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Potential Application of the Modulated Scatterer Technique to Multilayered Material Evaluation and Health Monitoring

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Abstract *– Modulated scatterer technique (MST) is based on illuminating a small antenna, usually a dipole, loaded with a PIN diode, with an electromagnetic wave. The scattered (or reflected) wave from the probe may then be used to determine dielectric properties of the material in which the probe is located or embedded. The PIN diode is turned "on" and "off" which not only changes the impedance of the probe, but also modulates (with the same rate) the reflection from the probe. A major challenge associated with MST is detecting and distinguishing the desired probe response in the ever-present reflections from surrounding structures and materials. This challenge can be overcome by incorporating a swept-frequency method into the measurements. A swept-frequency technique allows the use of the Fourier Transform method which results in separate detection of the reflection from the probe (similar to pulsed methods). Having the ability to discriminate the probe response renders the MST technique useful for multilayer structure applications as well. The probe can be placed in a given layer of a material, and the properties of that layer can be monitored (regardless of the presence of other layers). Additionally, the probe can be placed at an interface and changes in that interface (such as disbonding) can be detected. The ratio of the reflection from a probe, between the "on" and "off" states, has been shown to be a unique technique for evaluating properties of materials. This paper presents the basis and some results of applying swept-frequency MST for inspecting layered materials.*

Keywords *– Microwave Nondestructive Testing, Modulated Scatterer Technique, Material Characterization, Life Cycle Health Monitoring*

I. INTRODUCTION

Many composite and reinforced concrete structures are approaching the end of their service lifetime and may require significant rehabilitation. Environmental impacts such as freeze/thaw cycles and salt (de-icing) applications can also cause structural degradation in reinforced concrete structures. One viable rehabilitation option is the use of fiber-reinforced polymer (FRP) composite materials. However, FRP installation quality and its long-term structural integrity remain issues of concern. Additionally, composite structures used in a variety of critical applications are complex in design and need robust and new health monitoring methodologies to overcome some of the limitations associated with standard inspection methods when trying to examine their structural integrity and properties. There are a number of nondestructive testing methods that can be used for life cycle health monitoring of existing and rehabilitated structures including microwave nondestructive testing. Modulated scatterer technique is one such microwave nondestructive testing tool that can be applied to multilayer composites and materials such as rehabilitated bridge members (i.e., deck, girder, etc.), stratified composite structures, etc.

II. BACKGROUND

In the electromagnetic regime, nonmagnetic materials are characterized by their dielectric properties. In general, the dielectric properties of a material are complex, and when referenced to free-space, are denoted as $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$. The real part, referred to as the relative permittivity, describes the ability of the material to store microwave energy. The imaginary part, referred to as the relative loss factor, describes the ability of the material to absorb microwave energy. The dielectric properties of a material, once accurately determined, can subsequently be related to its physical, mechanical, and chemical properties [1].

MST is based on illuminating a modulated probe (e.g., a resonant dipole antenna loaded with a PIN diode) with an electromagnetic wave, as shown in Fig. 1.

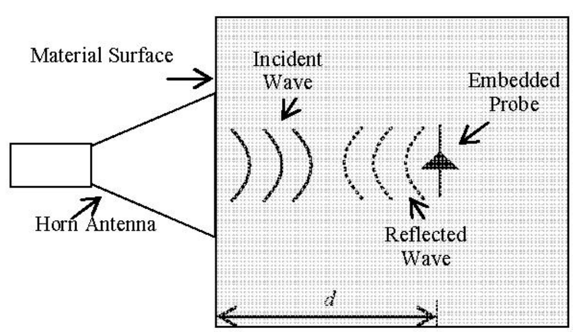


Fig. 1: Example of embedded MST.

In this case, the source of the incident electromagnetic wave is a horn antenna. The probe, placed a distance *d* from the source, is modulated by applying a forward bias to the diode (high-state) for a given amount of time, and then removing the forward bias (zero bias, low-state) for the same amount of time (i.e., modulating the probe impedance with a low frequency "on" and "off" waveform). The impedance of the dipole antenna itself is a function of the load and surrounding material. Therefore, by changing the load impedance (via modulation), the impedance of the probe is also changed. Since the impedance of the probe changes with modulation, so will the field that is reflected (scattered) by the probe. By measuring the reflected field, the electric field can be recalculated in the region between the probe and source [2]. For the case of a homogeneous material, the dielectric properties of the medium in which the probe is located can be determined from the recalculated electric field [3].

