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Microwave reflectometry system for non-invasive wood moisture content monitoring

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***Abstract* – The environmental conditions and the humidity level are crucial factors in caring for artworks. The aim of this work is to propose a method for on-site non-invasive moisture monitoring of wooden artworks or structures. In this regard, a truncated open-ended coaxial probe was designed, implemented, and tested to sense (in combination with a miniaturized Vector Network Analyzer) the variations of water content in woods and stones. More in detail, for the experimental tests, two types of wood (seasoned fir and not seasoned fir) and a limestone, used in Italian Artworks and structures, were analyzed at different moisture levels.**

I. INTRODUCTION

Museums, galleries, and building works suffer from humidity [1] which can cause dimensional changes and internal stresses in artworks. In this context, water content is one of the most critical factors responsible for the damage of historical objects and building conservation [2,3]. As a matter of fact, most historic works are made of natural organic materials [4] as wood, leather, traditional adhesives textiles or paper that are particularly sensitive to moisture infiltration. In particular, if the humidity is extremely high, a material such as the wood expands until it swells and rises [5]. This phenomenon is due to the physical–mechanical properties of this material that is characterized by remarkable hygroscopicity [6]. Water is found inside wood in two forms: free or bound. Free water fills wood cell cavities with water contents above the fiber saturation point, which is nominally around 30% [7-9]. Bound water is absorbed between the cellulose microfibrils in the wood cell wall [10], and this water causes the cell wall to expand, leading to swelling of the wood. On such basis, the humidity is a potential source of damage to building. Currently, gravimetric procedures are the most accurate techniques to measure water content in wood objects or structures. However, such methods are invasive and destructive since a sample of the object under test should be withdrawn in order to carry out the analysis. On the other hand, in spite of the great efforts produced for research in monitoring historical works through non-invasive instrumentations, the resulting solutions have notable limits. As a result, a wide variety of methods based on different physical principles have been developed [11]. In this context, the sensing technology at the current state-of-the-art relies on electrical conductivity-based methods [12] which are considered micro-destructive, or capacitive methods [13] that suffer from low accuracy. In addition, tests carried out with waveguides or planar resonators [14] are strongly influenced by temperature, material density, and sample thickness. Furthermore, other methods such as Ground Penetrating Radar (GPR) [15], Nuclear magnetic resonance (NMR) [16], or Near-infrared spectrometry (NIRS) [17] are quite expensive. In this context, microwave reflectometry (MR) technique [18,19] represents a convenient solution for non-invasive monitoring of wood moisture. More in detail, wood moisture measurements rely on the strong relationship between dielectric properties and water content of material under test. Starting from these considerations, this work investigates the possibility of using a customized open ended coaxial probe in combination with a miniaturized VNA (mVNA) for the monitoring of water content of woods through a microwave reflectometry technique. On such basis, the experimental tests were carried out on two types of woods and on a limestone.

The present work is organized as follows. Section 2 describes the basic theoretical background behind the proposed system, the used experimental setup, the chosen materials and the moisturizing and gravimetric process. Section 3 describes the experimental results. Finally, conclusions and future work are outlined in Section 4.

II. MATERIALS AND METHODS

As mentioned in Section 1, this study aims to develop a procedure based on MR for monitoring the moisture content of wood structures and objects [20]. In this regard, a group of three materials was selected. In the following subsections, after outlining the theoretical background for the MR technique, the proposed method and the selected materials are described in detail.

A. Microwave reflectometry: theoretical background

MR technique is a powerful method for a wide range of monitoring and diagnostic applications [21-29]. The principle behind this technique relies on measuring the reflection scattering parameter, $S_{11}(f)$ [30], of the sensing element (SE) when this is placed in contact with the material under test, and in relating it to the water content. It is worth noting that an increase in the water content corresponds to an increase in the dielectric properties of the materials (since water has a very high relative dielectric permittivity). On such basis any variation of the $S_{11}(f)$ can be associated to a variation in the dielectric properties of the woods.

B. Experimental setup

For the sake of ensuring non-destructive measurements and in order to guarantee very low costs, a customized truncated open-ended coaxial SE was designed, manufactured and used in combination with a mVNA. More in detail, this type of SE configuration, when in contact with the material under test, can be sensitive to dielectric variations. In particular, for the specific application, the main requirements to be simultaneously optimized in the design phase were the use in a low-frequency analysis range (below 3 GHz) and an EM penetration depth confined in the sample. To this purpose, EM full-wave simulations were carried out on CST Microwave Studio ® software in order to obtain the optimal geometric parameters. Subsequently, it was realized from a standard SMA panel connector with an additional flange, useful to exploit the so-called EM fringing-effect and to enhance the sensitivity of the SE.

