Parametric Study of The Microstrip U-Slot Patch Antenna for Concrete Strength Monitoring

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***Abstract*—This paper presents a parametric study of a microwave microstrip patch antenna based using finite element modelling software to conduct simulations applied to dielectric material characterization. A probe-fed U-slot patch antenna has been designed to function as a material sensing applicator. The primary objective of this study is to provide non-destructive measurements for predicting the grades of cast concrete in the construction industry. The size, shape, and dimensions of the designed patch antenna are described in detail. The parametric study focuses on the shift in the minimum peak of return loss, $|S_{11}|$ (dB) of the antenna in relation to changes in the dielectric constant of the material under test. The modelling done on the antenna show a significant response in the $|S_{11}|$, when placed on materials selected to simulate concrete samples at different periods of the curing process, and also at different strength grades. It is known that different strength grades of concrete have varying relative permittivity and dielectric constant values. Consequently, the shift in the minimum peak of the measured $|S_{11}|$ (dB) correlates with changes in concrete strength, thus offering a simple, non-destructive, fast, and effective system for testing concrete quality.**

Keywords*—Microstrip patch antenna, non-destructive test, concrete strength, return loss, dielectric properties

I. Introduction

This paper is presenting the findings for the research and study of the use of microstrip patch antenna with U-slot for the purpose of non-destructive testing of concrete strength determination. Typically, the compressive strength of concrete is determined by physically applying a compressive force to a concrete cube using a machine until it is crushed. This load that the concrete can withstand before experiencing failure is the compressive strength value. This value can be correlated to the initial concrete-sand-aggregate-water mixture during the mixing and casting process in making the concrete. Non-destructive concrete strength testing is seen as a viable lower cost and time saving alternative in determining concrete strength as the process is faster, and does not require the physical destruction of concrete materials. However, the accuracy of non-destructive strength testing for concrete depends on the method used to obtain the strength values. In this paper, the proposed method is based on the use of the microstrip patch antenna, designed with a U-slot to achieve a better performance for the antenna return loss or its $|S_{11}|$ parameter. The purpose of this research is mainly for determining the strength of concrete commonly used for the construction industry in the local sector, thus a research into a testing method which can be carried out in the early stages of the concrete casting.

II. Literature Review

A. Non-Destructive Testing (NDT) of Concrete

There have been several types of research work and studies on the use of non-destructive testing methods on concrete based materials, such as concrete strength, moisture content, and crack detection. There are many methods for NDT concrete testing, but there are challenges with each of them; typically requiring expertise in interpretation, analysis and automation in getting the data. While no single technique has been singled out as the most effective method, the fact that most are using sensors as the NDT tool which lead to lower monitoring costs and minimizing sudden failure accidents [1]. In one study, the researchers use ultrasound method to correlate the mechanical properties of pervious concrete, with that of ultrasonic pulse velocity test. What they found is a high correlation coefficient for the properties of concrete, with values for compressive and tensile strength at 0.79 and 0.84 specifically respectively [2]. In another study on moisture content of cement based mortar, the NDT test method employs GHz dielectric resonator oscillator and horn antennas as demonstration of viability. The conclusion is that moisture content can be related to the compressive strength of concrete [3]; although establishing that relationship was not the focus of the study.

B. Permittivity and Dielectric Properties of Concrete

The use of permittivity and/or dielectric properties of concrete as a parameter to establish the relationship between their values with concrete strength has been used in several studies. In this particular study [4], ground penetrating radar

(GPR) is used to test concrete during the curing process, with the dielectric value of the material serving as the parameter to establish relationships for concrete strength, and its porosity. The findings indicate that the water content in the concrete can be correlated to the dielectric property during the curing process. Consequently, the researchers in that study published another paper [5], which is on investigating the dielectric properties of concrete in relation to the curing process. Their GPR system showed that there are other factors which may affect their testing results; namely the types of aggregate used, the environment and even electromagnetic interference, all of which do warrant further studies.