Other targets near the probe, including the interface between the source aperture and material in which the probe is located, also produce reflections. This and any other reflection from targets in the vicinity are referred to as *static* reflections, and are considered together as the static reflection coefficient, Γ_{static}. In order to use the wave scattered by the probe to determine dielectric properties of the material in which the probe is embedded, the effects of Γ_{static} must be properly and completely removed.

This embedded MST method has shown promise in determining dielectric properties of materials using only one modulation state of the probe. However, applying MST in this way suffers from serious limitations in the measurement process. That is to say, measurement parameters such as the distance *d* between the probe and source and the polarization of the probe and source must be explicitly and accurately known [3]. However, such a requirement renders the measurement technique difficult to apply in practice.

To this end, and as a viable solution to this problem, it has also been shown that dielectric properties can be determined by using the (complex) ratio of the modulated states [4]. Using the ratio (instead of one probe state) removes the dependence on many measurement parameters including probe orientation, separation distance between the source and probe, etc. [5]. These dependencies are removed since the effects of each parameter are present in both states and thus cancel out when determining the ratio of the two reflected waves. As a result, these parameters are no longer necessary for recalculation purposes. However, the effects of Γ_{static} still remain.

When operating at a single frequency, it is difficult to accurately characterize Γ_{static}. The ideal method for determining Γ_{static} would be to simply remove the probe from the material, and make a measurement. Then, Γ_{static} could be subtracted from the measured response that includes that of the probe so that the probe response alone can be obtained. For obvious reasons, this procedure is not possible or realistic in most practical applications. This issue is further complicated by the fact that the probe response is much smaller than Γ_{static}, resulting in minor deviations in the measured Γ_{static} significantly affecting the probe response obtained via subtraction.

Since embedded MST implies that the probe cannot be removed in order to characterize Γ_{static}, another option is to change the source polarization such that there is no coupling between the source signal and probe, or take a set of measurements around the location of the probe and use the average in an attempt to obtain Γ_{static}. However, the results of these two methodologies oftentimes render different characterizations of Γ_{static} (deviations in the measurement, from the mean, are on the same order of magnitude as the probe response). Hence, a process by which Γ_{static} and the probe response can be separately and accurately detected is necessary [6], which is described here.

III. APPROACH

An option for determining the probe response separately from other reflections is to implement a pulsed measurement process, similar to that of a pulse radar. Pulse radar systems transmit a narrow pulse signal. A narrow pulse is advantageous for a pulsed measurement process since the range resolution that can be obtained is related to the width of the pulse. Thus, the ability to discriminate between reflections caused by interfaces is improved when a narrow pulse is used [7].

At microwave frequencies, however, it is relatively difficult to use pulsed measurement techniques in which a very narrow pulse (corresponding to a wide-band signal) can be generated. Thus, in place of such narrow pulse measurements, swept-frequency measurements may be made. The range resolution (in air), *R*, can be calculated using Eq. 1, where *c* is the speed of light, and *B* is the bandwidth.

