A MICROCONTROLLER BASED MEASUREMENT SYSTEM FOR PERMITTIVITY DETERMINATION USING FREE-SPACE METHOD

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ABSTRACT

A Microcontroller (μC) based free-space measurement system for the determination of permittivity of loss materials is proposed. The proposed system is easy adaptive, flexible, cheaper and dynamic. The main feature of the system is to measure only the amplitudes of transmission and reflection coefficients using free-space method and determine the permittivity online by using a microcontroller. For the determination of the permittivity, some numerical methods are applied, namely Bisection, Secant and Newton's methods. The best and suitable method among them is found Newton's method according to time consumed for determination of the permittivity and occupation less space for the code. It is shown that the determined permittivity is in good agreement with previous study that is realized with the PC based measurement system. The proposed measurement system can be used for the determination of the properties of the loss samples in industrial based applications.

I. INTRODUCTION

The interest in dielectric properties of materials has historically been associated with the design of electrical equipment, where various dielectrics are used for insulating conductors and other components of electrical equipment. During much of the past century, material research has provided many dielectric materials for application in electronics. As the use of higher and higher frequencies came into practice, new materials suitable for use in radio frequency, microwave and millimeter wave regions of the electromagnetic spectrum have been developed, and many applications begin to require the knowledge of the complex permittivity [1-9]. Therefore determining the dielectric properties of these materials has become an important task.

Lots of suitable techniques for measuring the permittivity of materials for various applications have been developed, as they were needed. In [1,2], the attenuation and phase shift were used to determine the permittivity of material. The instantaneous and non-contacting measurements of these two parameters can be realized. However, the measured value of the phase shift may differ by an integral multiple of 2π from the actual value caused by the material. To obtain the actual value of the phase shift, it is necessary to do the measurement at least twice using different thicknesses. Furthermore, it is difficult in dynamic measurement to prepare the samples with the same permittivity and different thicknesses because the sample under measure changes instantly. Therefore, the actual value of the phase shift and then the permittivity cannot, in fact, be measured instantaneously [5].

However, the phase ambiguity problem is solved by performing the measurement for two frequencies [6]. Although the determination of the dielectric properties of samples is dynamic, it requires special measurement equipments to measure the phase shift such as vector network analyzer that is very expensive.

Different methods that utilize the automatic measurement of permittivity were also developed [3-4]. These methods are often complicated, especially when accurate results are required. Moreover, they require special and expensive equipment such as a vector network analyzer (VNA) in order to perform the purpose, too.

A more recent study [5, 7-10] shows that it is possible to determine the permittivity of loss materials by using only the amplitudes of transmission and reflection coefficients. If the amplitudes of reflection and transmission coefficients are determined, the instantaneous and non-contacting measurement of the permittivity can be realized. In this case, the problem is reduced to designing a simple, adaptive and flexible but online and inexpensive automated system that can measure the amplitudes of reflection and transmission coefficients, and determine the complex permittivity of loss samples.

In addition, it is well known that microcontrollers (μCs) are very cheap, adaptive, and have easy connection with other measurement systems. That is why; we have realized the determination of the permittivity by using a general μC [11].

In this paper, a cheap, adaptive, flexible, and online μC based free-space measurement system for measuring the amplitudes of the reflection and transmission coefficients and determining the permittivity of high-loss materials is presented. Firstly, theoretical background for the permittivity determination of loss materials is analyzed. Then, description of the microcontroller based measurement system for permittivity determination using free-space method is given. Finally, the results of the measurement and the permittivity determination are shown, and expected applications are discussed.

II. THEORETICAL BACKGROUND

The typical situation for the measurement of reflection and transmission properties of cement-samples by using free-space method is shown in Figure 1.

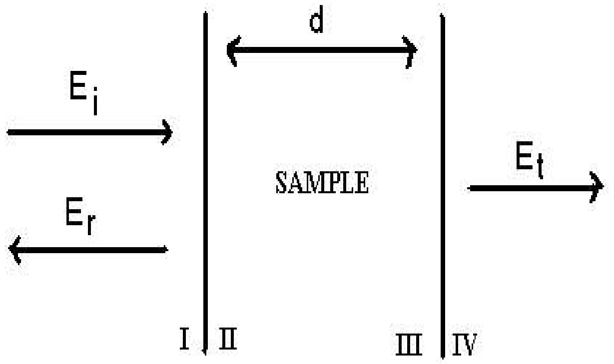

Figure 1. The typical situation for the measurement of reflection and transmission measurements by using free-space method.

The wave travels from the radiating antenna to the receiving antenna through the two media of the air and one medium of sample. Reflection occurs at the interfaces of the air-sample and multiple reflections occur between each sides of the sample.