C. Microstrip Patch Antenna with U-slot

Microstrip patch antenna has the potential to be used in conjunction with a sensor-based system to determine the properties of concrete. This antenna type usually has a flat plane, can be custom designed to a desired dimension, and the its implementation can be suitably adapted to the surface of the concrete material under test. The coaxial fed microstrip patch antenna in the GHz range is one that has the connector placed on the opposite plane to the antenna patch [6]. One method to improve the performance of the microstrip patch antenna is to introduce slots to the antenna surface or the ground plane. This paper shows that a slot in the ground plane can improve its bandwidth by 32.20% [7].

In creating a cut-out slot shaped as the letter U on the antenna patch, this has been shown to improve the bandwidth; as presented in this paper [8]. There are no set design rules for the slot dimensions for the antenna, but the paper provided approximations that can be used as a starting point for designers. A combination of slots can also be introduced onto the microstrip patch antenna to improve its performance. In this study [9], the results showed a good reflection coefficient being achieved in the design presented. The authors compared their design to existing work at that time and the conclusion reached is that such design achieved improvements in frequencies from both S-band and C-band consecutively.

III. Methodology

A. Design of Microstrip Patch Antenna

The potential of using the microstrip patch antenna in the determination of concrete strength has been studied in a previous study [10]. The microstrip patch antenna can be designed in a way to be placed in close proximity to the concrete surface and its parameters are measured and recorded, as shown in Fig. 1, representing a mockup of how to measurement can be done.

Fig. 1. A mockup of placing a probe onto the concrete surface with network analyzer in the background

Through a prior modelling study, currently "in press" [11], the focus on using the permittivity values of concrete to find the correlation between the compressive strength and the return loss value has been proposed as a possible NDT method for concrete. Conventionally, it takes 28 days for concrete to be deemed fully cured. At the start of the curing process, i.e. once the concrete is casted, the permittivity of the concrete mixture is very high. When the curing process is on-going, the permittivity level is expected to decrease [12].Using a standard microstrip patch antenna, the change of permittivity can be observed to have an effect on the return loss value or $|S_{11}|$ parameter of the antenna. The design of the microstrip patch antenna is proposed to be coaxial fed, whereby the antenna feedline connection is placed on the opposite surface of the printed circuit board to the antenna side [13]. This design allows a direct surface-to-surface contact between the antenna and the concrete, suitable for conducting measurements and collecting of data.

B. Creating the U-slot

The findings of these papers [14 – 15] both showed that the performance characteristics of the microstrip patch antenna can be improved with the introduction of a U-slot in the surface of the patch, in addition to the effects caused by arm length, base length, and slot width of the U-slot. This is shown in Fig. 2. (a) Hence, the modelling and simulation here focused on using this type of antenna with U-slot for measuring the return loss of the concrete is carried out. The initial microstrip patch antenna is designed for 2.0 GHz, i.e. the lower bound frequency of the S-band microwave spectrum. The S-band frequency range is used due to the consideration of the physical antenna size and dimensions if it is to be fabricated for real-life testing and measurements later.

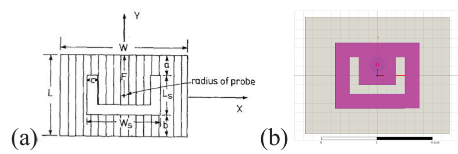

Fig. 2. (a) Referenced geometry of microstrip patch antenna with U-slot [14] (b) top view of antenna designed in Ansys HFSS modelling software

C. Modelling of Antenna with U-Slot

The antenna design shown in Fig. 2 (b) has gone through several rounds of iteration to achieve the best performance on the return loss value. The arm length, base width and slot width of the slot has been adjusted for various iterations to allow for the return loss value to be as high as possible. The final iteration has an antenna dimensions as such; W = 4.56 cm, L = 3.54 cm, F = 1.17 cm, W_S = 3.00 cm, L_S = 2.00 cm, a = b = 0.77 cm, and c = 0.5 cm. The substrate material is the standard FR4 epoxy type, with a thickness of 0.16 cm.