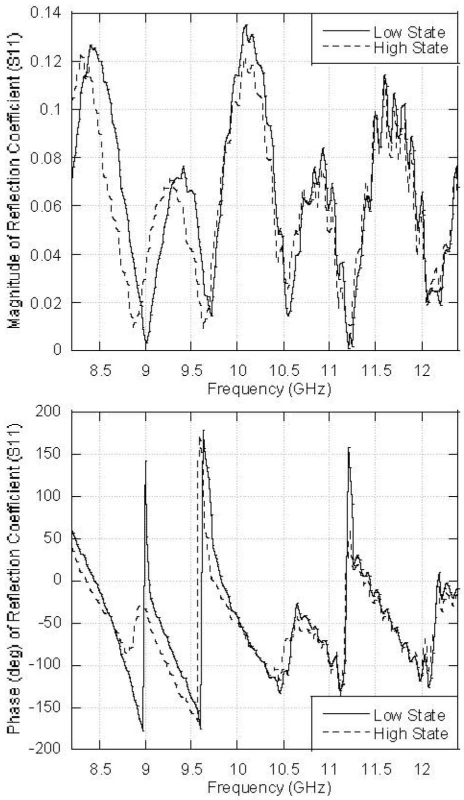
$$R = \frac{c}{2B} \tag{1}$$

For swept-frequency measurements (conducted in air) at X-band (8.2 - 12.4 GHz), *R* is approximately 3.5 cm. Due to signal processing, the realizable range resolution is greater than 3.5 cm. Practically, this means that so long as two interfaces (such as the front face of a material and the MST probe) are separated by a distance greater than 3.5 cm, the reflections from each can be separately detected.

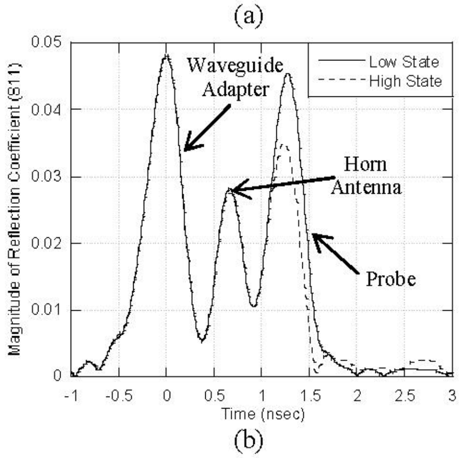
Additionally, a Fourier Transform of the data can provide a pulsed version of the data. Utilizing such a measurement and data processing scheme with MST allows for individual reflections to be detected separately, including the probe response [6].

In order to illustrate the advantages gained by incorporating a swept-frequency measurement scheme, a dipole probe was placed in a small anechoic chamber, and a horn antenna, separated from the probe by a distance of 8 cm, was connected to the calibrated port of a vector network analyzer (VNA). Swept-frequency complex reflection measurements (i.e., magnitude and phase of S_{11}) were conducted at X-band using a calibrated Agilent 8510C Vector Network Analyzer. The results are shown in Fig. 2 in both the frequency and time domains.

By examining Fig. 2a, it is evident that the detected response as a function of frequency does indeed change as a function of probe state. However, it is difficult to individually determine the probe response separate from other reflections in the frequency domain (Fig. 2a). By applying a Fourier Transform, the measurement results are translated into the time domain, as shown in Fig. 2b. As a result, each reflection is separately detectable, including the probe response.



(a)



(b)

Fig. 2: Measurement results in the a) frequency domain, and b) time domain.

IV. RESULTS

Incorporating swept-frequency measurements into this measurement approach also renders the method quite suitable for inspecting multilayer materials (i.e., a bridge rehabilitated with an FRP composite, composite structures, etc.). A multilayer structure can be modeled by placing a material of arbitrary thickness in between the source and probe, as shown in Fig. 3.

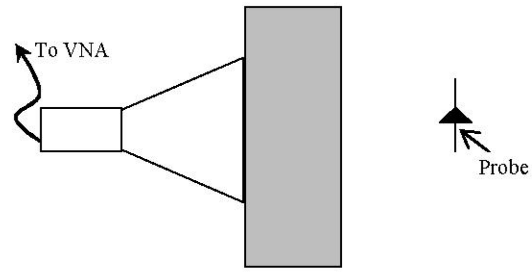
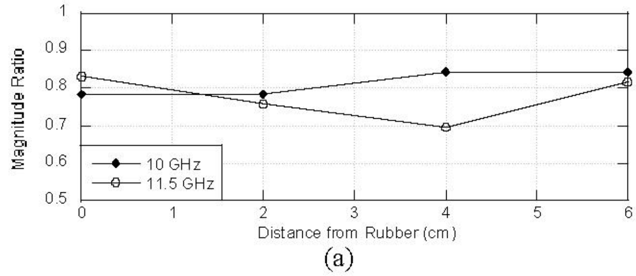


Fig. 3: Measurement setup including a front layer.

