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A comparative evaluation of patch resonators layouts for moisture measurement in historic masonry units

Livio D'Alvia[1], Eduardo Palermo[1], Zaccaria Del Prete[1], Erika Pittella[2], Stefano Pisa[2], Emanuele Piuzzi[2]

[1] *Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Italy*
livio.dalvia@uniroma1.it, eduardo.palermo@uniroma1.it, zaccaria.delprete@uniroma1.it
[2] *Department of Information Engineering, Electronics, and Telecommunications, Sapienza University of Rome, Italy*
erika.pittella@uniroma1.it, stefano.pisa@uniroma1.it, emanuele.piuzzi@uniroma1.it

***Abstract*—Monitoring water content in cultural heritage materials through non-invasive and easy-to-use TDR/TDT (time-domain reflectometry / time-domain transmission) measurement systems has the potential to enhance conservation/restoration activities. In this study, two different probes for TDR/TDT technology, Square Patch Resonator (SPR) and Split Ring Resonator (SRR), were compared. The two probes were tested on two different materials (*leccese* and *gentile* stone), each one of them at three different levels of water content. All tests were conducted ten times with two different external impressed forces (hand pressure and 2 kg). Resonant frequencies (f_r), fractional bandwidth (FBW), and standard deviation (σ) were evaluated to assess accuracy and repeatability in water content estimation. Results revealed optimum performance, FBW lower than 7 % and higher repeatability (σ < 5 MHz) with external mass, for the SRR probe. Our results reveal the possibility of monitoring the moisture level in the stone through a microwave tool based on a split ring and TDT device.**

Keywords—measurement repeatability; Q-factor; Dielectric permittivity measurement; Cultural Heritage; Patch resonator; Moisture content measurement

I. INTRODUCTION

The preservation of cultural heritage artifacts has always been a theme of vital importance, especially when critical economic implications are considered. Many causes concur in the deterioration of the historical-artistic-cultural object, but as highlighted in the literature, they could be classified in atmospheric and natural events, or anthropic causes [1]–[3]. In [4], [5] the authors showed how the moisture, the water content, or in general, the seasonal hydrothermal variation represent the most significant causes of the decay of ancient building materials [6], [7].

Nowadays, several methodologies have been validated to measure the percentage of humidity in historic masonry units, involving different techniques and sensors. We could summarize them as: (a) magnetic resonance imaging (MRI) [8], (b) infrared thermography [9], (c) Electrical Resistivity Tomography (ERT) [10], (d) Ground-penetrating radar (GPR) [11], (e) FBG optical sensors [12], [13], and (f) time-domain reflectometry (TDR) [14].

A patch resonator employed in conjunction with a TDR module was proposed by Piuzzi et al. [15] and D'Alvia et al. [16], in two recent studies. They have demonstrated how this kind of application could be a reasonable solution for a microwave reflectometry-based, non-invasive, and easy-to-use measurement system of moisture. The basic idea of these studies is to realize a measurement technique that does not necessitate in-depth technical/scientific knowledge by the operator [17].

The aim of this research is double: (i) deducing, uninvasively, the interrelation between dielectric properties as a function of an external pressure applied to the resonator and the moisture level of brick samples and (ii) comparing two different topologies of the probe.

About the first aim, an external force improves repeatability and increases the detectability of the first resonance peak [16]. As concerns the second aim the proposed probes are a Square Patch Resonator (SPR) and a Split Ring Resonator (SRR).

The two patch resonators and a VNA (vector network analyzer) are employed for the characterization of *leccese* and *gentile* stones: these two stones are commonly used in historical buildings in Apulia (southern Italy region) and are mostly affected by corrosion and degeneration phenomena as described in the next section.

In section II, we describe, in addition to the stonework units, the measuring system and the experimental setup. The results of the research are presented and discussed in section III. Finally, in the concluding section, significant achievements are summarized.

II. MATERIALS AND METHODS

A. Stonework units

We consider two types of masonry units (*Leccese* and *Gentile*) most used in the Apulian monumental building heritage as construction or ornamental matter.

The two species are marl organogenic calcarenite. In particular, *Gentile* stone is a lithological variety of *Leccese* stone characterized by a homogeneous fine grain whilst leccese stone presents higher porosity and lower cementation. Both the proposed stones have a good attitude toward absorbing and retaining water and the mechanical resistance changes as a function of the moisture level [18].

