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Application of Swept Frequency Measurements to the Embedded Modulated Scatterer Technique

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16. Abstract

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APPLICATION OF SWEPT FREQUENCY MEASUREMENTS TO THE EMBEDDED MODULATED SCATTERER TECHNIQUE

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Abstract. The embedded modulated scatterer technique has shown promise as a viable nondestructive inspection method for the evaluation of a variety of materials and composite structures. In order for the technique to be successfully applied, the scattered (reflected) response from the embedded probe must be separated from the reflections resulting from other targets. Therefore, swept-frequency measurements, in conjunction with using Fourier Transforms, are proposed as one such way to obtain an individual probe response. This investigation outlines the difficulties associated with the embedded modulated scatterer technique using a single frequency and presents the new method of incorporating swept-frequency measurements to obtain a probe response separate from other reflected signals.

Keywords: microwave nondestructive testing, materials evaluation, modulated scatterer technique

1 INTRODUCTION

Health monitoring of infrastructure is an important ongoing global concern. The existing cement-based infrastructure, along with new composite structures, is regularly subjected to loading that exceeds the original design considerations. In addition to excessive loading, environmental factors such as freeze-thaw cycles, seismic activity, and chloride ingress can also cause structural degradation. It is costly and unrealistic to repair and/or replace every existing structure. This highlights the need for a practical and cost-effective means to evaluate the condition of cement-based and composite infrastructure. Nondestructive inspection (NDI) is one such methodology that can be used for health monitoring and evaluation of cement-based and composite structures.

There are a number of nondestructive inspection techniques (e.g., thermography, ultrasonics, et.c.) that may be used to respond to some of the concerns mentioned above. However, a technique that can handle the majority of the cement-based and composite infrastructure characterization requirements has yet to be developed. To this end, this investigation focuses on the development of an embedded Modulated Scatter Technique (MST), using PIN diode-loaded dipole probes, for the evaluation of structural health and integrity.

2 BACKGROUND

At microwave frequencies, materials are described by their dielectric properties. Generally, this parameter is complex, and when referenced to free-space, is denoted by $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$. The real part is known as the relative permittivity, and describes the ability of a material to store microwave energy. The imaginary part, known as the relative loss factor, describes the ability of the material to absorb microwave energy. Dielectric properties can be related to important physical, chemical, and mechanical properties of a material. For compound materials (materials consisting of more than one constituent), dielectric mixing models can be used to determine the dielectric properties of the material from the individual dielectric properties and volumetric content of each constituent [1]. Thus, by characterizing the dielectric properties of a material, important information about the material (and its constituents) can be obtained.

The MST technique is based on illuminating a modulated probe (here, a resonant dipole loaded with a PIN diode), embedded in a material with relative dielectric properties ε_r, with an electromagnetic wave in the microwave frequency range. Probe modulation is accomplished by forward biasing the diode (high state) for a given duration of time, and then turning the diode off (low state) for an equal duration amount of time. Varying the state of the diode in this way changes the properties of the dipole antenna. By measuring the field that is scattered (reflected) from the probe, the electric field can be recreated anywhere, including the area between the source and MST probe [2]. When such a probe is embedded in a dielectric material, the measured reflected wave can be used to determine the dielectric properties of the material in which the probe is located [3].

In addition to the wave reflected from the dipole probe, other targets in the vicinity of the probe also produce reflections, one major reflection being the interface between the incident wave radiator aperture (e.g., horn antenna or open-ended waveguide) and the material under test. These reflections will be referred to as the static reflections, or the static reflection coefficient, Γ_{static}. In order to use the reflected wave from the probe to determine the dielectric properties of the material in question, the effects of Γ_{static} must be effectively and completely removed [4].

Removing the effects of Γ_{static} is problematic due to measurement limitations in addition to the fact that the probe response (Γ_{probe}) is much smaller than Γ_{static}. Γ_{static} could be measured explicitly if the probe were to be removed from the material in which it is embedded. However, the very nature of the technique renders this impossible. Thus, a method to determine Γ_{static} in the presence of the probe is necessary. This can be accomplished by implementing Time Domain Reflectometry (TDR) principles. In lieu of implementing a TDR procedure, swept-frequency measurements obtained using an Agilent 8510C Vector Network Analyzer and a Fourier Transform will be used in order to discriminate between Γ_{static} and Γ_{probe}.

