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Disbond Thickness Evaluation Employing Multiple-Frequency Near-Field Microwave Measurements

Mohamed Abou-Khousa, *Student Member, IEEE*, and R. Zoughi, *Fellow, IEEE*

Abstract—Near-field microwave nondestructive evaluation (NDE) techniques have shown great potential for disbond detection in multilayer dielectric composite structures. The high detection capability associated with these techniques stems from the fact that near-field microwave signals are sensitive to minute variations in the dielectric properties and geometry of the medium in which they propagate. In the past, the sensitivity of the near-field microwave NDE techniques to the presence and properties of disbonds in multilayer dielectric composites has been investigated extensively. However, a quantitative disbond thickness estimation method has yet to be introduced. In this paper, we propose a maximum-likelihood (ML) disbond thickness evaluation method utilizing multiple independent measurements obtained at different frequencies. We also introduce a statistical lower limit on the thickness resolution based on the mean-squared error in thickness estimation and a given confidence interval. The effectiveness of the proposed ML method is also verified by comparing simulation results with actual measurements.

Index Terms—Maximum likelihood (ML), multiple frequency measurements, nondestructive evaluation (NDE), thickness estimation.

I. INTRODUCTION

QUANTITATIVE nondestructive evaluation (NDE) has significant utility in an array of applications. One particular application where quantitative NDE is frequently employed is in the detection and evaluation of planner disbonds/delaminations in multilayer dielectric composite structures. In this context, the NDE modality must be capable of detecting the disbond, as well as closely evaluating its thickness. To this end, near-field microwave NDE techniques utilizing open-ended rectangular waveguides (RWGs) have shown great promise [1]–[7].

Detection and evaluation of disbonds in multilayer dielectric composite structures using near-field microwave NDE techniques have been investigated extensively in the past (see [2] for example). The physical model which describes the interaction between microwave signals and a multilayer structure has been developed and validated experimentally [2], [3]. The sensitivity of the phase and magnitude of the reflection coefficient, calcu-

lated or measured at the aperture of the open-ended waveguide probe, to variations in a disbond thickness was demonstrated in [5]. In [4], a similar model-based approach was used to estimate the thickness of synthetic rubber sheets using a root finding scheme. Furthermore, optimizing the measurement sensitivity by selecting the appropriate standoff distance and frequency of operation was considered successfully in [5] and [6].

The majority of the relevant work in the literature emphasizes the potential of microwave NDE techniques for detecting various disbonds and estimating their thicknesses rather than the estimation method or algorithm itself. The estimation algorithm is mainly a functional procedure that works solely on the measured data to produce a close estimate of the disbond thickness. A robust algorithm should exhibit immunity against measurement uncertainties. Such uncertainties include system noise, intrinsic errors in determining the nominal values of the dielectric properties and thicknesses of the other layers in the layered composite structure, and the measurement system calibration errors. Moreover, the estimation algorithm should produce unique (unambiguous) estimate of the disbond thickness. These requirements are crucial for robust disbond detection using near-field microwave NDE techniques since in general, the measurement parameter, i.e., the complex reflection coefficient (Γ), is nonlinearly related to the disbond thickness [2]. The nonlinearity in the measurement parameters compounded with the presence of measurement uncertainties renders root finding techniques not feasible when considering a relatively wide range of disbond thicknesses. An accurate estimation algorithm which is capable of estimating unambiguously the disbond thickness in the presence measurement uncertainty, using near-field microwave techniques employing open-ended RWGs, has not yet been introduced [8].

To address the above need, a maximum-likelihood (ML) disbond thickness estimation algorithm utilizing multiple independent measurements obtained at different frequencies was originally proposed in [8]. In this paper, we provide the underlying derivations for the ML estimator considered therein. Furthermore, we extend the performance analysis and assessment of the ML thickness estimator beyond the preliminary investigation presented in [8]. We also introduce a statistical lower limit on the thickness resolution based on the mean-squared error (MSE) in thickness estimation and a given confidence interval. By simulations and experiments, we show that the proposed algorithm produces highly accurate estimate of the disbond thickness.

