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Microwave Detection Optimization of Disbond in Layered Dielectrics with Varying Thickness

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***Abstract*—The detection sensitivity optimization of air disbond in layered dielectric composites, using an open-ended rectangular waveguide, is studied both theoretically and experimentally. The sensitivity of the disbond detection is strongly influenced by the proper choice of parameters such as the operating frequency and the layered composite geometry (conductor backed or terminated by an infinite half-space of air). The capability of optimizing the measurement system parameters to detect and estimate the thickness of a disbonded layer independent of some changes in the thickness of the dielectric coating is also demonstrated. The impact of the parameters influencing detection optimization is theoretically investigated and then experimentally verified.**

I. Introduction

NONCONTACT nondestructive inspection (NDI) of disbond and delaminations in stratified composite materials is of great interest in many industries such as aerospace, construction, and rubber industries. Some examples are the shuttle heat tiles, dry fuel casings, rocket boosters, honeycomb structures, and layered rubber structures such as tires, timing belts, and hoses. A typical composite is either a layered structure which is backed by a conducting plate (including a dielectric coating on top of a conducting sheet), or a stratified dielectric composite backed by free space (particularly during manufacturing, when quality control NDI may be applied). Microwave NDI techniques have demonstrated tremendous potential in such applications although they have not received the acknowledgment of other conventional NDI techniques such as ultrasonic, eddy currents, and X-rays. The ability of microwaves to penetrate inside a dielectric medium, and their sensitivity to the presence of a boundary between two dissimilar layers, make them suitable for this type of measurement. Several investigators have used open-ended waveguide sensors to study the properties of plasma layers and other stratified dielectric composites [1]–[5]. Important practical advantages of using microwaves for these type of inspections are 1) the ability to conduct the measurements in a noncontact manner, and 2) the need to access only one side of a test specimen (reflection measurements). The investigations conducted in recent years have shown that microwave nondestructive inspection techniques can achieve dielectric thickness measurement resolutions in the micrometer range at relatively low microwave frequencies [6]–[9].

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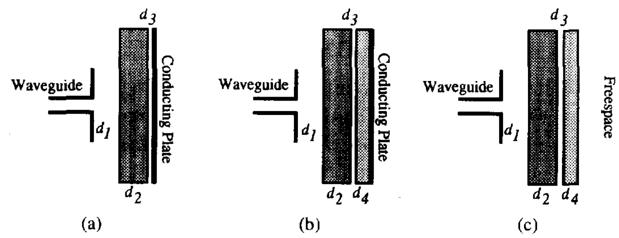

Fig. 1. Open-ended rectangular waveguide sensor radiating into different layered dielectric composite geometries: (a) a three-layer conductor backed, (b) a four-layer conductor backed, and (c) a four-layer terminated by an infinite half-space of air.

II. Considered Practical Geometries

The geometries which are most often encountered in practice are depicted in Fig. 1. Cases (a) and (b) pertain to multilayered composites backed by a conducting plate, and (c) is a multilayered composite terminated by free-space. These cases encompass important practical geometries: (a) a disbond between a coating and its metal base, (b) a disbond between dielectric layers in conductor backed composites, and (c) a disbond between dielectric layers terminated by an infinite half-space of air. In all geometries, d_1 is the standoff distance (in air) between the rectangular waveguide sensor and the second dielectric layer, which makes these measurements inherently noncontact, and d_3 is the thickness of the disbond.

III. Theoretical Simulations and Measurements

The theoretical development for an open-ended rectangular waveguide radiating into a multilayered dielectric composite has been described in [6] and will not be repeated here. The theoretical derivation is based on Fourier transform boundary matching to construct the field components in each dielectric layer. A variational expression for the terminating aperture admittance of an open-ended waveguide in an infinite ground plane is used to obtain the solution. Here, the results of this theoretical modeling are used to calculate the phase of the reflection coefficient, at the waveguide aperture, as a function of composite geometry and various measurement system parameters. This phase is more sensitive to the changes in these parameters than is the magnitude of the reflection coefficient [6]–[9]. In all calculations, the dielectric constant of the dielectric layers is taken to be $\epsilon_r = 9.55-j1.1$, which corresponds to the measured dielectric properties of carbon black resistive strips compounds. The measurement setup used to conduct the experiments for this investigation is described in [6].

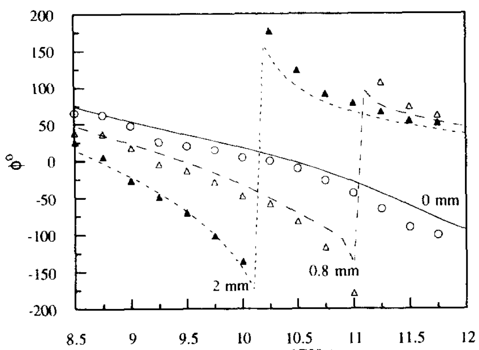

Fig. 2. Measured and calculated phase versus frequency for the geometry of Fig. 1(a) where standoff distance is $d_1 = 5.05$ mm, $d_2 = 6.33$ mm (with $\varepsilon_r = 9.55\text{-}j1.1$), and the three disbonds used are $d_3 = 0, 0.8, 2$ mm.