3 APPROACH

Initially, calibrated reflection measurements were conducted with the probe located in air. To facilitate the measurement procedure, a dipole probe was attached to a piece of microwave absorbing foam with a thin balsa wood rod through the middle. Such an arrangement permits the probe to be placed in front of the radiating source (X-band horn) inside an anechoic chamber. The use of microwave absorbing foam helps keep the support mechanism (balsa wood rod) from affecting the measured data, and the use of an anechoic chamber reduces unwanted interference. Figure 1 shows the measurement configuration, in addition to a close-up of the dipole probe.

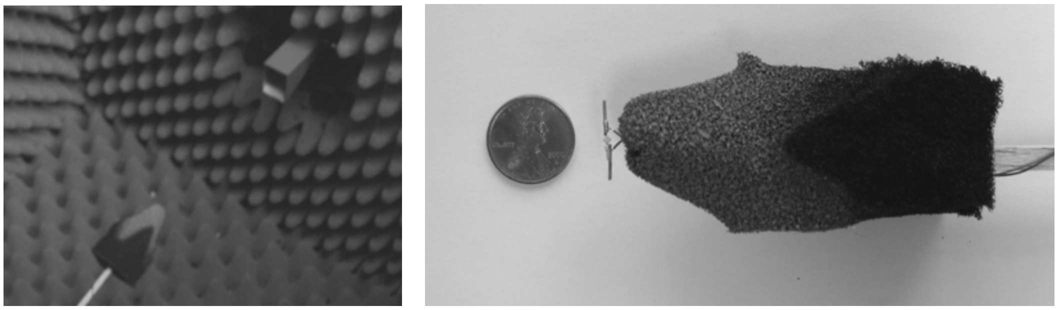

Figure 1: Measurement configuration (left), and X-band probe (right).

4 RESULTS

Using the measurement configuration and probe shown in Figure 1, calibrated reflection measurements (S_{11}) were obtained using an Agilent 8510C Vector Network Analyzer operating at 10 GHz. The probe was located 13 cm away from the horn aperture, and was aligned parallel to the incident electric field polarization, as illustrated in Figure 2.

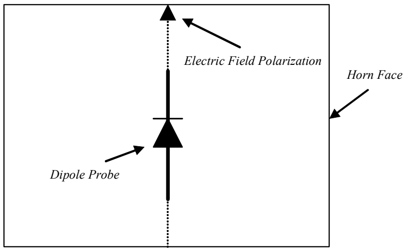

Figure 2: Geometry of probe orientation with respect to incident electric field polarization.

The probe was modulated at a rate of 2.5 kHz, and the measured results (magnitude and phase) are shown in Figure 3, along with the measurement in the absence of the probe present (i.e., static reflections). Using the ambient measurement, the static reflections were coherently subtracted from the modulated data to obtain the probe response (also shown in Figure 3). Since the ambient measurement in air is easy to acquire by simply removing the probe, obtaining the individual probe response seems to be fairly straightforward. However, should the probe be embedded in a material, removing the probe in order to measure the static (ambient) reflections is no longer an option.