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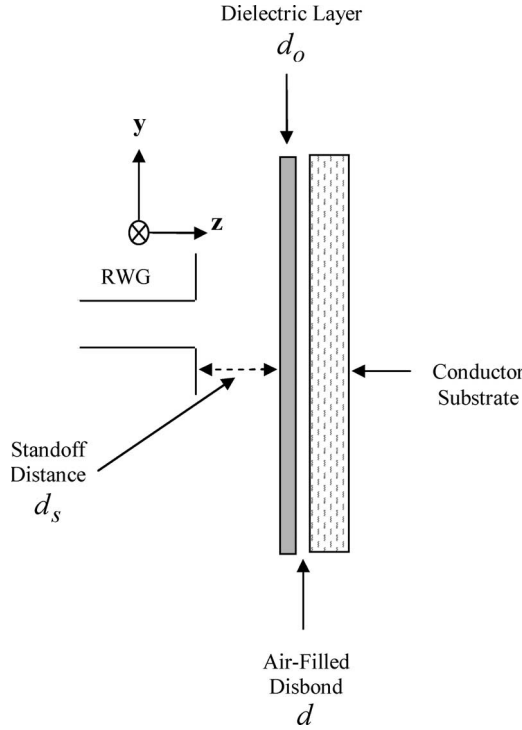


Fig. 1. Multilayer structure configuration with air-filled disbond.

II. ML THICKNESS ESTIMATION

A. Measurement Model

The multilayer dielectric composite structure configuration pertaining to this investigation is shown in Fig. 1. In particular, a generally lossy and homogeneous dielectric layer of relative permittivity ϵ_r and thickness d_o is backed by a conducting substrate and is irradiated in the near-field of an open-ended RWG. An air-filled disbond of certain thickness d may be present in between the dielectric layer and the conducting substrate. The objective is to estimate the thickness of this disbond d from the measured reflection coefficient referenced to the waveguide aperture. It is assumed that the dielectric properties, as well as the thickness of the dielectric layer are known (i.e., ϵ_r and d_o), which is true in a practical situation. We further assume a finite discrete set of disbond thicknesses to be estimated. That is, $d \in \{d_1, d_2, \dots, d_N\}$ with $d_1 = 0$ representing the no-disbond case.

As described in [8], the information sought about the disbond can be acquired upon comparing the phase and magnitude of the measured reflection coefficient to corresponding theoretical values obtained from the model [2], [3]. The standoff distance d_s , the number of frequencies, and the frequencies of operation are used as optimization parameters to maximize the estimation accuracy.

The measured complex reflection coefficient as a function of frequency, disbond thickness, and standoff distance can be written as

$$\Gamma_m(f_i, d, d_s) = \Gamma_a(f_i, d, d_s) + \gamma_i \quad (1)$$

where Γ_m is the measured complex reflection coefficient, Γ_a is the actual/theoretical complex reflection coefficient, as ex-

pected from the model [2], f_i is the i th frequency of operation $f_i \in \{f_1, f_2, \dots, f_M\}$, d is the disbond thickness to be estimated, d_s is the standoff distance, and finally, γ_i is an uncertainty term that represents the noise contaminating the i th measurement, errors in the nominal values of the dielectric property and thickness of the dielectric layer, and the measurement system calibration errors. Henceforth, this term will be collectively referred to as “noise,” and it is modeled as complex Gaussian random variable of zero mean and variance $N_0/2$ per dimension. The parameter N_0 represents the total power of the noise contaminating the measurement. The choice of a Gaussian noise model is justified here by the fact that the different sources of uncertainties are fairly independent, and consequently, their joint distribution function tends to be Gaussian, as suggested by the central limit theorem [9].

The objective of the estimation method is to produce accurate estimate of the disbond thickness based on the measured reflection coefficient. Given the measurement model in (1), the optimum estimator, in the MSE sense, would be the ML estimator [10]. The ML estimator is optimum as long as the disbond thicknesses are equally probable in practice, i.e., the probability that the disbond occurs with any thickness in the finite set $\{d_1, d_2, \dots, d_N\}$ is $1/N$. In practice, there is rarely *a priori* knowledge about the disbond thickness being of certain value with a higher probability than any other value in the range of interest. This situation, i.e., lack of knowledge, is effectively modeled by considering all the disbond thicknesses as being equally probable. Otherwise, the Bayesian estimators outperform the ML estimator [10]. Consequently, for equally probable disbond thicknesses, the ML estimator provides a lower limit on the MSE performance, which is a limit against which other estimators can be benchmarked.

