Ultrasonic Guided Wave Nondestructive Testing for Helicopter Rotor Blades

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Abstract

Ultrasonic guided waves are used to detect the delamination between skin and honeycomb of a composite helicopter rotor blade. Theoretical work is carried out for guided waves in the trailing edge of a rotor blade, which is a multilayer composite skin/NOMEX half space structure. The dispersion relation is obtained with the global matrix method. Theoretically driven experiments are conducted on a composite rotor blade section to illustrate the effect of delamination to through transmission ultrasonic energy. Animations will be shown to demonstrate the delamination detecting concept. The study of guided wave excitation and propagation provide analytical background for optimization of ultrasonic transducers.

Keywords: Guided wave; Dispersion curve; Global matrix method; Rotor blade; Nondestructive testing

1. Introduction

Composite materials are well known for favorable strength and low weight. In the trailing edge of a helicopter rotor blade, composite layers are bound on honeycomb substrates to enhance mechanical properties. The complex structure of composite materials makes the task of nondestructive testing (NDT) more difficult than tests on homogeneous isotropic materials. Many methods have been raised to evaluate the structural integrity, among which the ultrasonic guided wave based NDT technique has received considerable attention because of the advantages of large inspection range, focus and mode-select abilities, greater sensitivity and low cost[1,2].

Predicting the wave characteristics, such as the dispersion relations and wave structures, is a preliminary consideration for ultrasonic guided wave tests. To understand the nature of guided waves in a multi-layered anisotropic plate, a transfer matrix method (TMM) was developed by Thomson[3] and refined by Haskell[4]. This method is also available to the structure of a plate on a half-space. In the TMM, the wave field at the top surface of a layer is connected to that at the bottom surface with a matrix. Multiplying the matrices of all of the layers generates a transfer matrix, which connects the wave fields at the top and bottom surfaces of the plate. The displacements and stresses at any location inside the laminate can be conducted from the transfer matrix and boundary conditions. The weakness of the transfer matrix method is its instabilities when the product of frequency and thickness is large[5]. An alternative technique is the global matrix method (GMM), provided by Knopoff[6] to avoid the instability problem. In GMM, the wave fields at all the interfaces and boundaries are assembled together in a single matrix. This method is robust but relatively computationally slow because of the large matrix. Besides these analytical methods, the finite element method (FEM)[7] and semi-analytical finite element methods (SAFE)[8] have been established to solve the problem of wave propagation in irregular shape media and wave scattering from discontinuities.

The paper starts with the analytical calculation of guided wave propagation in the trailing edge of a helicopter rotor blade section. The GMM is applied to obtain the dispersion relation. Then the FEM simulation demonstrates the damage detection ability of leaky guided waves. Finally, theoretically driven experiments are conducted on a composite rotor blade section to detect the debonding between a composite skin and honeycomb substrate.

2. Analytical model

The trailing edge of a rotor blade is usually a skin/honeycome/skin sandwich structure. The honeycomb can be treated as a half-space because its thickness is much larger than the guided wave wavelength. In this case, the skin is a fiber glass/epoxy composite with the layup sequence of [45/-45/(0)$_3$-45/45]. The honeycomb material is Nomex. The skin and the honeycomb are glued with epoxy. Figure 1 shows the sketch of the rotor blade trailing edge section. The thickness of each lamina in the skin is 0.127mm. The glue thickness is 0.0635mm. The elastic constants of the composite skin are E_1 = 41GPa, E_2 = E_3=10.4GPa, G_{12} = G_{13} = 4.3GPa, G_{23} = 3.5GPa, υ_{12} = υ_{13} = 0.28, υ_{23} = 0.50. The density ρ = 1.97 g/cm^3. The elastic constants and density of epoxy are E = 4.46GPa, υ=0.35, ρ = 1.52 g/cm^3. The elastic constants and density of Nomex are E = 9GPa, υ=0.30, ρ = 1.38g/cm^3.

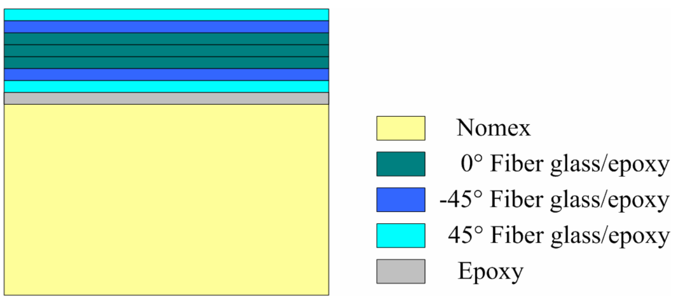


Figure 1: Sketch of a rotor blade trailing edge section.

The phase velocity dispersion curves are calculated from GMM[6]. Because the leaky modes have complex wave numbers, the mode search is in both the real and imaginary domains.

