Simultaneous Evaluation of Multiple Key Material Properties of Complex Stratified Structures with Large Spatial Extent

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SIMULTANEOUS EVALUATION OF MULTIPLE KEY MATERIAL PROPERTIES OF COMPLEX STRATIFIED STRUCTURES WITH LARGE SPATIAL EXTENT

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ABSTRACT. Measured complex reflection coefficient of a spatially-extended stratified composite structure, using an open-ended waveguide, can be effectively used to extract key material and geometrical characteristics of any given layer. This is accomplished using a combination of an electromagnetic model and corresponding measurement data. Previously, it was shown that one parameter can be extracted if all others are known. However, practically it is desirable to extract as many pieces of information as possible. To this end the model must be "inverted". However, there is no closed-form solution for the inverse problem, given the mathematical complexity of the forward model. Consequently, we introduce a forward-iterative optimization method to simultaneously extract several pieces of information about the structure. This method defines key unknowns and uses an analytical approach to estimate the reflection coefficient by minimizing a cost-function using conjugate gradient descent (CGD) as optimizer. This paper presents this method along with an experimental result. Information such as thickness and dielectric properties of a layer in a stratified structure is shown to be extracted concurrently.

Keywords: Conjugate gradient descent (CGD), stratified composite structure, thickness, and complex permittivity estimation, aircraft radome
PACS:

INTRODUCTION

Near-field microwave nondestructive testing (NDT) methods, using open-ended rectangular waveguide, have shown great practical utility for detecting a host of varied flaws in structures made of many different layers with different dielectric and thickness characteristics [1-4] such as an aircraft radome. Flaw detection is the first important step in investigating the health of a structure. However, for repair and maintenance considerations it is important to have a clear understanding of the geometrical (i.e., thickness) and materials properties of the detected flaw. Material properties may consist of moisture content, chloride permeation in concrete, etc. To this end, nondestructive evaluation (NDE) of the structure becomes an important issue as well. For structures that have larger spatial extent and flaws (i.e., disbond in stratified composite structure such as aircraft radome) compared to the relatively small dimensions of a probing open-ended waveguide, developed full-wave electromagnetic models may be used along with measurement data to not only detect such flaws but also give comprehensive information about the flaw's characteristics. This paper investigates the efficacy of such an approach and the results of a complex stratified composite structure being evaluated in this away.

ELECTROMAGNETIC MODELING OF STRATIFIED STRUCTURE

Open-ended rectangular waveguides are the most widely used probes for near-field microwave NDT [1]. Particularly, some techniques are developed to use open-ended rectangular waveguides for estimation of the properties (thickness or dielectric) of a layer in a stratified structure. The accuracy of these techniques to estimate thickness or dielectric properties highly depends on the applied electromagnetic model. The electromagnetic model that is used to interpret the electromagnetic wave behavior inside the stratified structure should consider the dominant as well as the higher-order modes. To this end, we use the multimodal (e.g., full-wave) solution for a rectangular waveguide radiating into stratified structures, which was developed in [5]. Using this model, one can theoretically calculate the reflection coefficient seen at the open-ended waveguide aperture radiating toward a specified stratified structure.

As mentioned earlier, although the model can be used to calculate the reflection coefficient for a defined stratified structure, in NDT applications we are also very interested in the inverse problem (i.e., estimating geometrical and materials properties from measurement data). In fact, using the method described below we need not know anything about the structure and will be able to closely estimate its properties (thickness and dielectric constant). Unfortunately, there is not any closed form formula to calculate these properties from the measured reflection coefficient. However, owing to a robust and full-wave forward model [5], we can use forward-iterative optimization techniques to explore different combinations of layer properties to achieve a close estimate between the measured and calculated reflection coefficient values. In order to use optimization techniques, first we need to define a proper cost-function and then use a suitable minimum search technique. In the following, this optimization process along with a general example will be presented in detail.