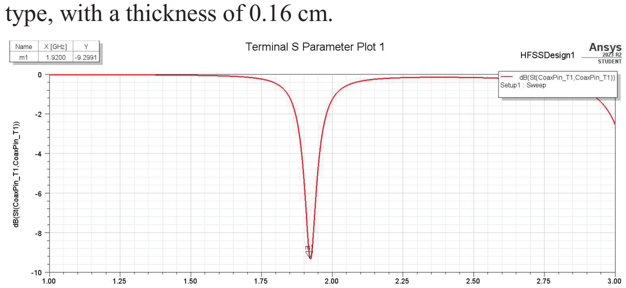

Fig. 3. Return loss response of micostrip patch antenna without U-slot

First, the standard patch antenna is created without the slot. This yields a return loss of -9.30 dB, at 1.925 GHz, indicated in Fig. 3. When a U-slot is introduced, as in Fig. 2 (b), the return loss is observed to be -30.92 dB, at 2.150 GHz, shown in Fig. 4. Thus, it can be seen now that the addition of a U-slot has a significant improvement towards the return loss of the antenna.

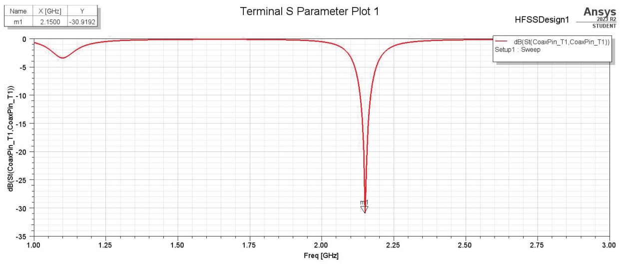

Fig. 4. Return loss response of micostrip patch antenna with U-slot

It is from similar responses above that the modelling results are obtained later, and they are to be compared across various materials under test.

D. *Modelling on Materials with Various Relative Permittivity*

Next, the antenna is modelled on various materials of various relative permittivity values using the simulation software.

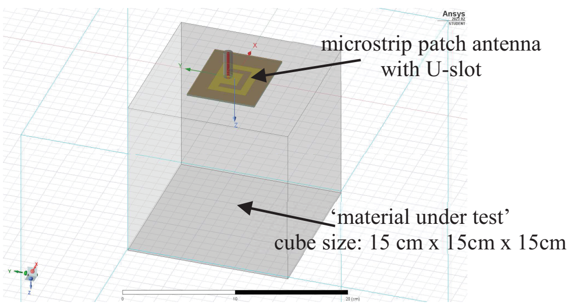

Fig. 5. Modelling the antenna placement on a cube block in Ansys HFSS

As concrete is not a material in the software library, these materials are selected as they approximate concrete permittivity varying from high to low during the curing process. The method of placing the antenna in close proximity to the material of choice has been previously conducted [10], using a conventional microstrip patch antenna without the U-slot, shown in Fig. 5. The material under test is modelled as a block with dimensions of 15 cm x 15 cm x 15 cm to represent a concrete cube that is casted in a mould in real-life. By using different materials available from the software library, the return loss values for each of them can then be obtained after every simulation run.

IV. Results and Discussions

The following are the results obtained from the modelling of the respective material. The return loss value of each material is measured using the in-built function of the modelling software. From this literature [12], concrete permittivity is seen to decrease over the curing period; starting at a high value and decreasing from day-to-day as it cures. Several types of materials have been selected from within the modelling software library as substitution for the concrete in the cube, representing the various stages of the curing process. The selected materials and results obtained are listed in TABLE I. A set of materials of similar types are chosen to reduce the differences of other properties on the outcome of the results. The materials are two types of ceramic – alumina (92% and 96%), three types of Arlon laminates (AD410, AD600 and AD1000), three types of Rogers laminate (TMM4, TMM6 and TMM10). The range of relative permittivity for the materials is from 4.0 to 10.2.