B. ML Disbond Thickness Estimator

Since the noise appearing in (1) has a Gaussian distribution, the probability distribution function of the measured reflection coefficient γ_Γ at the i th frequency is given by

$$\begin{aligned} g_\Gamma(\Gamma_m(f_i, d, d_s)) \\ = \frac{1}{\pi N_0} \exp \left[-\frac{|\Gamma_m(f_i, d, d_s) - \Gamma_a(f_i, d, d_s)|^2}{N_0} \right]. \end{aligned} \quad (2)$$

Assuming that the noise samples γ_i , $i = 1, 2, \dots, M$ are independent and identically distributed, i.e., being Gaussian, the joint distribution function of the M measurements is found as

$$g_\Gamma(\mathbf{\Gamma}_m) = \frac{1}{(\pi N_0)^M} \exp \left[-\frac{M|\mathbf{\Gamma}_m - \mathbf{\Gamma}_a|^2}{N_0} \right]. \quad (3)$$

The log-likelihood function when the actual reflection Γ_a is evaluated at the n th disbond thickness $n = 1, 2, \dots, N$ is found by taking the natural logarithm of both sides of (3) [11], that is

$$\mathcal{L}(\mathbf{\Gamma}_m; d_n) = -M \ln(\pi N_0) - \frac{M}{N_0} |\mathbf{\Gamma}_m - \mathbf{\Gamma}_a|^2 \quad (4)$$

where Γ_m and Γ_a are $M \times 1$ vectors given by

$$\Gamma_m = [\Gamma_m(f_1, d, d_s) \quad \Gamma_m(f_2, d, d_s) \quad \dots \quad \Gamma_m(f_M, d, d_s)]^T$$

$$\Gamma_a = [\Gamma_a(f_1, d_n, d_s) \quad \Gamma_a(f_2, d_n, d_s) \quad \dots \quad \Gamma_a(f_M, d_n, d_s)]^T.$$

The ML estimate of the disbond thickness \hat{d} is the one which maximizes the log-likelihood function given by (4). Since the first term of the right side of (4) is independent of the disbond thickness, it is sufficient to maximize the second term only. Based on maximizing the log-likelihood, the ML estimator can be formulated as

$$\hat{d} = \min_{d_n} \arg \{Z(d_n)\} \quad (5)$$

where the ML decision metric $Z(d_i)$ is given as

$$Z(d_n) = \frac{1}{M} |\Gamma_m - \Gamma_a|^2. \quad (6)$$

The metric in (6) represents the square of the Euclidian distance between the measured and actual/simulated reflection coefficient vectors. Basically, the ML estimator searches for the disbond thickness that minimizes this distance. This search is conducted numerically over the disbond thickness range of interest.

Since the ML estimator is based on minimizing the Euclidian distance between the measured and actual/simulated reflection coefficients, estimation errors are most likely to happen when the reflection coefficients corresponding to different disbonds have close values at the frequencies $\{f_1, f_2, \dots, f_M\}$. In this case, it becomes more difficult to differentiate between the different disbond thicknesses. To reduce this possibility, the standoff distance and the set of frequencies are selected such that reflection coefficients corresponding to different disbonds are as distinct as possible. Consequently, the standoff distance and the set of frequencies that maximizes the estimation accuracy of the above estimator should be selected according to the following rule:

$$\langle F, d_s \rangle = \max_{f, d_s} \arg \{Y\} \quad (7)$$

where $F = \{f_1, f_2, \dots, f_M\}$, and

$$Y = \frac{1}{NM} \sum_{i=1}^M \sum_{\substack{n=1, k=1 \\ k \neq n}}^N |\Gamma_a(f_i, d_n, d_s) - \Gamma_a(f_i, d_k, d_s)|^2. \quad (8)$$

The optimization can be accomplished using the theoretical model [2].

To inspect a structure similar to the one described above for disbonds, the proposed estimation method can be summarized as follows.

- 1) Decide on the range of disbond thickness of interest.
- 2) Optimize the standoff distance and the set of frequencies to be used according to (7).
- 3) Measure the complex reflection coefficient at the selected standoff distance and frequencies.
- 4) Evaluate the metric in (6) for all possible disbond thicknesses.

Subsequently, the disbond thickness estimate would be the one which minimizes (6).