The thickness of the stones is chosen according to Piuzzi et al. [19] that have evaluated how the thickness of the sample should be higher than 1.5 cm to reduce the error due to the edge effects.

B. Stonework conditioning

According to D'Alvia et al. [16], the stonework conditioning is carried out by following a recursive procedure (Figure 1), to obtain different levels of water content. Firstly, the weights of samples W_d at dry condition are evaluated, and after a twelve hours bath in deionized water, we evaluate the weight of hydrated samples W_h until saturation. To have more different levels of water content W_i, we put the samples in an oven in order to remove part of the water.

Equation (1) shows the relation between the volumetric water content θ_v and the weights.

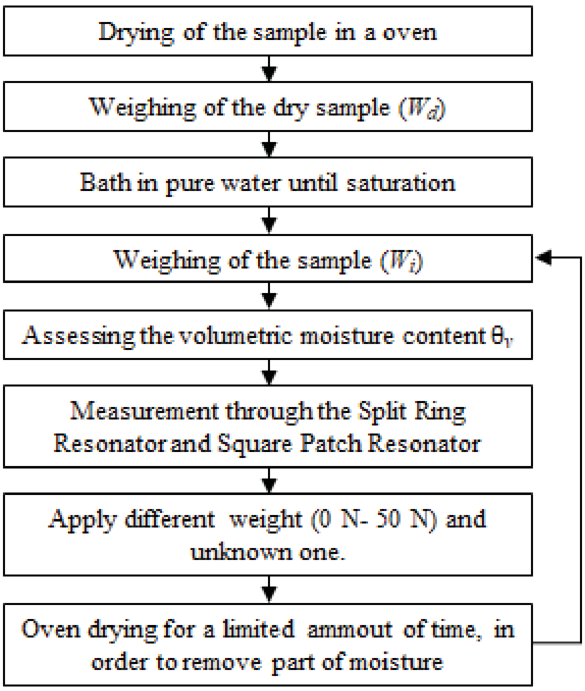


Fig. 1. stonework conditioning flowchart

$$\theta_v = \frac{(W_i - W_d)}{V_s \cdot \rho_w} \quad (1)$$

V_s and ρ_w represent the volumes of the chosen sample and the density of water, respectively.

We measure the different levels of θ_v through the Square Patch Resonator (SPR) and the Split Ring Resonator (SRR) probes, as described in the following sections.

C. Measuring system

The SPR (square-patch) (Figure 2-a) has an area of 23.04 cm^2 etched on a substrate with a total thickness of 3.175 mm and a copper metallization thickness of 35.6 µm. The resonant frequency in the air is f_r = 2 GHz, and the substrate permittivity is $\varepsilon_{r,sub} = 2.32$.

The SRR (split-ring) (Figure 2-b) is realized to increase the Q factor (Q = 172.98), with an area of 8 cm^2 etched on a substrate with a total thickness of 3.18 mm with 3 µm of copper metallization thickness. The resonant frequency in the air is f_r = 2.27 GHz, and the substrate permittivity is $\varepsilon_{r,sub} = 2.5$.

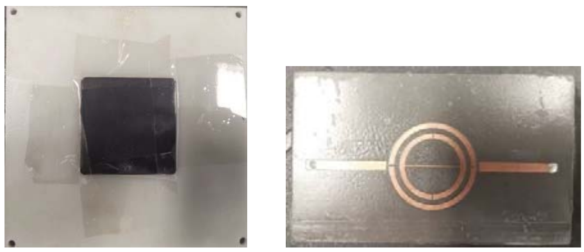
Both resonators were connected to a vector network analyzer (VNA) Agilent-E8363C.

D. Experimental setup

The resonance frequencies f_r of the two resonators are dependent on the permittivity of the irradiated materials, placed in contact with the resonators, and not only on the permittivity of the substrates. Furthermore, due to the high relative permittivity of water ($\varepsilon_w \approx 78$), the dielectric permittivity of the chosen masonry units ($\varepsilon_r \approx 5.5$) is significantly increased by moisture absorption.

We present a measurement chain able to prove the experimental relation between the volumetric water content (θ_v) of the stone sample and the resonant frequency (f_r) of the patch resonators when they are placed on the samples. In particular, to reduce measurement uncertainties in the reflection coefficient, we use two lapped samples.

