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Article

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The feasibility of using electromagnetic waves in determining the moisture content of building fabrics and the cause of the water ingress.

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Abstract— **In this paper, the feasibility of using electromagnetic (EM) waves is determining the moisture content of building fabrics and the case of water ingress in experimentally assessed. This paper will concentrate on investigating the propagation of EM waves through typical structures and their interaction with concealed pipework, wiring and timber. All current methods are overviewed and analysed. Novel microwave sensor described in this paper operates in 6 GHz to 12 GHz frequency range using Marconi 6200A microwave test set. Results of experimental test confirm that microwaves can be used as an alternative non-destructive method for identifying different object behind the walls.**

Keywords: Horn Antenna; Electromagnetic waves; Microwaves; Water Ingress; Dampness; Sensor; Building fabrics.

I. INTRODUCTION

In recent years there has been an increase in the need for sustainability in buildings and civil engineering structures. To achieve the optimum life span of these structures it is important to monitor parameters such as the moisture content, temperature, influence of vibration and material fatigue. This is especially important for constructions which are sensitive to environmental influences. Moisture is everywhere from the air to porous building materials such as bricks, concrete, wood, mortar and rock wool insulation. In the modern environment it is necessary to investigate the moisture content of building materials, because moisture has a negative influence on most physical, chemical, and biological corrosion processes [1], [2]. Currently there are a few methods available to determine the dampness of building fabrics, which are discussed in details further in Section III. Notably, available equipment to measure moisture content is destructive for building fabrics as it requires additional drilling in the wall to take a sample of the content. Moreover, these methods provide inaccurate results. Better results are provided by the gamma ray method [3] however use of this technique can lead to health problems. Therefore it is necessary to develop non-destructive equipment which will provide accurate readings for identifying the cause and the location of the water ingress. It is also important to investigate methods to propagate EM waves through the structure and determination of failures of building fabrics such as membrane failure, a pipe burst or ground source. To solve the mentioned problems research was undertaken in developing a novel method which will use electromagnetic waves. During the research different ranges of EM waves were tested and also different types of antennas were used to identify the best parameters to provide accurate measurements.

II. RESEARCH BACKGROUND

A. *Moisture Content of Building Fabrics*

Moisture content of building fabrics varies depends on type of building fabrics, vapour pressure and other factors. If a brick at the wall face obtains 10% actual moisture content after rain, to dry out later it may not be a problem for the building or any users. However, if similar brick located to the inner thickness of the wall were to achieve persistent moisture content of above 3%, problems could result such as damp plasters, damaged decoration, and damp timbers from contact with the masonry- leading to timber rot [4]. Another part of the building set aside for damages is roof where membrane getting damaged and water leakage is getting to timber which is rewetting and getting broken. This situation is dangerous as the current method which is able to detect leak is not accurate enough to avoid water leakage which could lead to roof's collapsing. Standard moisture contents are quoted [4] as follows:

- Exposed (external leaf) brickwork and concrete 5%
- Protected (internal leaf) brickwork 1%
- Protected (internal leaf) concrete 3%.

It is suggested [4] that brick moisture contents above 20%, lightweight concrete above 12% and high density concrete above 15% are within the 'Damage likely' category where it is necessary to consider the remedial actions. Over the winter period, moisture contents can increase by 2–3 % [5].

Source of moisture in buildings can be various, and some examples are given in Table I:

TABLE I. SOURCE OF MOISTURE [4].

Moisture source	Typical examples
Air moisture condensation	-Cooking
	-Heating
Penetrating dampness	-rainwater, snow
	-Leaking external rainwater goods
Internal plumbing leaks	-Long-term breakdown of plumbing joints
	-Burst pipes
Below- ground moisture	-Underground plumbing leaks
	-Leaking ponds

B. *Mircowaves*

Microwaves are radio waves with wavelengths ranging from one meter to one millimeter, or equivalently with frequencies between 300 MHz (0.3 GHz) and 300 GHz [6]. Figure 1 depicts the full electromagnetic spectrum from long waves up to Gamma Ray [7].

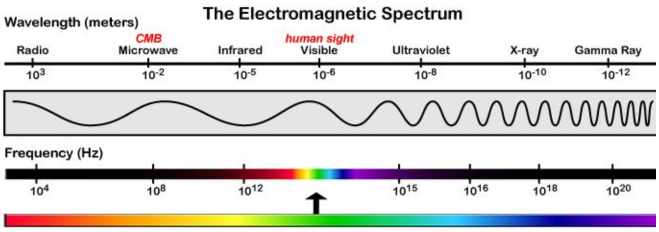

Figure 1 The electromagnetic spectrum **[8]**.

