. 4. Calibration curve for carparo stone.

Fig. 4 shows the calibration line obtained for *carparo* stone. Comparing Fig. 3 and Fig. 4, it can also be noticed that *carparo* stone reaches saturation for higher water content values (approximately in the order of 29%). However, the slopes of the calibration lines are similar.

The obtained results demonstrate that this solution appears robust and suitable for in-the-field applications. In fact, it is also possible to employ portable, low-cost time-domain reflectometer for retrieving the $S_{11}(f)$ curves from time-domain measurements [6].

Also, the positioning of the probe is easy and easily repeatable. Additionally, by studying the optimal patch geometry, it is possible to enhance the sensitivity and repeatability of the measurement system.

V. CONCLUSION

In this work, a microwave-based system for monitoring water content in stone materials was presented. By placing a planar resonator in contact with the considered stone sample, trough VNA measurements of the reflection scattering parameter, it is possible to associate the resonant frequency of the resonator to the moisture content of the sample. In this way, an experimental relationship between resonant frequency and moisture content can be obtained.

Experimental tests were carried out on two types of materials, namely *gentile* and *carparo* stones: these materials are typically found in Cultural Heritage structures in Southern Italy and they are particularly affected by deterioration and decay phenomena. Measurements were performed for five levels of water content of the stone samples, and the empirical relationship between each considered level of water content and the corresponding measured quantity were derived. The obtained results demonstrated that this solution appears robust and suitable for in-the-field applications.

In the extended version of this work, additional types of stones used in Cultural Heritage structures will be characterized through the considered measurement system.

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