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CALCULATION OF ULTRASONIC REFLECTION SPECTRUMS OF BONDED COMPOSITE PLATES WITH THICK ADHESIVE LAYERS

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ABSTRACT

Bonded composite plates with thick adhesive layers are widely distributed in wind turbine blades. Consequently, extracting the ultrasonic reflection spectrums of these bonded structures is of great significance in evaluating the bonding quality. On account of this, the major purpose of this paper is to develop a calculation method for obtaining ultrasonic reflection spectrums of the proposed bonded structures. First of all, according to the constitution of bonded composite plates with thick adhesive layers, the analytical model of triple-layers with "anisotropic - isotropic - anisotropic" material distribution pattern is set up. Considering the non-negligible thickness of the adhesive layers, the established model consists of two composite layers and one adhesive layer actually. Then based on the partial wave technique and the global matrix method, the displacement field and stress field in each layer are solved. Meanwhile, by combining the boundary conditions on those two interfaces between composite layer and adhesive layer integrated by spring model, the ultrasonic spectrums related to the excitation frequencies and incident angles are extracted eventually.

Keywords: ultrasonic reflection spectrum, bonded composites, thick adhesive layer, spring model

1. INTRODUCTION

Wind turbine blades are considered to be one of the most critical components in wind turbine system. Usually, blades are fabricated by glass fiber reinforced polymer (GFRP) or carbon fiber reinforced polymer (CFRP) in bonded composites with thick adhesive layers (in several millimeters). Because of the existence of thick adhesive layers, weak bonding is inevitable during either fabrication or service life [1-2]. Thus, theoretical calculation of ultrasonic reflection characteristics of bonded composite plates with thick adhesive layers is of great significance in non-destructive testing (NDT) and structural health monitoring (SHM) for wind turbine blades when ultrasonic testing technology is applied.

Because of the anisotropic properties of composites used in wind turbine blades, the process of calculating ultrasonic reflection spectrums is more complicated than in isotropic media. Rokhlin [3] presented a general algorithm for obtaining reflection and refraction coefficients of elastic waves on a plane interface between two generally anisotropic media which have arbitrary acoustic-axis. For orthotropic plates with arbitrarily-oriented fibers immersed in fluid, Nayfeh [4] deduced the ultrasonic reflection coefficients by calculating the waves' propagation characteristics. Meanwhile, when analyzing multi-layered composite plates or bonded composite plates, matrix method like transfer matrix and global matrix are used frequently. Compared to the former, global matrix method has the advantage of being more stable at high frequency-thickness products [5-8] and is well-suited to bonded composite plates with thick adhesive layers.

In addition, when dealing with bonding interfaces of bonded structures, spring model is shown to be very effective for simulating different boundary conditions [9]. Besides, in current researches, adhesive layers in bonded composite plates are always very thin compared to wavelength and are often neglected in spring models [10]. So carrying out a research on calculating of ultrasonic reflection spectrums of bonded composite plates with thick adhesive layer is necessary and practical.

2. THEORETICAL ANALYSIS METHOD

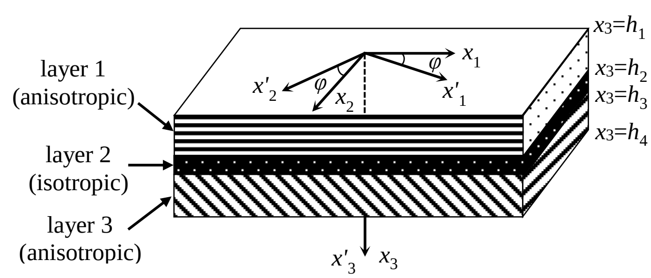

FIGURE 1: BONDED COMPOSITE PLATES WITH THICK ADHESIVE LAYER

Consider two orthotropic plates with two different fiber directions bonded together by an adhesive layer and immersed in fluid. The symmetry axes of the top layer (layer 1, as illustrated

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in **FIGURE 1**) are oriented originally along the Cartesian coordinate system $x_i = (x_1, x_2, x_3)$. The x_1-x_2 plane is chosen to coincide with the upper surface of layer 1, the axis x_3 of the global coordinate system (x_1, x_2, x_3) is normal to the whole bonded structure. Besides, with a rotation of angle φ in the x_1-x_2 plane, waves in arbitrary layer propagating along off-fiber-directions can also be analyzed.