There are different types of antennas which can be used to transmit and received microwave signal:

- Wire Antennas

Wire Antenna has various shapes such as a straight wire (dipole), loop, or helix. This type of antennas is one of the most common antennas which can be found in lots of applications such as cars, buildings, ships [9].

- Aperture Antennas

There are different types of aperture antennas such as pyramidal horn, conical horn or rectangular waveguide. Microwave horn antenna produces a uniform phase front with larger aperture than the waveguide with greater directivity. A horn antenna consists of a rectangular metal tube closed at one end, flaring into an open-ended pyramidal shaped horn on the other side. The microwaves are introduced into the waveguide by a coaxial cable attached to horn antenna [10].

- Microstrip Antennas

Those antennas consist of a metallic patch on a grounded substrate. The metallic patch can take different configurations. The microstrip antennas are low profile, comfortable to planar and nonplanar surfaces, simple and inexpensive to fabricate using printed-circuit technology [9].

C. *Dielectrics Properties of Building Fabrics at Microwave Frequency*

Microwave imaging for building fabrics detection is based on the contrast in dielectric properties of different types of materials and moisture content. These properties will allow finding the source of the leak behind the wall and to determine what objects are located in the gap between the materials [11].

The materials used in this research have different dielectric properties at microwave frequency which allow transmitting the microwave signal that could be analysed by collected reflection from the material as all materials will absorb signal at different level. [12] . To provide the most accurate results it is essential to estimate the value of dielectric constant. It is important to use Double Debye Relaxation equation to calculate dielectric constant of water [13].

The dielectric loss of water increases with increase in the salinity in the water. Dielectric loss of pure water increases with increase in frequency, whereas in case of saline water it is found to decrease with increase in frequency [14]. At this stage of the research pure water will be used, where S=0 [15] [13]. Knowledge of the attenuation or losses of building materials is important for the study of microwaves signal propagation in either indoor or outdoor environments [16]. It is essential to take into the account the permittivity of different materials such as gypsum, brick wall or concrete and objects which will be placed behind material such as timer, cables and pipes. Dielectric properties of the building materials will allow determining the condition of building structure by analysing changes which will occur in wave amplitude.

III. CURRENT METHODS TO DETERMINE MOISTURE CONTENT OF BUILDING FABRICS

A. *Radiological Measurements*

- Neutron Method

Neutrons interact mainly with the hydrogen nuclei and give a direct measurement of water content by volume. Higher energy neutrons emitted from a radioactive substance such as a radium beryllium source are slowed and changed in direction by elastic collisions with atomic nuclei. The process in which the high energy neutrons lose energy by kinetic collisions with surrounding nuclei is called thermalization, the neutrons being reduced in energy to about the thermal energy of atoms in a substance at room temperature. Hydrogen has a nucleus of about the same size and mass as the neutron has much greater thermalizing effect than any other element. A measurement of the thermal neutron density in the vanity of a neutron source will be a measure of the concentration of hydrogen nuclei on a volume basis, and thus a measure of the water concentration. The source and detector are placed in a probe. The neutron source is mounted in a lead shield at the bottom of the gas filled detector tube. The unit is constructed to be set over an access hole in the porous material, and the probe lowered through the bottom of the shield into the hole. The resolution of probe is not great. It is impossible to measure accurately the water content within 6 in. of the surface [17].

- Gamma Ray Method

Gamma rays interact with the orbital electrons of matter in three ways. Firstly, the photoelectric effect in which the whole of the energy of gamma ray is absorbed occurs at low energies. The Compton Effect, which is the scattering of gamma rays by electrons at medium energies and finally the creation of positron- electron pairs, becomes important at high energies. Measuring the attenuation of gamma radiation enables to determinate the density of material. The essential components of that system are source of gamma rays, a detector, an amplifier, a discriminator and a device to record the pulses from the detector. Gamma ray method offers the greatest accuracy in the determination of moisture content +/- 1.0 per cent. Therefore there is no hysteresis and it has short measuring time. Also there is no effect of temperature change or of dissolved conducting materials. Unfortunately, there are high capital costs and precautions are necessary with radioactive equipment. Gamma scattering method determines the moisture content of concrete by measuring the intensity of scattered radiation in limestone concrete using an indigenously built goniometer and an HPGe spectrometer [18].