As mentioned previously, information about the material in which the probe is located can be determined via the probe response ratio. This is a result of the dependency of the probe impedance on the surrounding material. In the case of a multilayered structure, the probe response (and thus the ratio) is still dependant on the material immediately surrounding the probe. Different materials placed in front of or behind the material containing the probe should not have an effect on the probe response, given that there is sufficient separation among them. This separation distance is dictated by the range resolution of the measurement system, as mentioned previously. Consequently, if the probe response can be detected separately from all other reflections, the probe response (and thus the ratio) should be the same as the case without the front layer. As a result, the original material containing the probe can still be monitored, even if additional materials are added later.

In order to illustrate this, a multilayer structure was created by placing a ~2 cm-thick piece of rubber in front of a probe located in air. In this way, a two-layer (e.g., rubber and air) structure was created, with the second layer containing the MST probe. To obtain the ratio as a function of distance, the probe was systematically moved away from the rubber. Measurements were conducted, per each probe location, at X-band using a horn antenna in conjunction with a calibrated VNA. The ratio (as a function of distance) obtained for this multilayer structure was compared to that of a single layer case (i.e., the probe in air). The results are provided in Fig. 4 at two operating frequencies.



(a)

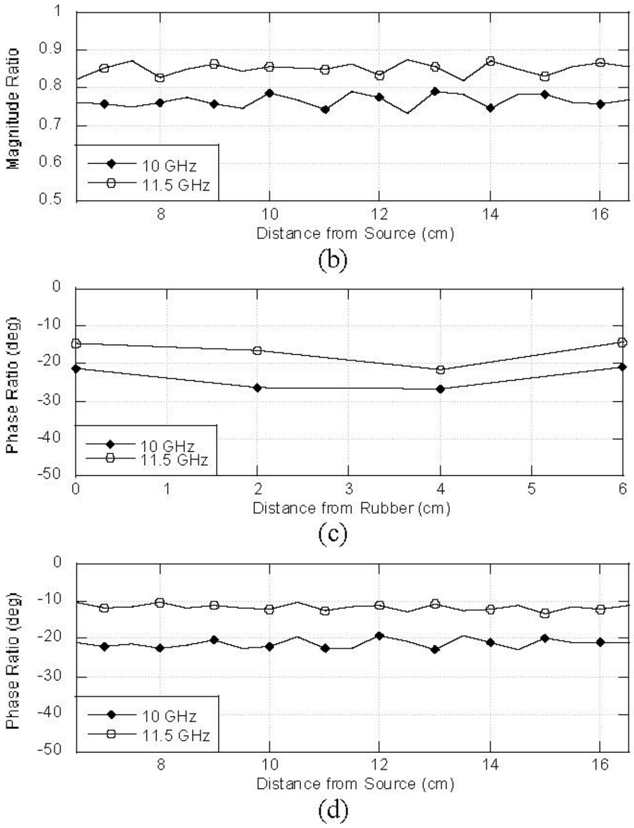


Fig. 4: Ratio with (a, c) and without (b, d) the rubber layer.

As expected, the ratio shown in both cases (with and without the rubber layer) remains fairly constant as a function of distance. In addition, the ratio of both cases is approximately equal. This is also expected, since in both cases, the probe is located in the same material (air) and its response can be isolated from other reflections. The minor deviations between the two cases are attributed to differences in the measurement configuration. More specifically, the measurements used to calculate the ratio in air (without the rubber layer) were obtained under ideal laboratory conditions. However, the measurements of the multilayer structure were conducted using a measurement configuration that may have resulted in minor inaccuracies of the probe response for that case.

An important observation can be made from the above results. The results shown in Fig. 4 indicate that the MST approach can be applied to a multilayered material, and, assuming favorable layer thicknesses and range resolution, a given layer (containing the probe) can be inspected and/or monitored, regardless of the presence of other layers. Thus, in the case of a rehabilitated bridge deck, the underlying concrete can still be monitored, even after rehabilitation (i.e., application of FRP material). This concept can be further applied to any stratified composite structure for life cycle health monitoring.