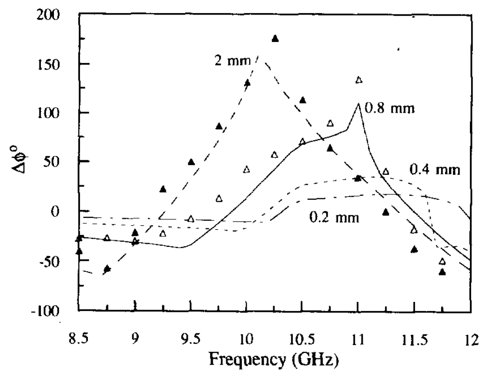

Fig. 3. Phase difference versus frequency for several disbonds (received from Fig. 2). Curves for disbonds 0.2 mm and 0.4 mm are theoretical.

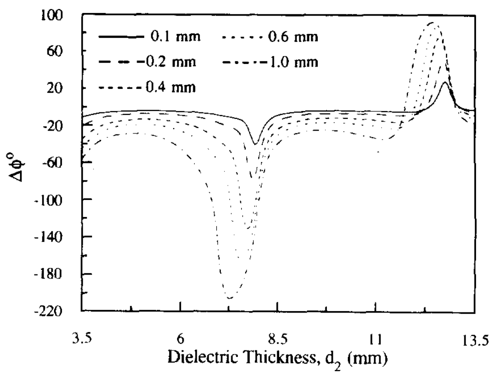

Fig. 4. Phase difference versus dielectric layer thickness d_2 for several fixed disbonds at 10 GHz.

The geometry shown in Fig. 1(a) is considered first. To illustrate the frequency dependence of the detection sensitivity for a disbond between the dielectric layer (coating) and the conductor backing, the following theoretical simulation and measurements were carried out. The phase $\phi°$ of a conductor backed resistive strip (coating) with a thickness of $d_2 = 6.33$ mm at a standoff distance of $d_1 = 5.05$ mm was calculated and measured for disbonds with thicknesses of $d_2 = 0, 0.8, 2$ mm ($d_2 = 0$ is the nondisbonded case) at X-band (Fig. 2). There is good agreement between the calculated and the measured results. The deviation of measurements from the theory is attributed to slight uncertainties associated with setting the exact disbond thicknesses during the measurements as well as slight variations in the dielectric properties of the coating with frequency. Next, the phase characteristics for each disbond are subtracted from the zero disbond phase characteristic and the phase difference $\Delta\phi°$ is plotted versus frequency (Fig. 3). The results demonstrate the measure of the disbond detection sensitivity for this particular geometry and in this frequency range. For comparison purposes, the theoretical simulations for smaller disbond thicknesses of $d_2 = 0.2$ mm and $d_2 = 0.4$ mm are also presented in Fig. 3. If we consider the more industrially prevalent cases of small disbonds (0.2–0.8 mm), then the lower part of the frequency band (8.5–10 GHz) offers very little detection sensitivity (to the disbond presence) compared to the upper part (10.5–11.5 GHz). This illustrates the importance of choosing the right operating frequency for these types of measurements.

Depending on the measurement requirements (in many industrial applications), the disbond detection and its thickness estimation may need to be conducted independently of small variations in the prescribed thickness d_2 of the coating. This may be achieved by optimizing the operating frequency. Thus, the influence of varying the coating thickness d_2 on $\Delta\phi°$ was investigated at 10 GHz. Fig. 4 shows the calculated phase difference between several disbond thicknesses and the zero disbond case versus the thickness of the coating at a fixed standoff distance of $d_1 = 5.05$ mm. At this frequency and standoff distance, there is maximum sensitivity to disbond presence in the thickness interval of 7–8 mm, and to a lesser extent in the range of 12–13 mm. It must be noted that for these intervals, despite the attractive sensitivity, a small change in the coating thickness (d_2) will not result in an accurate estimation of the disbond thickness. Conversely, in the thickness intervals of 5–6 mm and 9–11 mm, the disbond detection and its thickness estimation is nearly independent of changes in the coating thickness. For these areas, the disbond detection sensitivity is less; however, it may be adequate for most practical applications (as will be seen later). To experimentally verify these results, several measurements with different coating thicknesses ($d_2 = 5.2$, 6.33, 8.8, and 10.1 mm) were performed at 10 GHz (Fig. 5). This figure may be obtained from Fig. 4 for fixed values of d_2, while changing the disbond thickness d_3. There is good agreement between the measured (discrete points) and the theoretical (lines) results. If these lines are approximated to be straight (not true for all cases), their slope will be the measure of sensitivity to disbond detection. For example, for $d_2 = 6.33$ mm, a sensitivity of 2.8°/50 μm is calculated (for the considered range of disbond thicknesses). Such sensitivity is sufficient in many production environments. Usually higher sensitivity requirements are accompanied with production of dielectric coatings with tight thickness tolerances, and in those cases the thicknesses around maximum detection sensitivity intervals (Fig. 4) may be used.