B. Electrical Measurements

- Electrical resistance measurement

Electrical resistance measurement is based on the fact that each material possesses the electrical resistance and water content has a direct impact on the electrical resistance of material, more water means less resistance. Measurement of the electrical resistance is usually carried out using needle-shaped electrodes. Two measuring detectors are placed driving or drilling into a building element and electrical resistance as a function of the electrical conductivity is measured. Wet materials have higher conductivity and lower electrical resistance. Measuring device indicates the results according to different constructions materials which can be converted into percentages of moisture. This method for determining the moisture content of building elements is simple and fast [1].

- LTCC sensor

Low Temperature Co-Fired Ceramic (LTCC) sensor with design and fabrication of an inductor-capacitor (LC) planar sensor have been made to monitoring moisture content of the most often used buildings materials [1]. The sensor can be used at the following ways: it can be put into the building material through small cut for already build walls or it can be buried in the plaster during the building wall process. Variation of the water content in the tested specimens was measured wirelessly, with an antenna coil, tracking changes in the sensor resonant frequency. This sensor consists of two dielectric layers. First layer has screen printed LC structure and second layer has a window over capacitor's electrodes. Through this window the sensor is exposed to moisture, which will then cause change of its dielectric constant and total capacitance and consequently the resonant frequency of the LC sensor. The sensor exhibits from 0% to 70% wide detection range of water absorption with high linearity and fast response [1].

- Time Domain Reflectometry (TDR)

The Principle of TDR used for moisture measurement is to transmit an electromagnetic signal down parallel electrodes of a waveguide inserted into the dielectric material under investigation. The time taken for the signal to return after reflecting off the end of the waveguide is measured. This gives a direct measure of the permittivity of the surrounding material along the length of the waveguide [19].

C. Mechanical Property Measurements

- Thermal method

The thermal conductivity of a material increases with increasing moisture content. One of the methods used to determine the thermal conductivity is to supply a probe in the material with a known heat input, and to measure the temperature rise at a fixed distance from the heat source using thermocouples or thermistors. One advantage of thermal conductivity measurements is that they are independent of the salt content of the porous body. However, thermal conductivity does depend on environmental temperature which can be compensated for, and also upon the density of the material necessitating several calibration curves for different densities of the material measured.

The thermal conductivity method suffers from the difficulty in obtaining reproducible calibration curves, and each calibration curve is only valid for a specific density of the material.IR Thermography can be used to monitor moisture content of the buildings. This method requires scanning all surface of building and comparing it to the image of interested area. The identification of the damp areas is achieved by the comparison between the temperature of the dry and moist surfaces [20]. One of the thermal techniques is a 'pad' Sensor [21]. The inventors of this sensor demonstrated a non-destructive technique for the measurement of moisture content within a material using thermal diffusion wherein heat is delivered into a surface and the resulting temperature increase is detected at a distance from the injection point. In a 'pad' sensor method the heater and temperature sensor are fixed at the surface of a thermal insulation material block (the 'pad'). The device offers the benefits of the traditional dual probe, but with the important advantage that no holes are required to be drilled in the material of interest [21].

- Vapour pressure

Measurement of the equilibrium relative humidity of air in contact with a porous body enables to deduce directly the water tension of the porous body, which can be correlated with the moisture content. The conversion of water tension values to moisture content requires an individual calibration for each type of porous material and is not a reliable procedure. Vapour pressure method requires very accurate measurements of the equilibrium relative humidity between the porous body and the surrounding air [22].

IV. Methodology

There is increase of interest in moisture content of building fabrics because of the increasing amount of mold in the properties and health problems according to this issue. The novel non-destructive EM wave sensor will be able to determine the moisture content of building fabrics and the cause of the water ingress. Also it will be used to determine the modes of building fabric failure due to membrane failure, a pipe burst and ground source. Finally, the sensor will be used to investigate the propagation of EM waves through typical structures and their interaction with concealed pipework, wiring and timber.

To be able to investigate the propagation of EM waves thorough typical structures it is essential to gain the knowledge about the modern methods of building wall's constructions. The main constructions used in this project will be walls assemblies based on bricks only, brick to brick technique, concrete to brick technique, dot and dab technique, plasterboard wooden construction plasterboard and plasterboard metal construction plasterboard.