A. *Results of Modelling and Simulation*

The simulation is set to run from 1.0 GHz to 3.0 GHz, since the antenna parameters are designed for 2.0 GHz. The results of the modelling for each of the eight materials are extracted and plotted into the chart of Fig. 6, as a summary of the corresponding return loss values. Within each of the material type, it can be seen that the return loss values are found near the frequency that the antenna has been designed for, with a variation of ± 0.1 GHz.

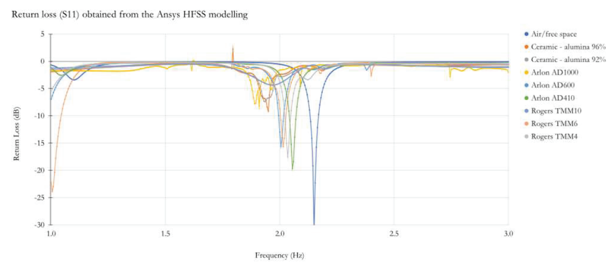

Fig. 6. Return loss (S11) obtained from the Ansys HFSS modelling

The observation is that within the material type, the difference(s) of their relative permittivity values does show that the antenna can obtain a measurable difference in the return loss value. As the antenna is placed on a block of material, the return loss value changes from that of the air/free space value. Usually, the return loss will increase. It is also noted that there is a shift in the frequency of where the return loss for each material happens at the lowest value.

TABLE I. Results of Modelling on Various Materials with Different Relative Permittivity Values

Material	Results of Modelling		
	Relative Permittivity, εr	***Return Loss, |S11| (dB)***	***Frequency, f (GHz)***
Air/free space[a]	1.0006	-30.92	2.15
Ceramic – alumina 92%	9.20	–7.44	1.94
Ceramic – alumina 96%	9.40	–9.16	1.95
Laminate – Arlon AD410	4.10	–19.64	2.06
Laminate – Arlon AD600	6.16	–15.58	2.01
Laminate – Arlon AD1000	10.20	–8.21	1.91
Laminate – Rogers TMM4	4.50	–17.51	2.04
Laminate – Rogers TMM6	6.00	–15.62	2.02
Laminate – Rogers TMM10	9.20	–4.36	1.97

[a] Air/free space serves as a baseline of the performance of the antenna, i.e. no material present

For ceramic – alumina, the 92% and the 96% has $\varepsilon_r = 9.4$ and $\varepsilon_r = 9.6$ values respectively. Their return losses are at -7.44 dB and -9.16 dB. Consequently, for the laminates, within the Arlon types, the AD410, AD600 and AD1000 have return loss values of -19.64 dB, -15.58 dB and -8.21 dB respectively. The return loss values are observed to be inversely related to the relative permittivity. Similarly, the Rogers laminates have the same trend. Their return loss values are -17.51 dB, -15.62 dB and -4.36 dB for TMM4, TMM6 and TMM10 respectively. These modelling results demonstrate that even for the same material type, the slight change of permittivity value can have a measurable effect on the return loss value.

B. *Discussion – Potential Application for Determining Concrete Strength*

The dielectric properties of materials is referred to by their relative permittivity (ε_r). The observation on the return loss values above show a pattern that indicates when relative permittivity of material changes, the return loss or S11 parameter value is also showing different values. Although the use of materials here is based on the availability in the modelling software library, the setup can be replicated in a laboratory environment in order to further explore the potential of using this antenna type to determine concrete strength. For future work, the antenna is to be fabricated and tested on actual concrete materials. The cubes can be made of concrete of different strength grades, i.e. from different mix ratios, which are to be casted, and then tested for their strength using a compressive strength machine [16].

V. Conclusions

This paper presented the results of finite element modelling on microstrip patch antenna designed in the S-band frequency for the purpose of studying its potential to be used in determining concrete strength based on the relative permittivity (ε_r) of concrete during the curing process. As concrete cures, its ε_r value is expected to decrease. The microstrip patch antenna designed with a U-slot cut-out shows potential in correlating the return loss obtained with the concrete strength. The results here show potential in designing a non-destructive test measurement system which can provide a fast and effective method for testing the quality of concrete, such as determining the compressive strength.

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