As per the measurement instrument, as is well known, the $S_{11}(f)$ can be measured directly in the frequency domain through VNAs [25] which are very expensive instruments. However, in this work, a portable and low-cost mVNA, namely the NanoVNA, was adopted. This type of instrument has a very advantageous cost/performance ratio, since in its work frequency range (0-3 GHz) it shows a degree of accuracy very close to that of more expensive instruments. The experimental setup is shown in Fig. 1

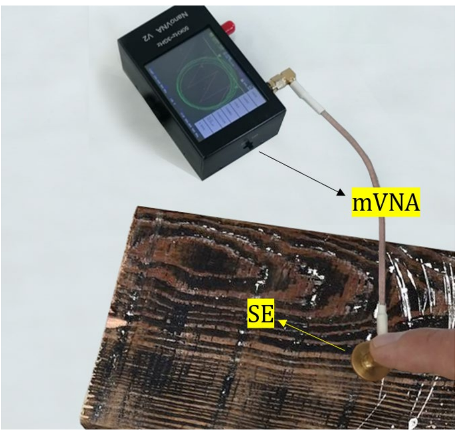

Fig. 1: Experimental setup showing a measurement on the dry seasoned fir. The sensing element was just placed on the material without the application of any substances.

C. Selected materials

The group of selected materials consists of two types of woods and a limestone. More in detail, a seasoned fir with slow growth process and a not seasoned fir with rapid growth process are considered. The main difference between the two types of wood is based on the seasoning. More in detail, seasoning is the process of drying wood that is necessary to remove the moisture contained in its cell walls and that allows for the creation of a new product called seasoned wood. This type of wood is much more resistant to deterioration than fresh wood. For this reason, it can be interesting to carry out the experimental procedure on both seasoned and unseasoned woods. In addition, also a limestone (Lecce stone) has undergone tests. The materials used for the experimental tests are reported in Fig. 2.

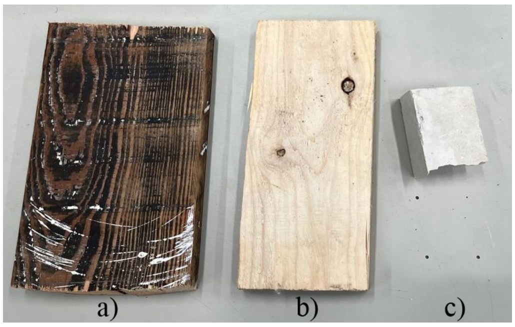

Fig. 2: The selected materials: a) seasoned fir, b) not seasoned fir and c) limestone

D. Methodological Procedures and Description of the Experiments

The frequency-domain (FD) measurements were carried out on the three materials in the following conditions:

- Dry condition;
- placing each material in a basin filled with water so that only one side of the material is wet. Operating in this way, it was possible to monitor the degree of water absorption over time. More in detail, the measurements were repeated after 10 min, 30 min, 1 hour, 5 hours and 72 hours from immersion in water.

Finally, the volumetric water content θ at each considered time instant was assessed according to Eq. 1 through the gravimetric method, weighing the sample before each measurement.