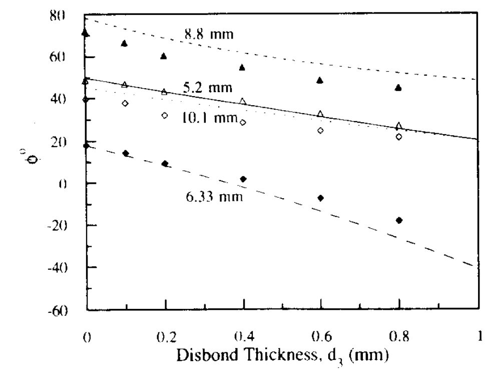

Fig. 5. Phase versus disbond thickness d_3 for several thicknesses of the dielectric (d_2 = 5.2, 6.33, 8.8, and 10.1 mm).

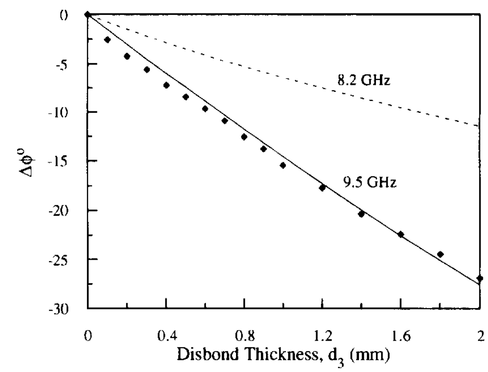

Fig. 7. Phase difference versus disbond thickness d_3 for 9.5 GHz (together with the measurement points) and 8.2 GHz (theory). The geometry used is that of Fig. 1(c), where d_1 = 5.05 mm, d_2 = 5.2 mm, and d_4 = 6.33 mm.

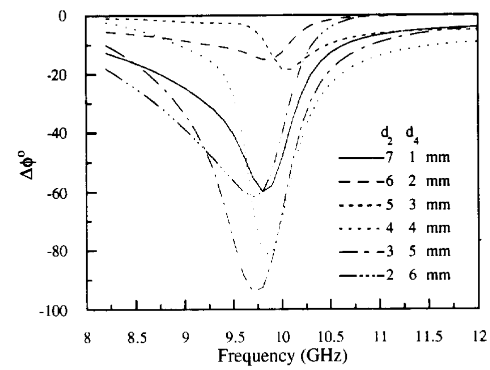

Fig. 6. Phase difference versus frequency when fixed thickness disbond (d_3 = 0.03 mm) is at different depths from the dielectric surface (d_2), keeping $d_2 + d_4$ = 8 mm.

The geometry depicted on Fig. 1(b) is investigated next. This geometry depicts layered composites in which the disbond may occur in between two dielectric layers. Fig. 6 shows $\Delta\phi^\circ$ as a function of frequency for a fixed disbond of $d_3 = 0.03$ mm and a standoff distance of $d_1 = 5.05$ mm for changing d_2 and d_4 while keeping $d_2 + d_4 = 8$ mm. For this arrangement, some frequencies are more sensitive to detecting a 0.03 mm propagating disbond (9.75 GHz) than other frequencies. Conversely, it is seen that at some depths from the surface, the disbond is more difficult to be detected (i.e., $d_2 = 6$ mm and $d_4 = 2$ mm). If the thickness of one of the dielectric layers is known (which is usually the case in practice), the measurement may be optimized to be very sensitive to the presence of disbonds at those depths.

For the geometry depicted in Fig. 1(c) (layered dielectrics terminated by infinite half-space), calculated and measured $\Delta\phi^\circ$ for a standoff distance of $d_1 = 2.5$ mm, dielectric thicknesses of $d_2 = 5.2$ mm and $d_4 = 6.33$ mm, and a varying disbond thickness at 9.5 GHz is presented in Fig. 7. In this case, the sensitivity to disbond thickness (calculated from the slope) is 1.3°/0.1 mm. Generally, better disbond detection sensitivity is achieved for the conductor backed case. The theoretical curve for 8.2 GHz demonstrates that the sensitivity is frequency dependent.

IV. Conclusions

The optimization of air disbond detection, using an open-ended rectangular waveguide sensor, is studied for layered dielectric materials terminated by conductor or infinite-half space. The theoretical results are checked with measurements for these geometries. The sensitivity of the disbond detection is dependent on the frequency of operation and the geometry of the layered dielectric composite. Depending on the measurement requirements, the disbond detection and the estimation of its thickness may be independent of the changes in the dielectric coating thickness. Conversely, the measurement system may be adjusted to achieve maximum sensitivity to disbond presence at certain depths from the surface. An array of sensors may be tuned each to be sensitive to disbonds between different layers of a multilayered composite.

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