C. Statistical Resolution Limit

The resolution limit is one of the fundamental performance metrics needed to assess the performance of disbond estimation methods. Basically, this limit establishes the minimum change in disbond thickness that these methods can determine accurately. This is an important practical issue which demonstrates the capabilities of thickness evaluation methods in distinguishing between two close disbond thicknesses. For instance, consider the scenario where two structures are to be inspected. While the first structure has a disbond of thickness $30 \mu\text{m}$, the disbond in the second structure is $45\text{-}\mu\text{m}$ thick. If the resolution afforded by the disbond thickness estimation method is $50 \mu\text{m}$, then this method will not be able to distinguish between these two disbonds. On the other hand, the two disbonds can be easily distinguished from one another if the method is capable of disbond thickness resolution of $5 \mu\text{m}$. The resolution limit offers the needed practical insight into the capabilities of the estimation method and facilitates performance optimization, e.g., using different frequencies and standoff distances. It also constitutes a framework to compare different disbond thickness estimators. Such a resolution limit has not been introduced previously for near-field microwave-based inspection of disbonds in layered dielectric composite structures. The determination of the statistical resolution lower limit against which other estimators can be benchmarked follows.

The statistical nature of the resolution limit (as opposed to deterministic) is a direct consequence to the random variations in the measurements due to the noise. Therefore, the estimated disbond thickness is essentially a random variable with a certain mean and standard deviation. Since the noise is zero mean, the mean of the estimate is the actual disbond thickness, and its standard deviation is a function of the noise power. The mean of estimate would wander around the actual value of the disbond thickness in an interval related to the standard deviation. The confidence level that the mean of the estimate is indeed in the neighborhood of the actual disbond thickness is directly related to the way we define that neighborhood. The statistical resolution limit we introduce herein is based on defining that neighborhood as a function of the average MSE of the estimator and the confidence level in the estimate.

As previously mentioned, the ML estimator is the optimum estimator that works on the measurement model as per (1). In other words, the ML estimator is capable of providing the minimum MSE in estimating the disbond thickness. Hence, the MSE performance offered by the ML estimator is basically a lower limit on the resolution for disbond thickness estimation. The average MSE, over all possible disbonds, can be expressed as

$$\text{MSE} = \frac{1}{N} \sum_{n=1}^N |\hat{d}_n - d_n|^2 \quad (9)$$

where \hat{d}_n is the ML estimate of the n th disbond thickness d_n . For the p confidence interval of the obtained estimate $0 \leq p \leq 1$, the resolution lower limit δ can be expressed as

$$\delta = 2\alpha\sqrt{\text{MSE}} \tag{10}$$

where p is the probability that the actual disbond thickness lies within resolution limit around the estimated disbond thickness, and the value of α is determined by solving the following equation:

$$p = \frac{1}{\sqrt{2\pi}} \int_{x-\alpha}^{x+\alpha} e^{-\frac{x^2}{2}} dx \tag{11}$$

The resolution limit in (10) is derived based on the assumption that the average estimation error $(1/N) \sum_{n=1}^N (\hat{d}_n - d_n)$ is Gaussian distributed with zero mean and has a standard deviation equal to $\sqrt{\text{MSE}}$. This is a reasonable assumption since the underlying noise is Gaussian.

Basically, the resolution limit given by (10) is the confidence interval of the disbond thickness estimate as drawn from the measurements. Finer resolutions can be obtained by reducing the MSE and/or the confidence level. High confidence level indicates higher percentage (from the total number of measurement attempts) that the actual disbond thickness lies within the resolution limit around the estimated disbond thickness. Consequently, attempting to obtain finer resolution by using a low confidence level results in lower percentage that the targeted resolution is actually attained. The practical ramification of the derived resolution lower limit will be discussed in the following section.

III. NUMERICAL RESULTS

For simulation, an air disbond with a thickness varying from 0 to 0.5 mm, in steps of 0.01 mm, was considered in the X-band (8.2–12.4 GHz) frequency range and a standoff distance ranging from 0 to 5 mm in steps of 1 mm. The disbond was introduced under a dielectric slab with a thickness of 0.778 mm and a measured average complex permittivity of $6.1 - j0.37$ in the X-band [12].