It has been established that MST can be applied for the evaluation of a given material in which it is embedded. Now, consider the evaluation of an interface between two layers. In this case, the probe response cannot be explicitly determined (separate from other reflections) since the reflection caused by the interface itself occurs at the same location in time (and distance) as the probe response. However, if the reflections from the layered structure are known prior to probe placement, these reflections can be subtracted and thus the probe response can be obtained. Such a requirement is likely not useful for practical applications of MST. Nonetheless, in a controlled setting, measurements without the probe can be obtained for proof of concept purposes.

To illustrate this concept, consider the case of a layered structure with an MST probe placed at the interface between two layers. Such a setup is depicted in Fig. 5.

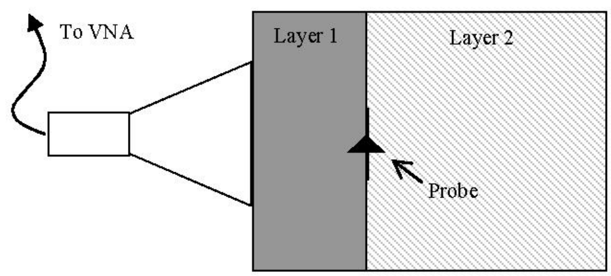


Fig. 5: Multilayer measurement setup including MST probe.

This scenario was simulated by attaching a probe to the back-side of a ~2 cm-thick piece of rubber. The second layer was air. As before, calibrated reflection measurements were obtained at X-band for cases with and without the probe. As a result, the probe response can be isolated and the ratio calculated. The results are shown (as a function of frequency) in Fig. 6. For comparison, the ratio for the probe in air is also shown in Fig. 6.

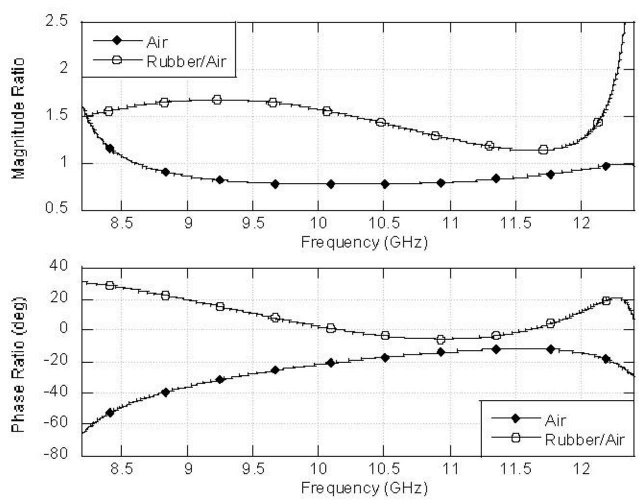


Fig. 6: Ratio as a function of frequency for a probe in air and between rubber and air.

A few important points can be seen by examining Fig. 6. First, the ratio from both cases is not constant as a function of frequency. This is expected since the ratio is a function of probe impedance, and the impedance of the probe is not independent of frequency [8]. Additionally, it should be noted that the ratio at the ends of the frequency band suffers from inaccuracies resulting from the data processing [9]. Most importantly, the ratio for when the probe is in air is markedly different from that when the probe is at a rubber/air interface. This is quite important since it illustrates the fact that the probe response is sensitive to the material surrounding it, even when the probe is located at an interface between two different materials.

V. DISCUSSION

Based on the results shown above in Fig. 6, it can be seen that another potential realm of application for MST with regards to layered structures is the field of composite structures. Detection of delaminations between composite layers (i.e., separation of layers) is important because the intended physical properties of the composite are altered when the individual composite layers are not properly bonded [10]. Placing an MST probe at an interface between layers will result in a probe response that is a function of the two material layers on either side of the probe. If a delamination should occur, the detected probe response will differ, and the presence of the delamination can be detected.