2.1 Elastic field in each layer

In **FIGURE 1**, layer 1 and layer 3 are composite plates with anisotropic characteristics, so each of these two layers has six partial waves, a longitudinal wave (L+), a vertically polarized shear wave (SV+) and a horizontally polarized shear wave (SH+) propagating down from the top of each layer and three more waves propagating up from the bottom of each layer (L-, SV-, SH-). For layer 2 (adhesive layer) with isotropic properties, it's treated as a pseudo-anisotropic layer and partial waves inside it are studied similarly to those in layer 1 and layer 3. Applying Hooke's law, equations of motion and stress-strain relations, the displacements and stresses at anywhere in each layer as a function of the partial waves can be expressed as shown in equation (1), provided the system is linear.

$$\begin{Bmatrix} u_1^i \\ u_2^i \\ u_3^i \\ \sigma_{33}^i \\ \sigma_{13}^i \\ \sigma_{23}^i \end{Bmatrix} = \left[T^i\left(x_3\right)\right]_{6\times 6} \cdot \begin{Bmatrix} A_1^i \\ A_2^i \\ A_3^i \\ A_4^i \\ A_5^i \\ A_6^i \end{Bmatrix}, i = 1, 2, 3 \qquad (1)$$

where $u_1^i, u_2^i, u_3^i, \sigma_{33}^i, \sigma_{13}^i, \sigma_{23}^i$ are components of displacements and stress respectively, $A_1^i, A_2^i, A_3^i, A_4^i, A_5^i, A_6^i$ are displacement amplitudes of six partial waves inside each layer, and $\left[T^i\left(x_3\right)\right]$ is the characteristic matrix of each layer which is closely related to elastic constants, mess density and wavenumber.

2.2 Boundary conditions at bonding interfaces

In the bonded composite plates with thick adhesive layer as shown in **FIGURE 1,** interfaces at $x_3=h_2$ and $x_3=h_3$ are bonding areas. So in order to model the bonding states from perfectly-bonded to weakly-bonded interfaces, the spring model is utilized here.

$$\begin{cases} (u_1^2)^+ - (u_1^1)^- = \dfrac{\sigma_{13}}{K_{13}} \\ (u_2^2)^+ - (u_2^1)^- = \dfrac{\sigma_{23}}{K_{23}} \\ (u_3^2)^+ - (u_3^1)^- = \dfrac{\sigma_{33}}{K_{33}} \end{cases} \qquad (2)$$

Using one normal stiffness coefficient K_{33} and two tangential stiffness coefficients K_{13}, K_{23}, the ultrasonic wave's interaction with one given interface can be described. Take the interface at $x_3=h_2$ as an example, the displacements and stresses up and down the spring interface can be expressed as shown in equation (2), where – and + indicate the up and down side of one spring interface respectively.

2.3 Extraction of reflection coefficients

For the bonded structure immersed in fluid, at the interface of $x_3=h_1$ and $x_3=h_4$ (liquid-solid interfaces), only normal displacements and stresses are continuous. Based on the expressions of displacements and stresses of each layer shown in equation (1), combing boundary conditions at bonding interfaces and liquid-solid interfaces, a global matrix $[G(x_3)]$ assembled with individual layers and boundary conditions is formulated as:

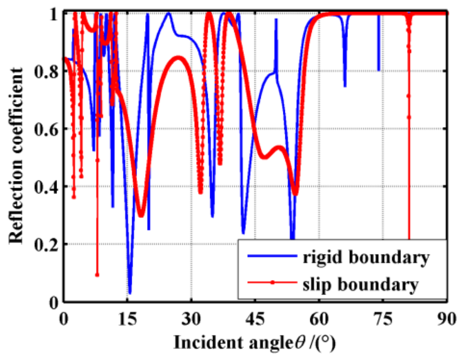
$$\left[G\left(x_3\right)_{20\times 20}\right] \cdot \begin{Bmatrix} \{A^1\} \\ \{A^2\} \\ \{A^3\} \\ \{R\} \end{Bmatrix} = \{0\} \qquad (3)$$

where $\{A^1\}$, $\{A^2\}$, $\{A^3\}$ are abbreviated forms of the displacement amplitudes of six partial waves in each layer, and $\{R\}$ are reflection coefficients. By solving the implicit matrix equation (3), ultrasonic reflection coefficients can be extracted, when excitation frequency or incident angle varies.