For high-loss materials, the expressions for reflection and transmission coefficients can be simplified. We assume that the sample has large enough attenuation that the multiple reflections between the two surfaces of the sample can be neglected. By using the following assumption [8-10]

$$e^{-2\,\mathrm{Im}\left\{\sqrt{\varepsilon_{rs}}\right\}k_o d} \ll 1, \tag{1}$$

total r and t are written as

$$r = r_{12} \tag{2}$$

$$t = (1 - r_{12}{}^2)e^{-j\Theta} \tag{3}$$

where

$$\Theta = k_s d, \quad k_s = \alpha + j\beta = \frac{2\pi}{\lambda_o}\sqrt{\varepsilon_{rs}}\,. \tag{4}$$

Here, d, λ_o, r_{12} and ε_{rs} are the thickness of the sample, wavelength in free-space, the coefficient for the reflected wave from interface I-II, and relative permittivity of the sample, respectively ($\mu_r = 1$).

In experimental techniques, the amplitudes of reflection and transmission coefficients $|r|$ and $|t|$ are measured in decibels defined as

$$T = -20\log|t|, \qquad R = -20\log|r|. \tag{5}$$

From the above expressions, it is seen that R and T are functions of permittivity. That is,

$$R = R(\varepsilon', \varepsilon''), \qquad T = T(\varepsilon', \varepsilon''). \tag{6}$$

In order to find the permittivity, equations in (2) and (3) should be solved simultaneously. For the solution, let $\sqrt{\varepsilon} = a - jb$. Then the expressions for reflection and transmission coefficients become

$$r = r_{12} = \frac{1-(a-jb)}{1+(a-jb)} \quad \text{and} \quad t = \frac{4(a-jb)}{(1+a-jb)^2}. \tag{7}$$

Regarding the equations in (7), the amplitudes of reflection and transmission coefficients can be written as

$$|r| = \frac{\sqrt{(1-a)^2 + b^2}}{\sqrt{(1+a)^2 + b^2}} \tag{8}$$

and

$$|t| = \frac{4\sqrt{a^2+b^2}\,\mathrm{e}^{-bk_0 t_s}}{(1+a)^2 + b^2}. \tag{9}$$

After substituting $|r|$ in the equation of $|t|$, we get an equation that depends on only a as

$$\sqrt{2a(1-|r|^4)-(1-|r|^2)^2}$$
$$x\ \exp\left\{-k_0 t_s \sqrt{\frac{2a(1+|r|^2)}{(1-|r|^2)}-(1+a^2)}\right\}-|t|\,a=0. \qquad (10)$$

Equation (10) can be solved to find the value of a by means of an appropriate numerical method. Then, the value of b is calculated by using either (8) or (9).

Finally, the real and imaginary parts of the permittivity are then calculated by using the following simple formulas

$$\varepsilon' = a^2 - b^2 \qquad \text{and} \qquad \varepsilon'' = 2ab. \qquad (11)$$

III. MEASUREMENT SYSTEM

The schematic diagram of the measurement system is shown in Figure 2.

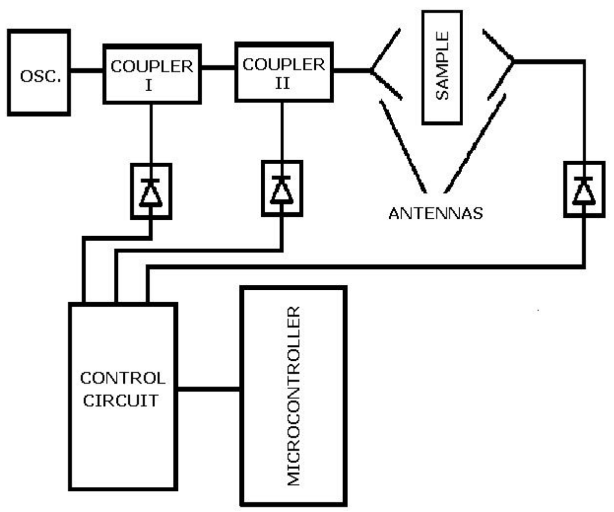

Figure 2. The schematic diagram of the measurement system.

In general, the measurement system can be divided into three parts:

A. The microwave experimental set-up
B. Electronic Circuit

A. Microwave Experimental Set-up

The microwave part of the measurement system is setup to determine the amplitudes of incident, reflected and transmitted waves as three separate parameters.

The wave from the oscillator is used to feed the system. The waves that are incident wave Pi, reflected wave Pr and transmitted wave Pt are used to measure the transmission and reflection coefficients.