This investigation of MST and multilayer structures also leads to a unique embedded MST application. As mentioned previously, when the probe is placed at an interface between two layers, the probe response cannot be explicitly determined without having measurement data obtained prior to probe placement. However, for certain material evaluation purposes, detecting a change in the probe response is sufficient (as opposed to determining the ratio and thus having the capability to evaluate material properties). For example, consider the case of chloride ingress in cement based materials. If the goal of the measurement technique is to determine whether or not chloride has ingressed to a critical depth in a concrete bridge, then an embedded MST probe placed at that location can provide this information. Chloride ingress changes the dielectric properties of concrete. Thus, when the chloride concentration has reached a detectable intensity at the probe location, the probe response will be different than that of no chloride ingress, and the presence of chloride can be detected.

VI. CONCLUSION

Applying a swept-frequency measurement scheme in conjunction with MST allows for individual reflections to be detected, including the probe response. This is especially useful in the case of a multilayer structure since any given layer (containing an MST probe) can be evaluated, regardless of other layers (assuming the layer thickness is sufficient for the measurement system range resolution). A practical example of such a scenario may be rehabilitated bridge members.

It has also been shown that the probe response, if placed at an interface between two layers, is sensitive to both materials. This can be useful in practice for the evaluation (i.e., defect detection) of composite structures, in particular the presence of a delamination between two composite laminas. This sensitivity of the probe to the surrounding material leads to a special application of the embedded MST as well. Considering a material such as a bridge deck, it is important to be able to determine if chloride ingress has occurred to a critical depth. Placing an MST probe at such a depth will allow for detection of material changes (i.e., the presence of chloride) at that depth.

Overall, this technique has been shown to be applicable to multilayer structures for both individual layer evaluation and interface integrity, including a special application of the single layer embedded case.

REFERENCES

[1] Sihvola, A., Electromagnetic Mixing Formulas and Applications, IEE Publishing, Electromagnetic Wave Series, London, 1999.

[2] Bolomey, J.C. and F.E. Gardiol, Engineering Applications of the Modulated Scatterer Technique, Artech House, Norwood, MA, 2001.

[3] Hughes, D.T. and R. Zoughi, "A Novel Method for Determination of Dielectric Properties of Materials Using a Combined Embedded Modulated Scattering and Near-Field Microwave Techniques. Part I – Forward Model," IEEE Transactions on Instrumentation and Measurement, vol. 54, no. 6, pp. 2398-2401, Dec. 2005.

[4] Freiburger, G.S. and R. Zoughi, "Dielectric Material Characterization by Complex Ratio of Embedded Modulated Scatterer Technique States," Proc. of the IEEE Instrumentation and Measurement Technology Conference, pp. 67-71, Ottawa, Canada, May 16-19, 2005.

[5] Freiburger, G. S., Investigation into a Measurement-Parameter-Independent Application of the Modulated Scatterer Technique (MST) for Material Dielectric Property Characterization, Masters Thesis, University of Missouri-Rolla, November, 2005.

[6] Muñoz, K. and R. Zoughi, "Application of Swept Frequency Measurements to the Embedded Modulated Scatterer Technique", Proc. of the 3rd International Conference on Electromagnetic Near-Field Characterization and Imaging, pp. 176-181, St. Louis, MO, June 2007.

[7] Ulaby, F. T., R. K. Moore, and A. K. Fung, Microwave Remote Sensing - Active and Passive, Volume II – Radar Remote Sensing and Surface Scattering and Emission Theory, Chapter 7, Artech House, Norwood, MA, 1986.

[8] Strickland, B. R. and N. F. Audeh, "Diode-Loaded Dipole Antenna Modeling and Design", IEEE Transactions on Antennas and Propagation, pp. 333-337, vol. 41, no. 3, March 1993.

[9] De Porrata-Doria i Yague, R., A. B. Ibars, And L. F. Martinez, "Analysis and Reduction of the Distortions Induced by Time-Doman Filtering Techniques in Network Analyzers", IEEE Transactions on Instrumentation and Measurement, pp. 930-934, vol. 47, no. 4, August 1998.

[10] Agarwal, B. D., L. J. Broutman, and K. Chandrashekhara, Analysis and Performance of Fiber Composites, Third Edition, John Wiley & Sons, Inc., Hoboken, NJ, 2006.