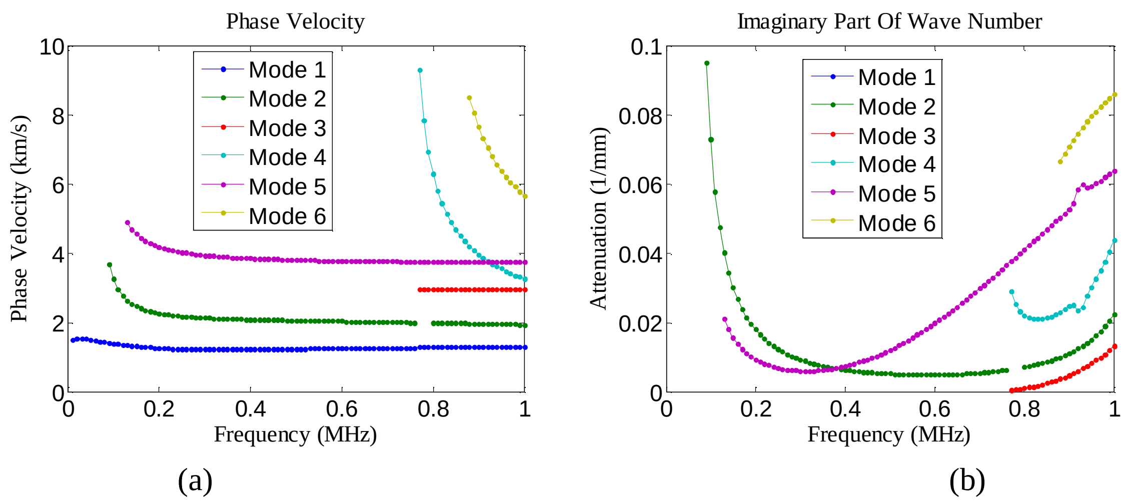


Figure 2: Phase velocity dispersion curves (a) and attenuation dispersion curves (b).

The phase velocity of the first five modes is presented in Figure 2 (a). The imaginary parts of these modes, which represent attenuation, are presented in Figure 2 (b). The attenuation of the first mode is zero. Therefore, Mode 1 is non-leaky. The others are all leaky modes. When a leaky wave propagates, it attenuates quickly because of losing energy to the half-space. A debonding or crack at the interface can block the leaky energy transmission into the half-space and hence reduce the attenuation. The size of the debonding can be measured by monitoring the leaky wave amplitude. Mode selection depends on the NDT requirement. A wave mode with a small attenuation coefficient can propagate a long distance in the layer/half-space structure. A mode with a bigger attenuation coefficient doesn't cover as large a region, however, even though being more sensitive to the debonding. Mode and frequency selection is based on propagation distance vs. sensitivity.

3. Numerical simulation

The commercial software ABAQUS is used to build the finite element model of a rotor blade trailing edge section. Figure 3 presents the sketch of the system. The length, width and thickness of the model are 150mm, 15mm and 21.3mm respectively. The thicknesses of the composite laminas and the epoxy are the same as those of the analytical model in section 2. Infinite elements are defined at the bottom boundary of the NOMEX honeycomb to eliminate reflection. Normal surface traction is applied to four evenly distributed fingers on the top surface representing a transducer on the surface. The distance between every pair of neighbored fingers is fixed to a half wavelength. The input signal is a 5-cycle pulse at the central frequency of 300KHz. The excited guided wave propagates along the x1 direction. In the damaged model, glue in the interesting region is removed to simulate debonding.

To study the effect of debonding to the ultrasonic guided waves, a leak wave is excited into a perfect bonding model and a damaged model, as shown in Figure 4 (a) and (b) respectively. Both of these models have the same geometry and loading. From Figure 4 (b), there is no energy leaking to the half-space in the damaged region. Therefore, the leaky wave can propagate further in a debonded structure.