As seen from the Figure 2, the sample is placed between two horn antennas. The distance between the two antennas is adjusted according to the fact that maximum amount of wave should be received by the receiving antenna when there is no sample between the antennas.

There are two directional couplers in the transmitting side. They are used for detecting the amplitudes of the incident and reflected waves. Since a directional coupler detects the electromagnetic wave in only one direction, the couplers in the transmitting side are mounted in reverse direction so that while the first one measures the incident wave, the other measures the reflected wave.

As is known from the working principle of a diode detector, it measures the amplitude of induced voltage according to square law, and the output of it can be input the electronic circuit.

B. Electronic Circuit

The schematic diagram of the electronic circuit is shown in Figure 3.

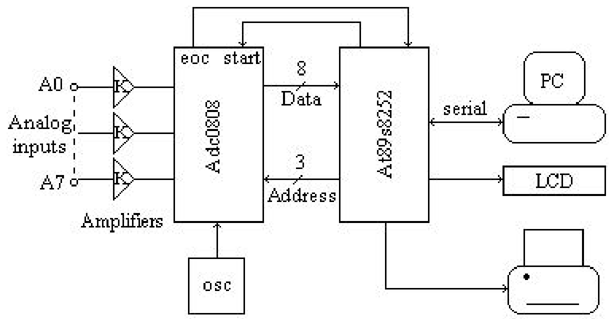

Figure 3. The schematic diagram of electronic circuit.

The main purpose of this circuit is to gather microwave measurement data and to process that data to determine the permittivity, and output the result.

Since the detector output is a DC voltage, it can easily be used as an input signal to a μC by the help of a control circuit. In paper [9], it was used analog multiplexer (MUX) and analog to digital converter (ADC) in order to enter the digital data to PC. The ADC used was ADC0804, and MUX was MUX4051. Instead of using that combination, a featured ADC converter can be used itself. The ADC used is ADC0808.

Because microwave power of the oscillator used in the microwave measurement set-up is not so high, an amplifier circuit is added to amplify the measurement data as shown in Figure 3. This amplification is realized by using a general operational amplifier (Opamp). The voltage amplification factor used for determination is 10, and can be adjustable from 1 to 100 if needed.

The voltage range of the ADC is adjusted to 0-3 Volts. This means that the output voltage level of the ADC will be between 0 and 3000mV. Thus, the resolution of the ADC is approximately 0.011V.

The purpose of the usage of the μC is to determine the permittivity without the necessity of PC.

The key advantages for using microcontroller in this system in place of a PC are that

1-) μCs are cheaper
2-) μCs are portable because they are very small
3-) μCs consume much less power
4-) μCs are applied to every interface.

The function of the process of the input data and of sending the result to peripherical devices is provided by At98s8252 μC. This μC performs the crucial calculations acquired from the 8 bit digital output data of ADC0808. The determined permittivity results can be either stored in embedded eeprom, displayed on LC display, printed on a paper by using printer, or sent to PC as shown in Figure 3. Any combination of them is possible, too. By means of embedded eeprom or printer, all the measurement data can be compared at a later time.

The programs for each method, Bisection, Secant and Newton's [10], are coded into μC. The permittivity results obtained from each method by using the μC are compared with those of the papers [7,9]. In the comparison, measured values of the amplitudes of the reflection and transmission coefficients are taken from [7]. The comparison results are given in Table 1.

Table I. The comparison of the results

Permittivity Results					
T (dB)		73.6	68.4	46.5	28.1
R (dB)		6.44	6.83	7.15	7.19
The result in the paper [7]	ε'	7.73	6.98	6.49	6.49
	ε''	1.28	1.11	0.71	0.42
The result in the paper [9]	ε'	7.76	6.97	6.51	6.49
	ε''	1.27	1.12	0.72	0.42
(μC)	ε'	7.76	6.97	6.51	6.49
	ε''	1.27	1.12	0.72	0.42

It can be seen from the comparison that the program for the determination of the complex permittivity by using μC is in good agreement with those presented in [7, 9] especially if the transmission coefficient increases, i.e. T decreases. It is concluded that the fastest and more accurate method among the applied methods is Newton's method.

IV. CONCLUSION

The possibility of the determination of the complex permittivity of the loss materials by using microcontroller (μC) based measurement system is realized. It is shown that the results of the developed programs are in good agreement with those of the other previous studies. The best and fastest method among the applied methods is Newton's method.

Because of being cheap, flexible, adaptive and dynamic features of the proposed measurement system, it can be used for the determination of the properties of the loss samples in industrial based applications. These applications can be the determination of the properties of agricultural products and cement-based structures.

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