The theoretical complex reflection coefficient was computed for each combination of disbond thickness d_n , standoff distance d_s , and frequency of operation using the formulation mentioned earlier [2]. Complex Gaussian noise/uncertainty with a known power N_0 was added to the computed reflection coefficients. Thereafter, the noisy reflection coefficient was presented to the proposed estimation algorithm to estimate the disbond thickness. The signal-to-noise ratio (SNR) in our simulation is defined as

$$\text{SNR} = \frac{\frac{1}{M} \sum_{i=1}^M |\Gamma_a(f_i, d, d_s)|^2}{N_0} \tag{12}$$

Starting with $M = 21$ uniformly spaced frequency points in the X-band frequency range, the first step was to find the optimum standoff distance (in the set 0, 1, ..., 5 mm) for de-

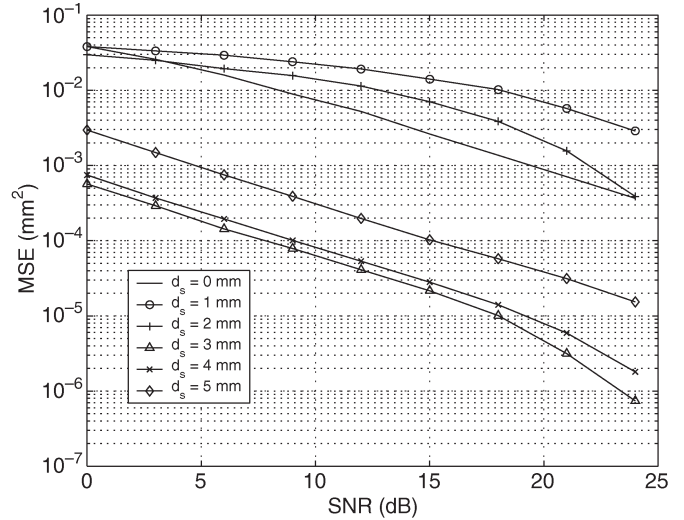


Fig. 2. MSE in estimating the thickness of the disbond as a function of SNR at different standoff distances in the X-band using 21 frequencies.

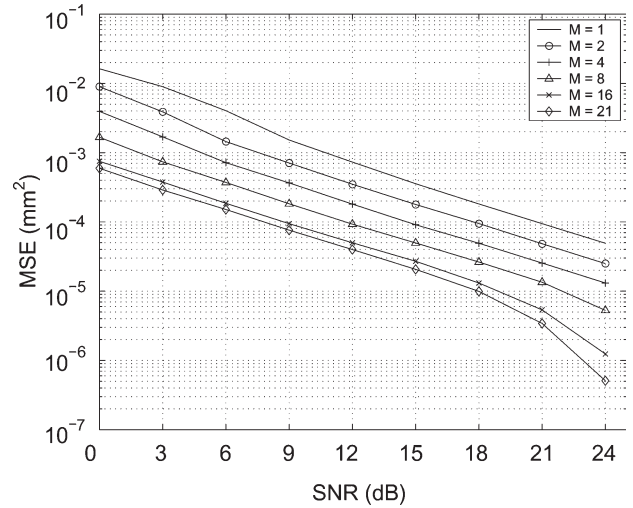


Fig. 3. MSE in estimating the thickness of the disbond as a function of the SNR with different number of X-band frequencies at $d_s = 3$ mm.

tecting the disbond and accurately estimating its thickness. The (average over all thicknesses) MSE as given by (9) was used as the figure-of-merit for this optimization. This is a rational figure of merit since the MSE is inversely proportional to selection metric in (8).

Fig. 2 shows the average MSE in estimating the disbond thickness as a function of SNR at different standoff distances. It is evident that the estimation accuracy represented by the MSE deteriorates at low SNR, as expected. This is attributed to the fact that at low SNR the noise dominates over the desired signal, i.e., the actual reflection coefficient. As shown in Fig. 2, the standoff distance of 3 mm results in the minimum MSE over the entire range of SNR considered. Hence, 3 mm is selected as the optimum standoff distance.

To illustrate the influence of the number of frequencies M on the estimator performance, the MSE with a different number of frequencies is computed when the standoff distance is set to 3 mm, as depicted in Fig. 3. It is clear that the disbond

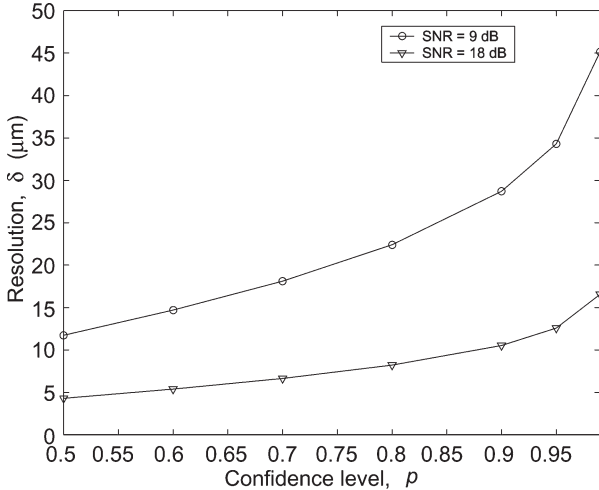


Fig. 4. Resolution lower limit as a function of the confidence level at SNR of 9 and 18 dB.

estimates become less accurate as the number of frequencies is reduced. This is expected since by reducing the number of frequencies, less averaging is performed over the measurement uncertainty. Increasing the number of frequencies beyond 16, however, provides marginal performance gain.