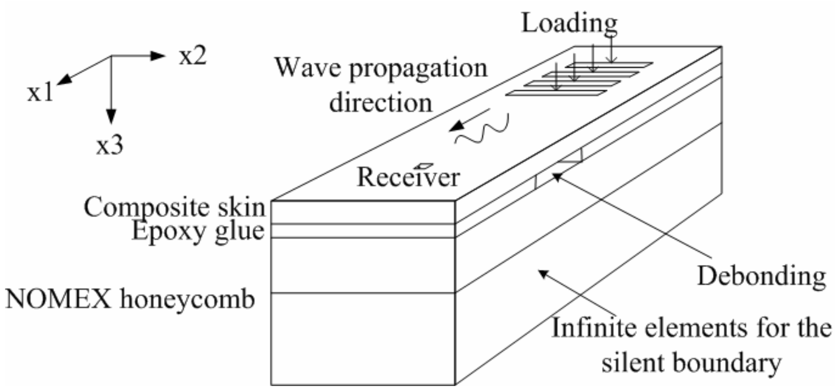
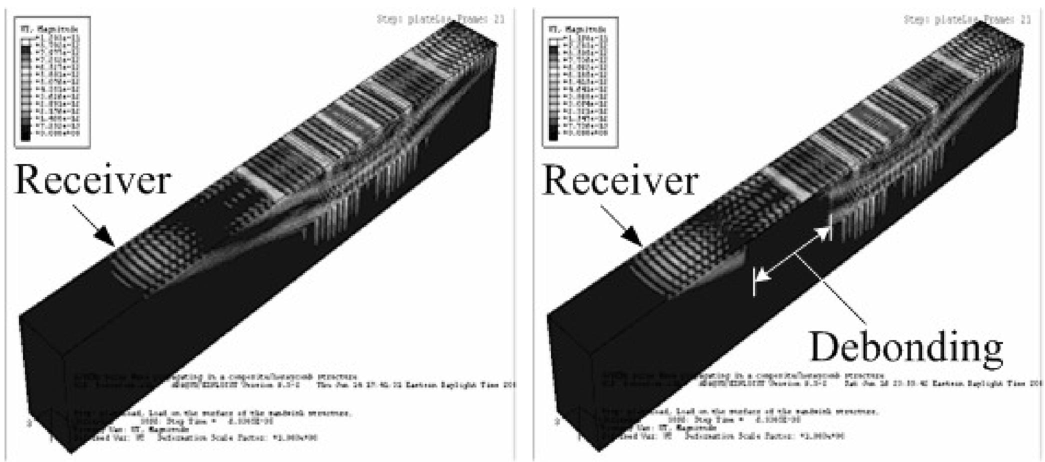


Figure 3: Sketch of the FE model for guided wave excitation and propagation in the rotor blade trailing edge section.



(a) (b)

Figure 4: Leaky wave (Mode 5 at 300KHz) propagation in a perfect model (a) and a damaged model (b).

Figure 5 presents the time domain through transmission signals for both debonding and perfect bonding models. The position of the receiver is shown in Figure **8**. Compared with the baseline, the amplitude of the third mode greatly increases because of the debonding. Since there is no leakage for the surface acoustic wave, the existence of debonding cannot enhance the first mode. Actually, the amplitude of the first mode decreases due to the scattering at the damage.

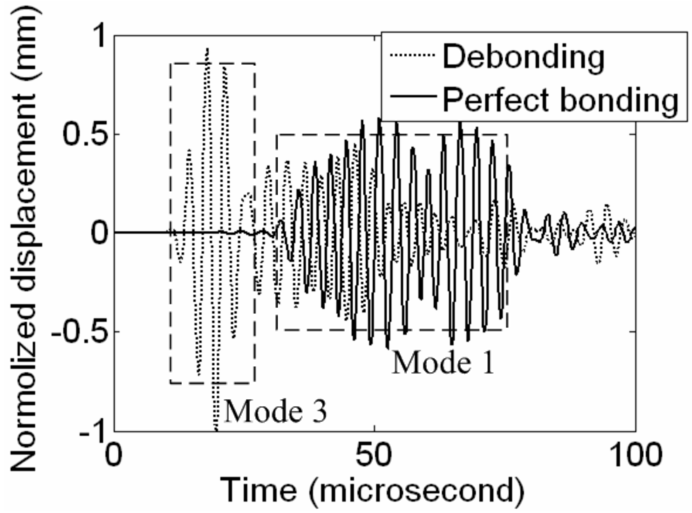
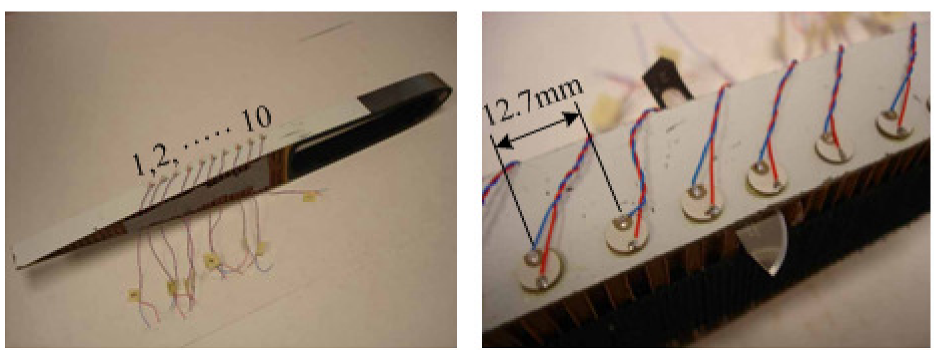


Figure 5: Comparison of the through transmission signals U1 for the damaged model (dash line) and the perfect model (solid line).

