THICKNESS EVALUATION OF KISSING DEFECTS IN DIELECTRIC LAMINATED COMPOSITES: A HIGH-RESOLUTION MICROWAVE METHOD

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ABSTRACT

Kissing defects remain a challenge in composite laminates. A high-resolution equiphase frequency truncation (EFT) method was proposed to characterize and evaluate the thickness of kissing defects in dielectric multilayers. Theoretical calculation and simulation consistently show that truncation frequency varies linearly with the thickness. Thickness in range of micrometer and nanometer correspond to frequency difference of several MHz and kHz, respectively. In summary, this method provides a new perspective for experimental study of kissing defects in multilayer dielectric medium with a high sensitivity and high resolution.

1 INTRODUCTION

Composite laminates have been widely used in aerospace, automobile and marine industries. They are superior to their metal counterparts due to high strength-to-weight ratio, fatigue tolerance, and corrosion resistance, etc. However, in spite of these advantages, they still suffer from various defects during manufacturing and in service.

Delamination is a main type of defects in laminated composites. It degrades the compression performance and shearing property of multilayer composite structures, and eventually results in catastrophic failures. Conventional non-destructive methods, such as ultrasonic, X-ray, and thermography, etc., have been applied and approved feasible to detect this kind of defect. The basic operation principle of these methods is to characterize the difference between intact regions and defective regions. However, it is difficult for conventional methods to detect kissing defects. Kissing defects, or called zero-volume defects, is a special kind of delamination. They are physically ultrathin air-gaps with thickness in order of far less than submillimetre, which offers insufficient contrast. Therefore, kissing defects remain a critical challenge in non-destructive detection of composite laminates.

To detect kissing defects in composite laminates, some advanced and improved techniques have been proposed by enhancing detection sensitivity or expanding detectable contrast. Nonlinear ultrasonic methods verified an enhanced sensitivity based on CAN effects in detecting kissing defects [1-3]. However, it is difficult to control the generation of harmonics and side-bands, which is dependent on specimens and frequency, let alone to quantitatively judge or adjust the sensitivity and resolution. In order to expand the detection contrast, an additional small load was applied in pulse phase thermography (PPT) method [4]. While this method expands the detection contrast to a limited extent, and few investigations have been performed on quantitative evaluation of the thickness of the kissing defects without loading.
In this paper, to identify and quantitatively evaluate the thicknesses of kissing defects in dielectric composite laminates, we present a theoretical and simulation study with a sensitive adjustable super-resolution method, i.e., microwave equiphase frequency truncation (EFT) method. Kissing defects induce extremely slight shifts of phase-frequency curve, not the phase differences, but the variations of frequency truncated by a certain equiphase line are used to characterize the thicknesses of kissing defects. Super high frequency sensitivity are available due to the high frequency characteristic of microwave, which greatly magnify the values of frequency difference. Both theoretical calculations and simulation results consistently verified that frequency difference in MHz can identify kissing defects in micrometer range, and several kHz difference can characterize nanoscale kissing defects. Besides, the truncation frequency is linear to the thickness and symmetric to the depth of kissing defects in quantity, respectively. Therefore, this method provides a new perspective for microwave detection and quantitative evaluation of kissing defects with super-resolution and super high sensitivity.

2 METHODS

2.1 Theory model

Figure 1 illustrates perpendicularly incident microwaves propagating through the dielectric multilayer structures terminated by a conduct plane (Fig. 1(a)) and infinite half-space of air (Fig. 1(b)). The arrows indicate propagation directions of the travelling waves in each layer. The superscript ‘+’ and ‘-’ refer to the forward and backward travelling waves, respectively. The subscript i (i=0,1,2,...,N) denotes to the layer number.

An equivalent impedance method (EIM) is applied to solve the problem of electromagnetic waves propagation in multilayer structures. The principle of EIM is to make a multilayer structure equivalent to one layer by making impedance transformations at different interfaces. Four basic steps constitute this recursive idea: (1) To obtain the effective reflection coefficient of r_N viewed from interface N-1 by using the parameters of layer N and Eq. (10). (2) To calculate the equivalent impedance of the equivalent layer from interface N-1 to the metal terminal. (3) To derive the effective reflection coefficient at interface N-1 according to the impedance mismatch between the equivalent layer and layer N-1. (4) To conduct the iteration by reducing index i from N to 0, and finally obtain the effective reflection coefficient of the N-layer structure.

![Figure 1: The schematic of microwave propagation in dielectric multilayer structures](image)

2.2 Simulation

Figure 2 shows the HFSS simulation model of a ten-layer glass fiber reinforced plastic (GFRP) laminate with total thickness of 2.50 mm. The complex relative dielectric constant of GFRP is $\epsilon_r=4.35\times(1-j0.02)$, which is obtained by measuring a home-made sample with the transmission line method, and it is the same value used in theory calculation. A kissing air-gap layer is inserted in the central depth of the laminate. The thickness and depth of this kissing defect are set as design variables in simulation. The side surface “a” and its opposite surface are assigned “perfect E” boundary conditions, while the side surface “b” and its opposite surface are assigned “perfect H” boundary conditions. The top surface is set as “waveport” excitation and the bottom surface is defaulted as “perfect E”. Therefore, a plane wave polarized in X direction is simulated to transmit through the laminate backed by a perfect conductor. The simulation process is based on a built-in adaptive grid algorithm with the tetrahedron element.
Figure 2: HFSS simulation model of a ten-layer glass fiber reinforced plastic laminate with an inner kissing defect.