FORWARD-ITERATIVE OPTIMIZATION PROCESS

To perform the optimization, a proper cost-function definition is necessary. Based on former experience, we selected our cost-function to be the square of the distance in the complex plane between the measured reflection coefficient and calculated reflection coefficient over the entire measurement bandwidth:

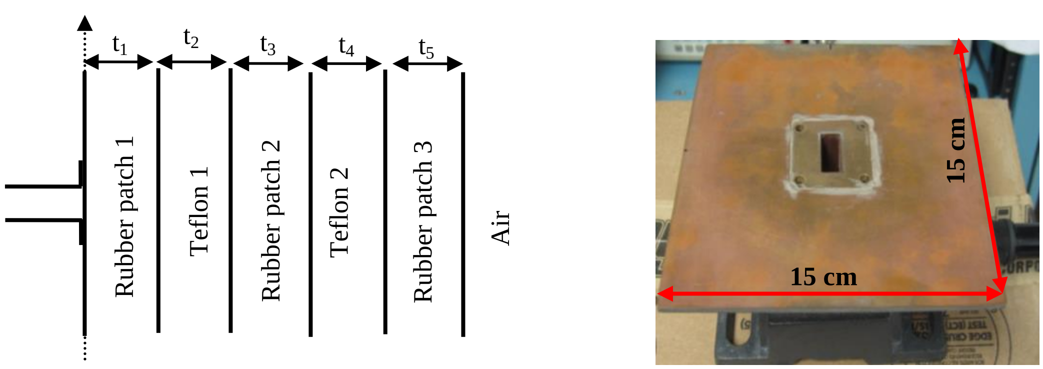
$$C(\varepsilon'_{r,n}, \varepsilon''_{r,n}, t_n) = \sum_{i=1}^{N_F} \left| \Gamma_{m,i}(\varepsilon'_{r,n}, \varepsilon''_{r,n}, t_n) - \Gamma_{c,i}(\varepsilon'_{r,n}, \varepsilon''_{r,n}, t_n) \right|^2$$

where $\varepsilon'_{r,n}$ and $\varepsilon''_{r,n}$ are real and imaginary parts of complex permittivity for n^{th} layer, respectively; t_n is the thickness of n^{th} layer; $\Gamma_{m,i}$ is the measured reflection coefficient and $\Gamma_{c,i}$ is the calculated reflection coefficient by optimizer, both at i^{th} frequency sample; and N_F is the number of frequency points that are used to calculate the reflection coefficient.

Now, we need to have an optimizer to minimize the defined cost-function by finding the optimum value for the unknowns (layers' physical and electrical properties). The conjugate gradient descent (CGD) was selected for this purpose. The CGD finds the minimum of a function using the gradient approach. It is fast, though it has the disadvantage that in some cases it may converge to a local cost-function minimum rather than the global minimum. Therefore, some care must be taken in implementing this method.

TEST AND MEASUREMENT

To show the ability of the proposed method to calculate layer properties, the following measurement setup was used, as shown in Fig. 1. The stratified sample was made of five layers of different materials stacked on top of one another. On the right side, an open-ended rectangular waveguide with an extended ground plane (Fig. 1b) was attached to a vector network analyzer (VNA) and the reflection coefficient of the sample is measured at 11 frequency points in the X-band (8.2-12.4 GHz) frequency range. Then, the measured reflection coefficient was fed to forward-iterative optimization algorithm and CGD is invoked to find the unknown parameters for layers. We considered two different cases. In the first case, we assumed that we know the thickness of the layers and only are interested in their dielectric constant values to be estimated. In the second case, we assume that the thickness and dielectric constant of the layers are all unknown. The calculated values are listed in Table I. For comparison, the measured thickness and the measured dielectric constant using loaded-waveguide technique are also presented in Table I [reference?]. The results show that the proposed algorithm is not only capable of effectively and correctly estimating the dielectric constant given the layer thicknesses, but also it can find both dielectric constant and thickness of each layer, concurrently. Moreover, the measured reflection coefficient and the calculated reflection coefficient using the estimated unknown parameters are compared for the two different cases in Figs. 2 and 3, respectively, showing very good agreement between measurement and calculation.



(a) (b)

Fig. 1. (a) Measurement sample configuration, (b) open-ended rectangular waveguide at X-band with extended ground plane.

Table I
Calculated thickness and dielectric constant for tested sample.

	Actual values		Case 1	Case 2	
Layer no.	t (mm)	ε_r	ε_r	t (mm)	ε_r
1	3.2	4.8-j0.17	4.3-j0.29	3.3	4.7 – j 0.15
2	0.38	2-j0.00	1.8-j0.00	0.36	1.7-j0.00
3	3.0	4.8-j0.17	4.7-j0.33	3.25	4.0-j0.11
4	0.51	2-j0.00	1.90-j0.00	0.67	1.98-j0.00
5	4.4	7.28-j0.27	7.7-j0.30	4.7	7.5-j0.17