In order to identify the best-performing work condition, we applied different forces produced by external masses



(a) (b)

Fig. 2. (a) Square Patch Resonator and (b) Split Ring Resonator

M. The mass *m* of the free sensors and VNA cable is negligible.

For each stone, the magnitude of the scattering parameters is measured at diverse values of M applied to the sensor, and from this, the resonance frequency (f_r) is retrieved. The coefficient $|S_{11}(f)|$ of reflection and $|S_{21}(f)|$ of transmission (in dB) are measured for SPR and SRR, respectively.

We also evaluated the repeatability σ of the system, measuring ten times in the proximity of the same point, the magnitude of S_{11} and S_{21}, and calculating the standard deviation. For each level of humidity, we performed two distinct measurements that represent two possible real cases: (a) applying a certified mass M = 2 kg; (b) applying a force manually.

The case (a) represents a controlled measuring system that guarantees to exert precise and constant pressure on the brick. The case (b) represents a manually exerted force, hypothetically representing the force impressed by a technician during a site inspection.

The last parameter taken into consideration is the fractional bandwidth FBW, directly linked to the Q factor. It explores the capability of the proposed system to sense dielectric losses in the sample.

The fractional bandwidth presented in Equation 2 is given by the ratio of the difference of lower cut off frequency f_L and the higher cut off frequency f_H (both at -3dB), and the center frequency f_c:

$$FBW = \frac{f_H - f_L}{f_r} * 100 \quad (2)$$

where we chose as central frequency, the resonant frequencies f_r.

III. RESULTS AND DISCUSSION

Figure 3 shows the frequency response of the two chosen stones for an applied mass of 2 kg at the three levels of water content.

In particular, column (a) shows the response for the *leccese* stones, with highlighted in blue the output of SPR and in red the output of SRR.
Similarly, column (b) shows the response for the *gentile* stones with highlighted in blue the output of SPR and in red the output of SRR.

A different resonant frequency for the same stone at the same condition depends on the different geometry of the patch. In the pictures, it is possible to see how the SRR presents a smaller FBW than SPR, which means that the split ring has a Q factor higher than the square patch resonator all results for the two stones, at the three different levels of humidity and two applied forces, are presented in Table 1.

The obtained results show that repeatability and, hence, the accuracy of the system might be improved by applying a constant and certified force on the sensor (σ≤ 5 MHz)

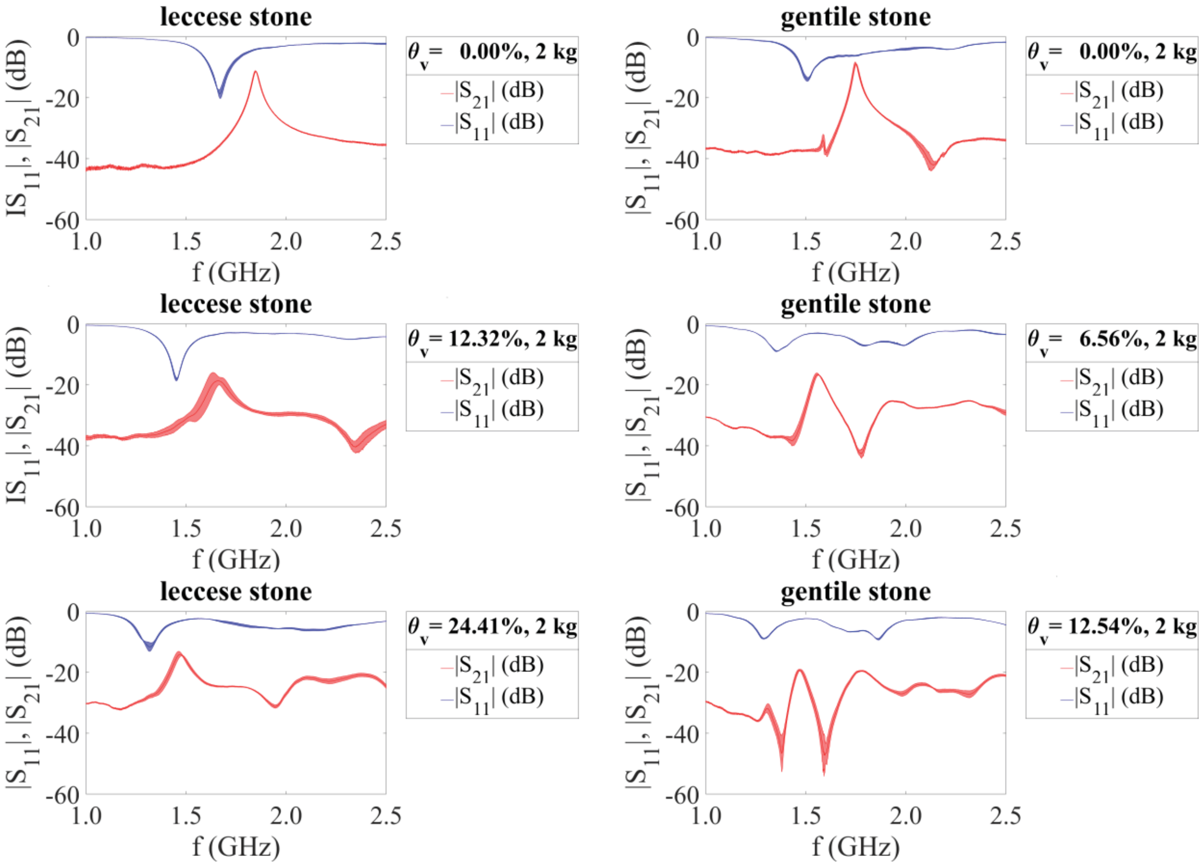
Furthermore, applying a weight of 2 kg, the magnitude of the first resonance frequency is higher and more easily detectable, especially at high water levels: the repeatability is always better than the case of hand-applied force.