Based on the results obtained above, the statistical resolution lower limit is computed as a function confidence level for SNR of 9 and 18 dB with 21 frequencies, as depicted in Fig. 4. It is evident that as the SNR increases, finer resolution can be obtained at all confidence levels. This is mainly due to the fact that the MSE decreases monotonically as a function of SNR as observed in Fig. 3. It is also shown that the possible resolution attained with higher confidence level is larger compared to the lower confidence levels. Basically, the higher the confidence level, the wider the interval in which the disbond thickness would exist.

As an example, consider the 95% confidence interval (i.e., $p = 0.95$) curve. Fig. 4 shows that the minimum achievable resolution is around 35 and 13 μm at SNR of 9 and 18 dB, respectively. For SNR = 9 dB, the resolution limit implies that if the measurements are repeated 100 times and presented to the ML estimator, 95 of those times, the actual disbond thickness would be in the interval $\pm 17.5 \mu\text{m}$ centered around the produced estimate of the disbond. Practically speaking, the ML estimator, at SNR of 9 dB and 95% confidence level, will not be sensitive to a change of less than 35 μm in the disbond thickness. If lower resolution than 35 μm is needed, one has to increase the SNR in the system. For example, doubling the SNR to 18 dB yields a resolution of around 13 μm with 95% confidence level. It should be noted that, in the X-band where the maximum available bandwidth is 4.2 GHz, the far-field thickness resolution limit is around 3.6 cm in air.¹ Thus, the improvement obtained by using a near-field approach in conjunction with ML algorithm has improved the attainable resolution by a factor of 1200 for this example.

¹The far-field resolution limit with inspection bandwidth of B is $c/2B$, where c is the speed of light in air.

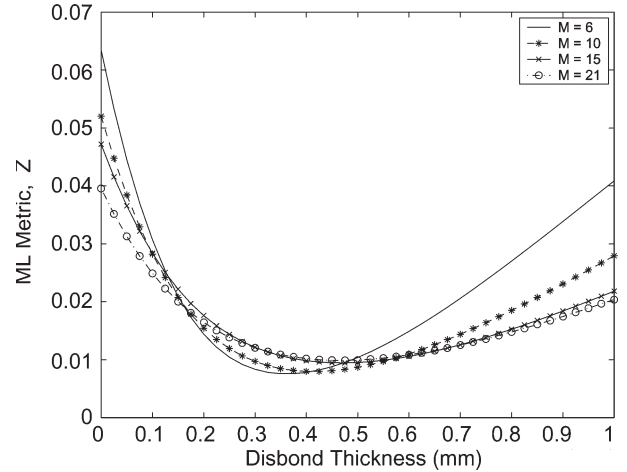


Fig. 5. ML decision metric obtained using (6) as function of disbond thickness with different number of frequencies.

IV. EXPERIMENTAL RESULTS

To demonstrate the efficacy of the proposed approach, a multilayer structure similar to the one depicted in Fig. 1 was assembled. We used synthetic rubber sheet of thickness 4.42 mm as the dielectric layer. The dielectric properties of the rubber sheet were measured as a function of frequency in the X-band using two-port loaded transmission line technique [12]. The average complex permittivity in the X-band was around $\epsilon_r = 7.2 - j0.34$. An air-filled disbond of varying thickness was introduced in between the rubber sheet and the conducting substrate by moving the substrate away from the rubber sheet using a high-precision positioning apparatus. The disbond range of interest was set to be from 0 to 1 mm. The thickness of the disbond was varied in this range with a step of 0.05 mm. Finally, the standoff distance was fixed at 3 mm, and an X-band (WR-90) open-ended waveguide probe was used to irradiate the sample. In practice, the disbond thickness is typically much smaller than the thickness of the dielectric layer. Some of the values used in this experiment, however, were for illustration purposes.