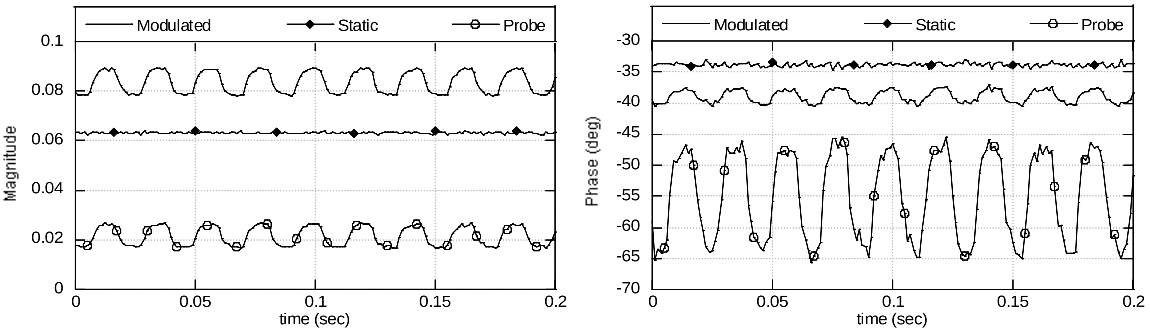

Figure 3: Results measured in an anechoic chamber at 10 GHz with a modulation rate of 2.5 kHz.

To this end, the measurement process discussed above was repeated on a probe embedded 7 cm inside a box filled with sand. The static reflections can be measured by turning the horn by 90 degrees (such that the electric field vector is orthogonal to the probe orientation and the signal from the horn will not be coupled to the probe), or by averaging a number of measurements of the material around where the probe is located. Both such methods to measure the static reflections were used and the results are shown in Figure 4, along with the modulated results.

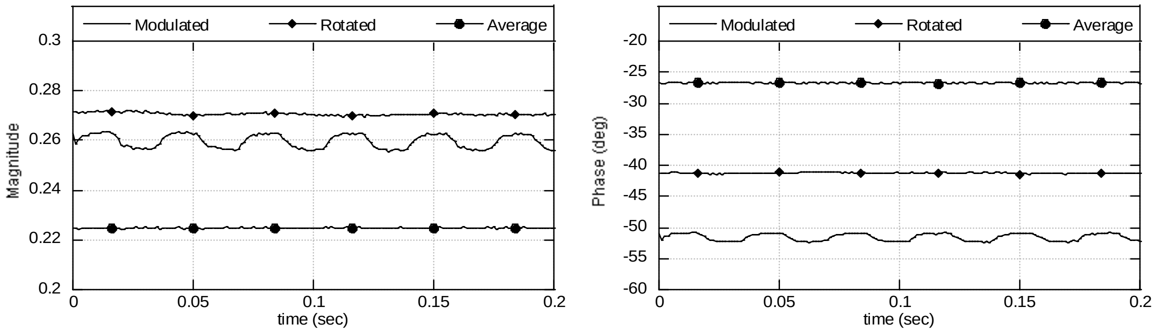

Figure 4: Results measured in sand at 10 GHz with a modulation rate of 2.5 kHz.

Upon observing Figure 4, the problem of characterizing the static reflections becomes immediately apparent when the probe cannot be physically removed. More specifically, the static reflections measured by way of rotating the source 90 degrees are not equivalent to the static reflections measured by averaging. Thus, there is no way to accurately remove the effects of the static reflections. This illustrates and emphasizes the need for a method by which the static reflections can be reliably separated from the probe response. Hence, a swept-frequency measurement procedure, in conjunction with a Fourier Transform, was developed.

In order to utilize the swept-frequency measurements to obtain the static reflections separate from the probe reflection, the relationship between the modulation rate and the sweep rate must be chosen appropriately. More specifically, this relationship must be such that one frequency sweep is complete prior to the probe changing state. This relationship is depicted in Figure 5, where the frequency sweep is shown as sweeping from frequency f_1 to frequency f_2.

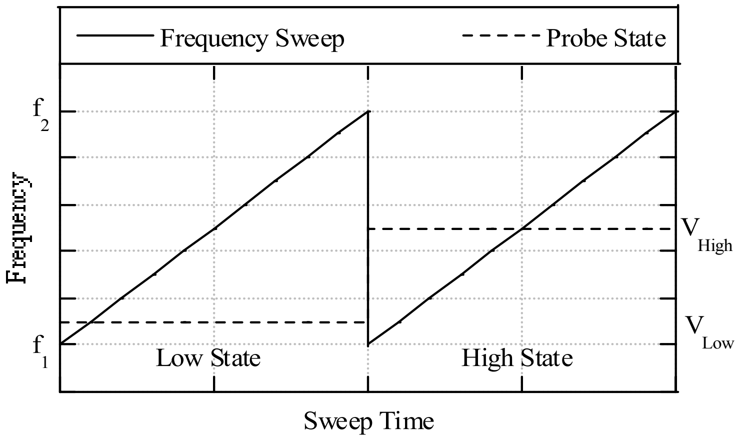

Figure 5: Relationship between sweep rate and modulation rate.