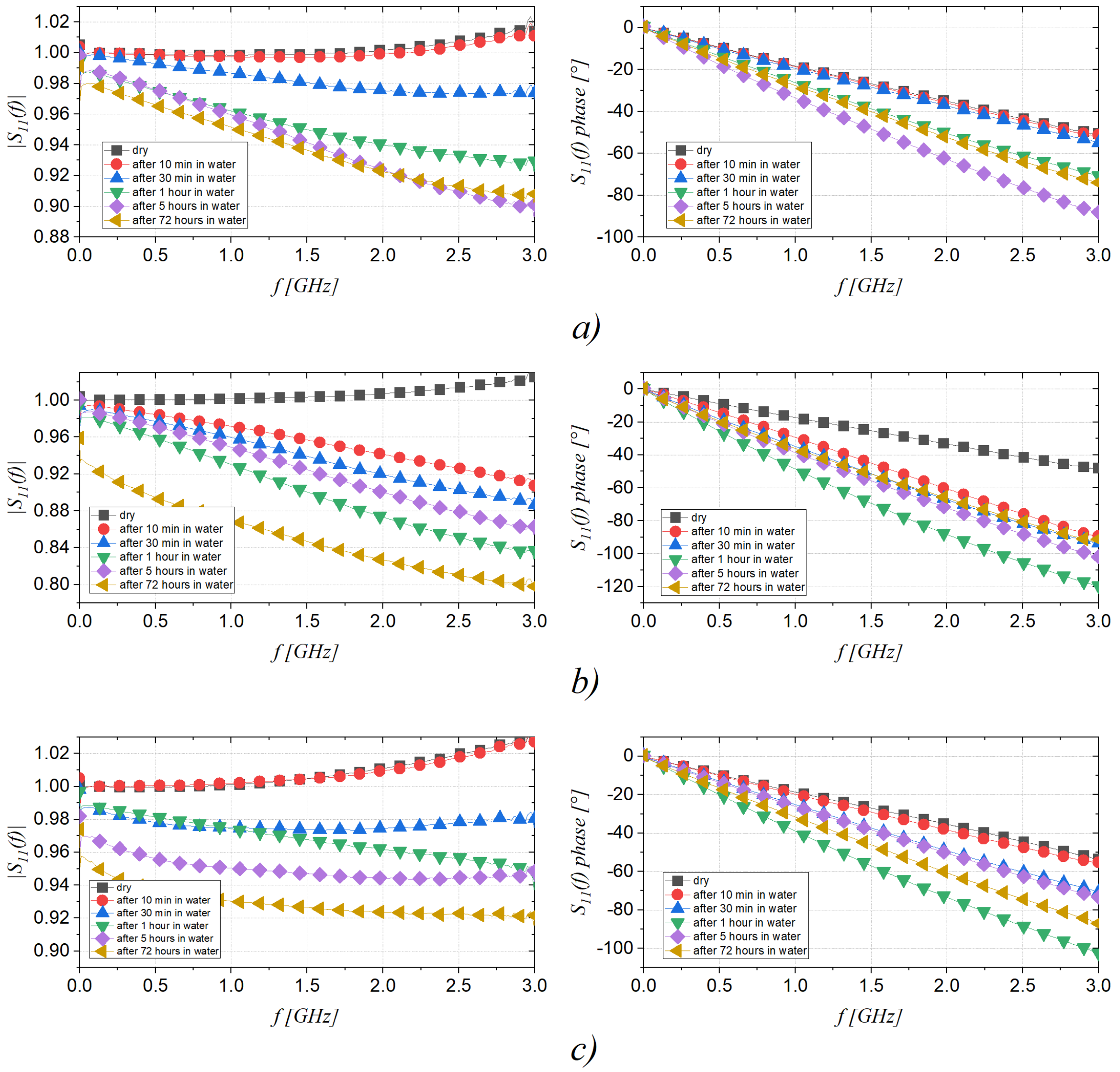

Fig. 1 Magnitude and phase of the $S_{11}(f)$ measured with the experimental setup on the 3 materials under test: a) seasoned fir, b) not seasoned fir, and c) limestone.

$$\theta\ [\%] = \frac{V_{water}}{V_{dry\ material}} \cdot 100 \qquad (1)$$

where $V_{dry\ material}$ is the volume of the material under test in the dry condition and V_{water} is the volume of the water, calculated as the ratio between the weight of water and its specific gravity (equal to $1\frac{g}{cm^3}$). The weight of water, in turn, was calculated as the difference between the weight of the material immersed in water and its original weight in dry condition.

These results are reported in Table 1. It is worth noting that the material c) (limestone) has the highest volumetric water content, probably due to its small volume that must also be taken into account. However, the dry condition was considered as a reference dried condition (i.e., θ= 0 %) for each material. In this way it was possible to correlate each measurement at specific degree of water content.

Table 1. Volumetric water content percentage in the three materials throughout the observation period. a) seasoned fir, b) not seasoned fir, c) limestone

Time	θ [%] a)	θ [%] b)	θ [%] c)
10 min	2.76	2.94	14.16
30 min	3.32	3.14	17.90
1 hour	3.65	3.50	19.46
5 hour	5.47	6.28	21.13

72 hour	12.38	14.23	23.18

III. EXPERIMENTAL RESULTS

As aforementioned, the experimental measurements were carried out on the 3 selected materials. The measurement results in terms of magnitude and phase of the $S_{11}(f)$ are reported in Figure 3. It is worth noting that, over the whole considered frequency, the response of the moisturized conditions is systematically lower than that corresponding dry material condition. More in detail, a specific trend can be observed as time and water content increase. Only in a few cases the trend is not exactly as expected and there is a reversal of some measures. Probably this phenomenon is due to the uneven diffusion of water within large volumes and to small variations in the SE placement. For these reasons, it might be useful to use a network of point sensors that can analyze the spread of water from multiple spatial coordinates.

IV. CONCLUSIONS

In this paper, the design, fabrication and test of a microwave reflectometry-based portable sensing system for real-time monitoring of water content level of woods and stones was presented. More in detail, the proposed system adopts a non-destructive technique that make it more attractive compared with several existing methods. This type of approach allows to correlate the response of the materials under test in terms of $S_{11}(f)$ to the water content variations. In this regard, the results showed that as the water content increases over time, the $S_{11}(f)$ decreases following a specific trend. This is particularly useful for allowing accurate monitoring of the water status of Artworks.

Further works will be dedicated to the development of a specific procedure in order to extrapolate the dielectric permittivity of materials from the FD measurements and to the comparison with other traditional measurement techniques.

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