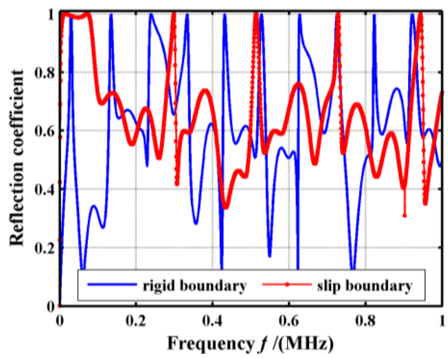
3. CALCULATION RESULTS AND DISCUSSION

Numerical examples for calculating ultrasonic reflection spectrums of bonded composite plates with thick adhesive layers are presented in order to verify and validate the mentioned procedure. Here T300/914 composite is selected with the following material properties: ρ = 1.56g/cm^3, C_{11} = 143.8, C_{22} = C_{33} = 13.3, C_{23} = 6.5, C_{12} = C_{13} = 6.2, C_{44} = 3.6, C_{55} = C_{66} = 5.7 (GPa). It should be noted that layer 1 and layer 3 in these routines are all T300/914 plates, but just with different fiber orientations. Adhesive layer here is epoxy layer and with the following material properties: ρ = 1.17g/cm^3, C_{11} = C_{22} = C_{33} = 7.9701, C_{23} = C_{12} = C_{13} = 5.1388, C_{44} = C_{55} = C_{66} = 1.4157 (GPa). Thickness of each layer are 10mm, 3mm, 10mm respectively for layer 1, layer 2 and layer 3.

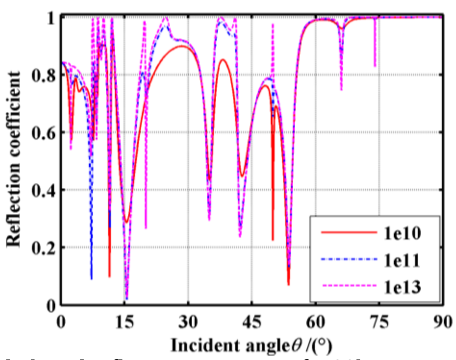
By varying normal stiffness coefficient K_{33} or tangential stiffness coefficients K_{13}, K_{23} at interface of $x_3=h_2$ or $x_3=h_3$, ultrasonic reflection spectrums relating excitation frequencies and incident angles of perfectly-bonded and weakly-bonded structures can be extracted numerically. Here, K_{33} is kept as infinity and K_{13}, K_{23} are varied equally. As shown in **FIGURE 2** (a) and (b), rigid (perfectly-bonded) and slip boundaries at $x_3=h_2$ are considered. While in **FIGURE 2** (c) and (d), weakly-bonded interface with different bonding qualities at $x_3=h_2$ are involved. Actually, both interfaces at $x_3=h_2$ and $x_3=h_3$ can all be modeled by spring stiffness, and this procedure is just the same as the method mentioned above.



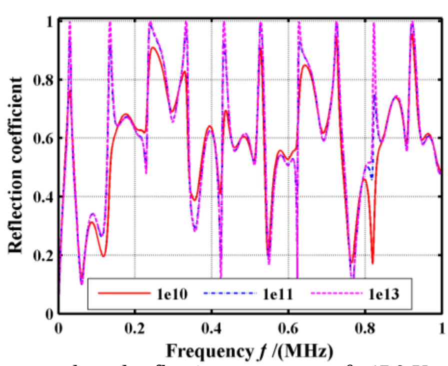
(a) angle-based reflection spectrums, f=200kHz



(b) frequency-based reflection spectrums, θ=45 º



(c) angle-based reflection spectrums, f=200kHz, $K_{13}=K_{23}=10^{10}$, 10^{11} and 10^{13}N/m^3, $K_{33}=\infty$



(d) frequency-based reflection spectrums, θ=45 º, $K_{13}=K_{23}=10^{10}$, 10^{11} and 10^{13}N/m^3, $K_{33}=\infty$

FIGURE 2: NUMERCIAL RESULTS OF ULTRASONIC REFLECTION SPECTRUMS.

4. CONCLUSION

In this paper, the ultrasonic reflection spectrums of bonded composite plates with thick adhesive layers are calculated based on partial wave analysis, global matrix method and spring model. It should be noted that the proposed method is not only suited to bonded-orthotropic plates but also available to bonded transverse isotropic plates and cubic materials. By extracting frequency-based reflection spectrums and incident angle-based reflection spectrums, respectively, more information about the bonding quality can be concluded synthetically.

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