At each disbond thickness, calibrated swept frequency S_{11} measurements were conducted using an HP8510C vector network analyzer. To randomize the measurement error (especially positioning errors), the measurements were repeated six times, and for each case, we repositioned the substrate and the rubber sheet. Thereafter, the measured six-sample data were presented to the proposed algorithm to estimate the disbond thickness, and the results were averaged.

Fig. 5 shows the computed metric from (6) as a function of disbond thickness with a different number of frequencies for a disbond thickness of 0.5 mm. At each number of frequencies, the ML estimator selects a disbond which corresponds to the minimum point on the curve as indicated in (5). Table I summarizes the estimation results for this example. As shown in the table, as the number of frequency increases, better estimates of the disbond thickness are obtained. Increasing the number of frequencies beyond 15, however, did not measurably improve the performance of the algorithm.

TABLE I
ESTIMATION RESULTS FOR 0.5-mm DISBOND

M	Estimated Thickness (mm)	Percentage Error (%)
6	0.375	25
10	0.421	15.84
15	0.475	5
21	0.475	5

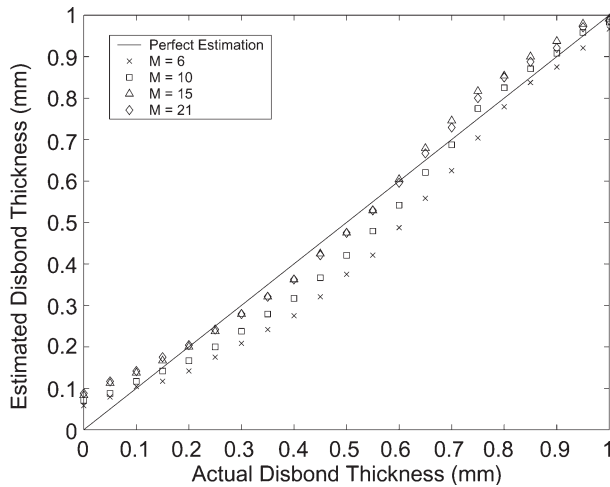


Fig. 6. Estimation results for all disbond thicknesses with different number of frequencies.

To further assess the capabilities of the proposed algorithm for providing high-resolution disbond thickness estimates, the estimates were computed for all disbonds. Fig. 6 shows the ML estimates as a function of the actual disbond thickness with different number of frequencies. A perfect estimation trace is also depicted on the graph as a performance reference. It is evident that the proposed algorithm was able to distinguish each disbond thickness independently and provide a good estimate of its thickness, particularly when large number of frequencies were used. However, the algorithm produced relatively large estimation errors when the disbond thickness was very small. This is mainly attributed to the positioning errors. Setting the disbond thickness to zero (i.e., the reference) was problematic due to the elastic nature of the rubber. Although repositioning for each sample was partially successful in randomizing the positioning errors for large disbond thicknesses (at the expense of increasing the standard deviation), it resulted in a consistent thickness bias for the zero disbond thickness case. Consequently, the ML estimator was sensitive to 50- μm change between the large disbond thicknesses (it provided very close estimates for these thicknesses), and it failed to distinguish the same 50- μm change between the zero and the 50- μm disbond thicknesses.

Other sources of inevitable measurement errors, including the uncertainty in the dielectric properties of the rubber sheet and the mismatch between the theoretical model and measurement (e.g., the theoretical model neglects the higher modes effect and assumes infinite waveguide flange), are deemed to impact the performance of the ML estimator as well.

V. CONCLUDING REMARKS

A quantitative high-resolution disbond thickness method has been presented in this paper. Based on ML approach, the proposed method utilizes multiple independent measurements obtained at different frequencies to estimate the disbond thickness. The proposed method lends itself to optimization with three degrees of freedom, namely, the standoff distance, the number of frequencies, and the frequencies of operation.

By investigating the performance of the ML estimator, we introduced a statistical lower limit on the thickness resolution offered by the proposed method. Since the ML estimator is optimum in the MSE sense, the resolution lower limit provides a framework to compare and analyze the performances of possibly different estimators.

By simulation and experiments, it was shown that the proposed estimation method provides a promising performance in detecting and evaluating the thickness of disbonds in multilayer dielectric composite structures. We remark that the proposed method might be computationally prohibited for real-time applications where the search for the disbond thickness should be conducted over wide span. In such applications, it is recommended to use efficient approximate ML estimators.

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