4. Experiment

The test bed is a helicopter rotor blade section with composite skin/epoxy glue/Nomex honeycomb structure. There are ten surface-bonded transducers on the test bed. These transducers are round PZT wafers numbered from 1 to 10, as shown in Figure 6 (a)**.** The thickness of each wafer is 0.4mm and the diameter is 6.3mm. The distance between two nearby transducers is 12.7mm. Transducer No 1 is the exciter and the other transducers are receivers.



(a) (b)

Figure 6: A helicopter rotor blade section mounted with PZT wafers (a). Produce debonding with a knife (b)

In the experiment, a Matec Explorer 2 NDT workstation recorded through transmission signals as baseline. After that, debondings were made with a knife and the measurements were repeated. All the signals were excited and received at 300KHz. Figure **6** (b) indicates the production of debonds. The length of the debonding increases from 0.5 inch to 2.5 inches.

The through transmission energy is calculated as an integral of the squared voltage express function in time domain. The energy for every damaged signal is normalized to the baseline energy. Figure 7 plots the normalized energy received at transducers 10. The received energy monotonously increases with the debonding size, which is nicely in agreement with theory.

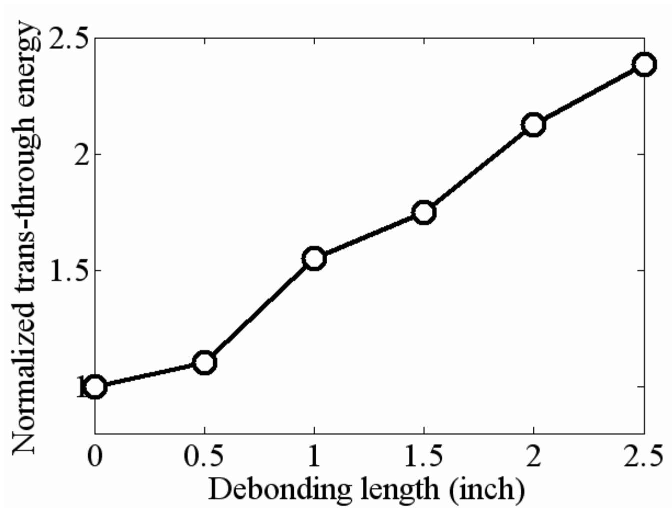


Figure 7: Normalized through transmission energy received at transducer No 10.

5. Conclusion

The global matrix method has been implemented to solve the problem of guided wave propagation in the composite/half-space structure. Both leaky waves and non-leaky wave were considered. The non-leaky wave is suitable for surface damage detection because it concentrates energy on the top surface. However, it is not so sensitive to the skin-substrate debonding. The imaginary part of wave number, which represents attenuation, is the key factor for leaky wave damage detection. The wave number selection depends on the sensitivity and penetration power in NDT. From the wave number and dispersion relationships, the wavelength and frequency can be fixed. This is important for transducer design.

A FE model simulates scattering of waves by debonding in a laminated semi-infinite half-space. Leaky waves have been proved to be effective for debonding detection. An experiment on a composite rotor blade section was conducted, which validate the analytical and numerical calculation. Since the through transmission energy monotonously increases with the debonding length, leaky waves could be applied to determine the damage size, and potentially predict the remained life of the structure.

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References:

[1] Rose Joseph L., Ultrasonic Waves in Solid Media, Cambridge University Press, 1999.

[2] Raghavan Ajay and Cesnik Carlos E. S., Review of Guided-wave Structure Health Monitoring, The Shock and Vibration Digest, Volume 39 Number 2, 2007, P91-114.

[3] Thomson William T., Transmission of elastic waves through a stratified solid material, Journal of Appied Physics, Volume 21, 1950, P89-93.

[4] Haskell Norman A., Dispersion of surface waves in multilayered media, Bulletin of the Seismological Society of America, Volume 43, 1953, P17-34.

[5] Lowe Michael J. S., Matrix techniques for modeling ultrasonic waves in multilayered media, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Volume 42 Number 2, 1995, P525-541.

[6] Knopoff Leon, Matrix method for elastic wave problems, Bulletin of the Seismological Society of America, Volume 54, 1964, P431-438.

[7] Paik Seung Hoon, Kim Ji Yeon, Shin Sang Joon and Kim Seung Jo, Numerical Simulation of Actuation Behavior of Active Fiber Composites in Helicopter Rotor Blade Application, Proceedings of SPIE, Volume 5390, 2004, P89-96.

[8] Hayashi Takahiro, Calculation for Guided Waves in Pipes and Rails, Key Engineering Material, Volume 270-273, 2004, P410-415.