When the sweep and modulation rates are chosen as shown in Figure 5, one complete set of data per probe state is obtained. The frequency data obtained when the probe is in its high state (forward biased) will be referred to as High, and when the probe is in its low state (off) as Low. Using the probe shown above, calibrated reflection measurements were obtained by placing the probe in an anechoic chamber and sweeping the measurement frequency from 8.2 - 12. 4 GHz (X-band). The distance between the horn aperture and probe was varied from 6.5 cm to 16.5 cm, in steps of 0.5 cm. Figure 6 shows the Fourier Transform of the measured frequency data for when the probe was located 7 cm and 14 cm away from the horn aperture. The static reflections caused by the waveguide and horn apertures are also visible.

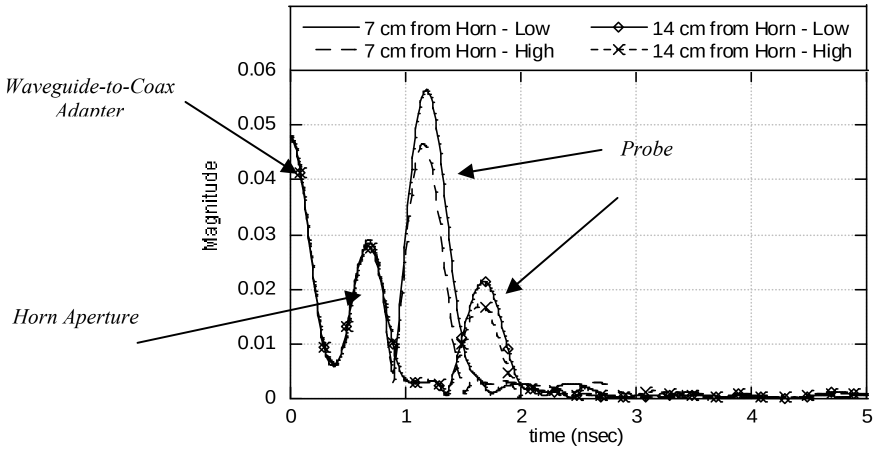

Figure 6: Time domain representation of swept-frequency measurements with the probe 7 cm and 14 cm away from the horn aperture.

A few important points can be made by examining Figure 6. First and most importantly, the static reflections caused by the waveguide-to-coax adapter and horn aperture are now explicitly available and separate from the probe response. Therefore, the probe response can be isolated by removing these static reflections via an appropriate gating process. In addition, the difference in response between the two probe states (FWD and RVS) is also evident in both sets of data. Figure 6 also indicates that the waveguide-to-coax adapter and horn aperture reflections remain the same, regardless of the probe location. Of course, as expected, the magnitude of the probe response is reduced as the probe is moved farther away from the horn aperture.

5 CONCLUSION

The modulated scatterer technique has shown promise as a viable nondestructive testing tool. However, a robust MST method requires exact knowledge of relatively strong and static reflections that subsequently need to be removed from the measured results in order to isolate the probe response. Such a requirement is not easily fulfilled if the measurements are conducted at one frequency. Thus, swept-frequency measurements, in conjunction with applying a Fourier Transform, were implemented. Making measurements in this way allows for the separation of the static reflections from the probe response. Using an appropriate separation scheme, the probe response can be used to recreate (calculate) the electric field between the probe and source (horn aperture). Subsequently, the calculated electric field can be used to determine the dielectric properties of the material in which the probe is located. The dielectric properties can be related to important material and/or structural properties. This investigation illustrated the difficulties encountered when applying the MST technique at one frequency, and also demonstrated how to incorporate swept-frequency measurements to overcome this limitation.

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