The SRR shows higher repeatability than SPR for both cases (2 kg and hand), besides a good FBW.

A particular case is presented in bold. For the *leccese* stone measured with SSR at 12.32% of water content, we observed an FBW in 2 kg condition higher than in ‘manual’ condition. The FBW with “hand pressure” results to be lower than 2 kg due to a high manually exerted force, as shown by a lower value of resonance frequency.

Table 1 Resonance frequency (f_r), repeatability (σ) and bandwidth as a function of the applied weight and water content θ_v for the square patch resonator (SPR) and the split ring resonator (SRR)

Kind of resonator	**SPR**				**SRR**			
Applied Mass	2 kg	hand	2 kg	hand	2 kg	hand	2 kg	hand
θ_v (%)	Leccese 0%		Gentile 0%		Leccese 0%		Gentile 0%	
f_r mean (GHz)	1.654	1.660	1.509	1.514	1.849	1.862	1.750	1.899
σ (GHz)	0.002	0.005	0.002	0.005	0.001	0.003	0.003	0.048
FBW (%)	2.72	2.79	3.73	5.02	1.75	3.60	1.64	3.33
θ_v (%)	Leccese 12.32%		Gentile 6.65%		Leccese 12.32%		Gentile 6.56%	
f_r mean (GHz)	1.453	1.442	1.356	1.349	**1.624**	**1.592**	1.559	1.574
σ (GHz)	0.002	0.002	0.004	0.004	**0.019**	**0.001**	0.005	0.020
FBW (%)	2.41	2.60	8.07	8.76	**5.72**	**4.35**	3.68	4.43
θ_v (%)	Leccese 24.41%		Gentile 12.54%		Leccese 24.41%		Gentile 12.54%	
f_r mean (GHz)	1.320	1.316	1.291	1.274	1.470	1.4868	1.470	1.490
σ (GHz)	0.002	0.003	0.005	0.009	0.008	0.080	0.005	0.014
FBW (%)	5.97	6.28	11.50	11.82	4.75	4.84	3.69	6.69



(a) (b)

Fig. 3. |S11| and |S21| *for (a) leccese and (b) gentile stones at the chosen levels of water content θ_v, with 2 kg applied*

IV. CONCLUSION

This work highlights that the application of a calibrated force to a resonant patch, used for non-invasive measurements of water content in stone materials, permits to:

a) improve measurement repeatability
b) enhance the detectability of the first resonance peak, thanks to an increase in the Q factor compared with studies where the authors do not use external forces [20].

A second significant result concerns the better affordability of a split ring resonator compared to the square patch. Independently by applying an external force or not, we always have an FBW lower of SPR's bandwidth.

Additionally, as for SPR, in order to increase the adherence between the antenna and the sample surface and consequently increase the impedance match, an electrically-conductive silicone layer could be applied.

Further future developments in the instrument design should include: (i) repeating the same procedure for different types of stones or materials; (ii) realizing a patch that integrates a load cell able to indicate the achievement of a proper force by hand. The last point might permit applications without the need for the calibrated masses whose use would become impractical when the sensor is used in a vertical position (which is the most common in "on-site" applications on walls).

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