It is important to understand the technique of measuring and analysing the electromagnetic waves propagation through typical structures and their interaction with concealed pipework, wiring and timber. At this stage of the research metal pipe, timber, plastic tube with water, wood and concrete will be used as tested objects. Also it is essential to test wall materials such as plasterboard, cork board, ceiling plasterboard and brick with the objects placed behind them. Taken data will be used to identify the characteristics of microwave signal of different materials and objects. First test will use plasterboard as a material and different objects will be placed in the back of it to observe changes of microwave signal. The results will be presented in "Preliminary Measurements" part. Undertaking design of the model and simulation of electromagnetic wave will be essential. The High Frequency Structural Simulator (HFSS) model of electromagnetic wave can be used to develop complex circuits. It integrates simulation, visualization and solid 3D modelling.

Moreover, different types of antennas will be tested at different ranges of frequencies. To identify the best set of antennas it is necessary to test antennas such as dipole, horns or patch antennas. At this stage, horn antennas will be used. One horn antenna will transmit the data and second horn antenna will receive signal reflection from the material. The frequency range used during this test is 6 GHz to 12 GHz. Specific sensor has been developed to control antennas' angles and the distance between the sensor and material. If this setup will have satisfying results, the sensor will be minimalized.

Finally, graphical user interface (GUI) has been developed in LabVIEW software to display data transmitted from the sensor. This Interface has a possibility to analyse the data and identify different objects placed behind the material. GUI is able to store historical data on hard drive.

V. Preliminary Measurements

This part of the research will provide preliminary tests and results which are presented graphically. Two horn antennas, were used to conduct the experiment, where one is a transmitter and second one is a receiver. Both antennas were connected to Marconi 6200A. Frequency was set up to range between 6GHz to 12 GHz. In this test plasterboard has been used as a material. Several objects have been placed behind the material such as metal pipe, plastic tube with water sample, brick and wood. Block diagram of experimental setup shown in Figure 2. Experimental setup is presented on Figure 3.

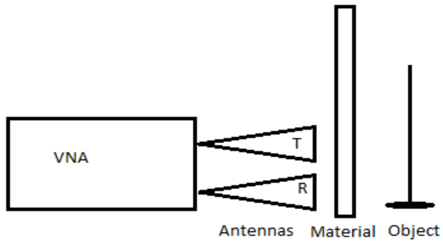

Figure 2 Block Diagram of experimental setup.

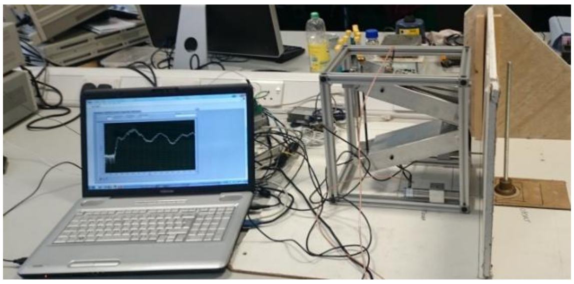

Figure 3 Experimental setup.

Results of the test are presented on Figure 4. Amplitude of the microwave signal is changing depending on object placed in the back. Data analyse allow to identify what object has been used.

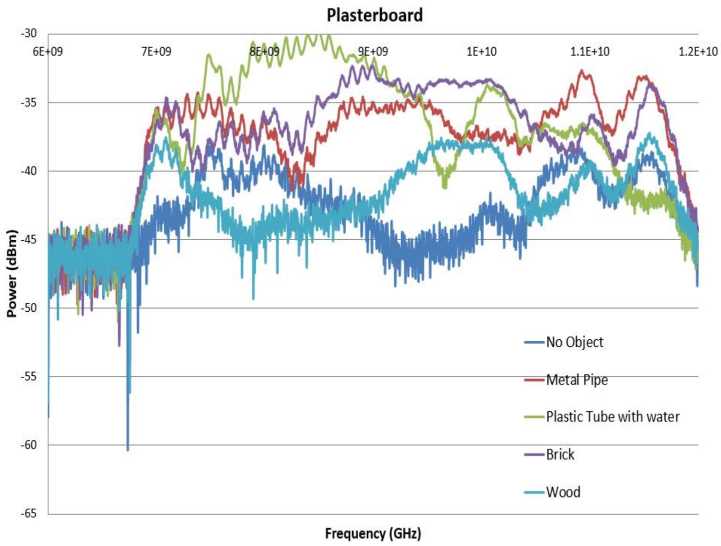

Figure 4 Comparison of objects placed behind plasterboard.

VI. Conclusion

It has been shown that microwave signal can be used to identify the different objects behind the plasterboard between 6 GHz to 12 GHz. Each object had different dielectric properties which absorb and reflect microwave energy that was captured and identified and displayed thorough the GUI.

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