2.3 Microwave equiphase frequency truncation method

The schematic diagram of the EFT method is shown in Fig. 3, “Line1” is the phase-frequency spectrum with no defect, which provides a baseline. It is truncated by a certain equiphase line \( \phi \), and the truncation frequency is noted as \( f_S \). When a kissing delamination exists, there will be a phase shift from the baseline, as indicated by the “Line2”. Therefore, the truncation frequency varies, noted as \( f_T \). Due to the high frequency characteristic (in GHz) of microwave, high resolution of frequency can be achieved and adjusted in experiment by increasing the number of sweeping frequency points. Therefore, the EFT method is potentially a high-resolution and high-sensitivity method to characterize kissing defects.

Figure 3: Schematic diagram of the idea of equiphase frequency truncation method.
3 RESULTS AND DISCUSSION

We performed a preliminary study of kissing delaminations with different thicknesses in the central depth of the dielectric laminate in theory and simulation. Figure 4 shows the scale relationship between frequency difference and the thickness of kissing delamination.

![Figure 4: Scale relationship of frequency difference and thickness of kissing defect: theoretical calculation and simulation results.](image)

Figure 4: Scale relationship of frequency difference and thickness of kissing defect: theoretical calculation and simulation results.

Both theoretical calculation and simulation result consistently show that the order of frequency difference increases with the order of kissing defect thickness. Specifically, thickness of kissing defect in range of nanometer and micrometer correspond to frequency difference of several kHz and MHz, respectively. It can be derived that frequency sensitivity with variation of several kHz or MHz is available to characterize and detect kissing defects with thickness in nanometer range or micrometer range, respectively.

The theoretical quantitative relationship is shown in Fig. 5 (a) and (b). There is a fine linearity between the truncation frequency and the thickness of kissing defects. The truncation frequency decreases linearly with the increasing of kissing defect thickness in nanometer and micrometer range. The slopes are -3.5392 kHz/nm and -3.501 MHz/µm, respectively, which quantitatively verify that frequency difference of several kHz and MHz correspond to nanometer variation and micrometer variation, respectively.
Figure 5: The relationship of equiphase truncation frequency and thickness of kissing defects in range of μm and nm.

To analyze the linearity between frequency and thickness of kissing defect, we discuss as follows.

For generally lossy dielectric medium, the complex propagation constant is $k = \beta - j \alpha$, where $\beta$ and $\alpha$ are the phase factor and attenuation constant, respectively. On the other hand, for non-magnetic and non-conductive materials, the complex propagation constant is

$$k = \frac{2\pi f}{\mu_0 \epsilon_0} = \omega \sqrt{\mu_0 \epsilon_0 \epsilon_r},$$

(1)

where $\omega = 2\pi f$, and the complex relative dielectric constant is

$$\epsilon_r = \epsilon_r' - j \epsilon_r'' = \epsilon_r' \left(1 - j \frac{\epsilon_r''}{\epsilon_r'}\right) = \epsilon_r' (1 - j \tan \delta).$$

(2)

The expression of $\beta$ is derived as

$$\beta = 2\pi f \sqrt{\mu_0 \epsilon_0} \sqrt{\epsilon_r'/2} \left(\sqrt{1 + (\tan \delta)^2} + 1\right)^{1/2}.$$  

(3)

The dielectric term in $\beta$ has a finite value, note it as $m$, i.e.,
\[ m = \sqrt{\varepsilon_r/2} \left( \sqrt{1 + (\tan \delta)^2} + 1 \right)^{1/2}, \]  

thus the phase equation is derived as

\[ \varphi = -\beta \cdot 2d = -4\pi \sqrt{\mu_0 \varepsilon_0} f \cdot m d, \]  

where \( d \) is the thickness of the total laminate.

When a kissing defect exists, the propagation path of microwave is lengthened, resulting in a phase delay. When a certain equiphase line is used to truncate the frequency spectrums, different values of frequency will be obtained. Therefore, we can derive the relationship of truncated frequencies.

\[ \varphi = -4\pi \sqrt{\mu_0 \varepsilon_0} f_s \cdot m d = -4\pi \sqrt{\mu_0 \varepsilon_0} f_T \cdot (m d + d_0), \]  

where \( d_0 \) is the thickness of kissing defects. Therefore,

\[ f_T = f_s \cdot \frac{md}{md+d_0} = f_s \cdot \frac{1}{1+\frac{d_0}{md}} \approx f_s \cdot \left( 1 - \frac{d_0}{md} \right) = -f_s \cdot \frac{d_0}{md} \cdot d_0 - f_s, \]  

when \( d_0 \ll md \), the truncation frequency decrease linearly with the increasing of kissing defect thickness.

4 CONCLUSIONS

In summary, the thickness of kissing defects in composite laminates were quantitatively characterized and evaluated by theoretical calculation and simulation. A high-resolution equiphase frequency truncation method was proposed based on high sensitivity of microwave frequency and phase shifts induced by kissing defects. Both the theoretical calculations and simulation results consistently show that the truncation frequency decreases linearly with the increasing of the thickness of kissing defects. This method provides a new perspective for experimental study of kissing defects by microwaves. It is potential to be promoted and applied to quantitatively evaluate the thickness and thickness uniformity of thin films, coatings, and provide thickness parameters in electromagnetic inverse problems of multilayer dielectric medium.

REFERENCES