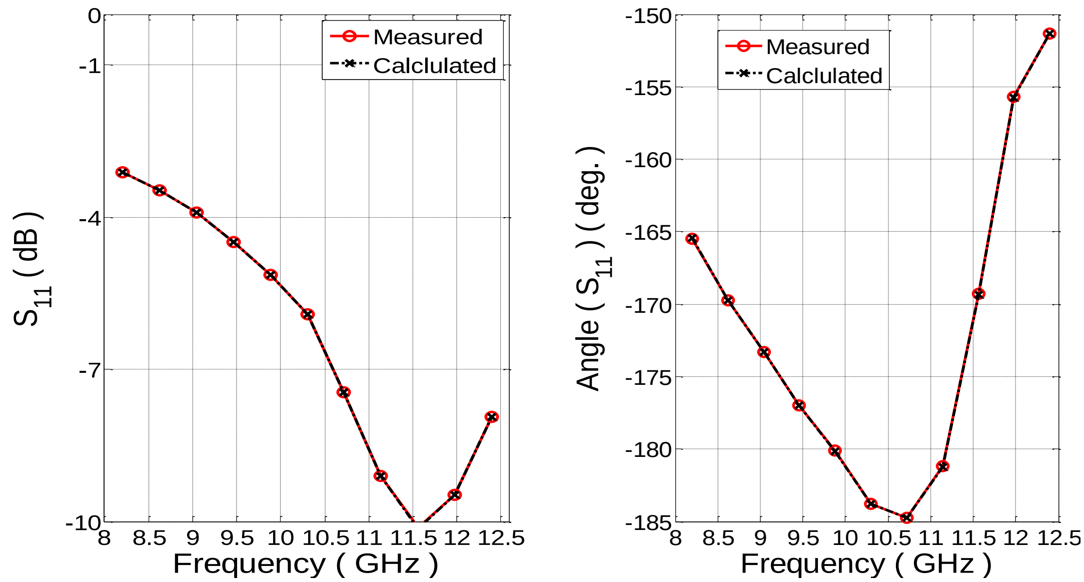


Fig. 2. Comparing measured and calculated reflection coefficient after estimating unknown parameters (case 1).

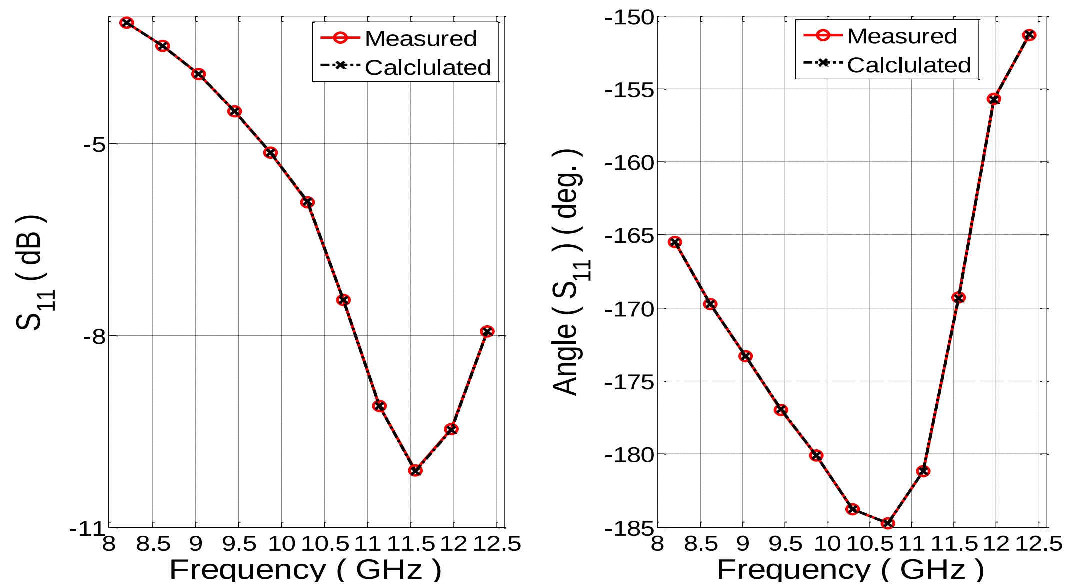


Fig. 3. Comparing measured and calculated reflection coefficient after estimating unknown parameters (case 2).

CONCLUDING REMARKS

In this paper, a forward-iterative optimization method was introduced to extract key parameters of a stratified structure concurrently. The optimization process uses a previously developed general full-wave electromagnetic model for stratified structures to calculate reflection coefficient of the structure. In comparison with formerly reported works, this method is effectively capable of closely estimating the thickness and dielectric constant of all layers concurrently. Experimental example verified the efficacy of the introduced method.

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