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Research on An Inspection Method for De-bond Defects in Aluminum Skin-Honeycomb Core Sandwich Structure with Guided Waves

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Abstract

In order to increase the ultrasonic inspection speed of skin honeycomb core sandwich structure, the application of guided waves in this field was researched on. The characteristics of guided waves was stated, the propagation of guided waves in the skin honeycomb core sandwich structure was analyzed. Guided wave mode was selected in term of signal amplitude relative change dependent on the wave structure theory. Through short time frequency transform time frequency analysis, the frequency change of signal due to defects was researched. Best line scan distance was determined based on the signal in different position. It is testified that A0 mode has a better sensitivity on de-bond defect. The de-bond defect can be inspected through the comparison of amplitude. Although some of energy would leak into the core, the guided waves can travel over longer distance which results that the guide wave line scan has quicker inspection speed.

Keywords: Skin-honeycomb core sandwich structure, Guided waves, Wave structure, Time-frequency analysis

Composite materials have been applied widely in many fields since this century. As a kind of special composite material, skin-honeycomb core sandwich plate is characterized by high special intensity, high special rigidity, light weight and heat insulation, and so it is widely used in aeronautics and astronautics, manufacture of vehicles and ships, and architecture. However, during the process of production and service, defects would come into. The kinds of defects are de-bond, short core and so on. Because these defects are usually hidden in the structure, no evidence will appear before the skin-honeycomb core plates crack or break down. The sudden wrong brings sever damage to the structure. It is very important for the nondestructive testing of skin honeycomb core sandwich structure.

Ultrasonic testing method is often used in nondestructive testing of skin-honeycomb core sandwich plate. The traditional ultrasonic testing method is time consuming and lower efficiency due to point by point scanning way. It is desirable to develop alternative inspection method, one possibility being to use ultrasonic guided waves. The ultrasonic guided waves can propagate over longer distance, the testing can monitor a line rather than a point and considerably savings in time may potentially be obtained. Due to their advantages, guided waves are very attractive and have begun to be used to inspect the skin-honeycomb core sandwich plate.

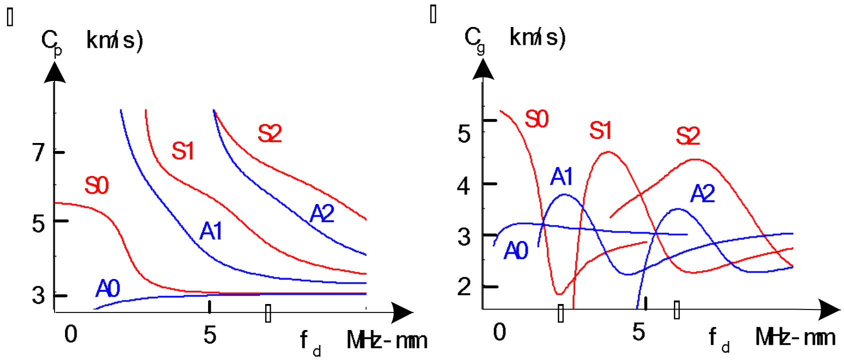
Based on the lowest order asymmetric plate wave excitation and swept frequency-phase display, Geng Rong-sheng inspected de-bond faults on the radar shade of a plane [1]. Hay T. R. presented that sweeping experimentally through the dispersion curves was an effective way to experimentally locate guided wave modes sensitive to skin-core delamination [2]. R Kazys described a new method for detection and visualization of inhomogeneities in composite materials using one-side access air-coupled ultrasonic measurement technique. After numerical predictions of Lamb wave interaction with a defect in a composite material had been carried out, the delamination and impact type defects in honeycomb materials was detected [3]. Michel casting tested a sandwich plate made of two glass epoxy skins of different thickness separated by a rigid, foam core with guided waves, and demonstrated a strong effect of viscoelasicity on the dispersion curves [4]. Claudio Cosenza made use of a Nd:YAG pulsed laser to generate the guide waves, and carried out the assessment of skin-core bond in honeycomb samples[4]. For the aluminum skin aluminum honeycomb core sandwich structure, the variable angle transducer is chosen to generate the guide waves in this paper, the guided wave inspection method would be stated respectively in mode selection, time-frequency analysis and best line scan distance.

1. Principle of guided waves inspection

1.1 Primary theories of guide waves

As a kind of ultrasonic waves, guided waves exist in wave-guide with boundary. Due to guide waves' reflection and refraction with boundary during the process of traveling, the mode conversion between transverse waves and longitudinal waves make the guided waves different to the standard ultrasonic bulk waves. The main characteristics are dispersion, multi-mode and long traveling distance.

The waves of different frequency propagate at different velocity, which named as dispersion. As far as guided waves in the plate (also named as Lamb waves) are considered, both their phase velocity and group velocity are functions of product of plate thickness and frequency, the disperse curves of guided waves in aluminum plate are seen in Figure 1. Multi-mode means that there is not only a king of mode propagate in wave guides. In term of the vibration displacement, the guided waves in the plate can be divided into two basic classes: symmetric ones (such as S0, S1 and etc) anti-symmetric ones (for example A0, A1 and etc). Every mode has different sensitivity to the different defects. In addition, the guided waves are constructive waves and can travel over long distance. The distance may be reach up to several meters. The received signal contains all the information of the line between the transmitting and receiving transducers. So line scan can be done to quickly carry out the large inspection, which can shorten the inspection time to a large extent and can be used in some cases that the inspection structures are coated with insulator layer or be placed underground, for example the pipes across the road.



(a) phase velocity curves (b) group velocity curves

Figure 1 the dispersion curves of guided waves in the aluminum , C_L=6.37km/s , C_T=3.16km/s

1.2 The propagation of guided waves in aluminum skin-honeycomb core sandwich plates

Aluminum skin-honeycomb core consist of aluminum skin, honeycomb core and adhesive layer. Because the adhesive layer is very thin, so it has hardly no effect on the disperse curves in the aluminum skin [5]. The disperse curves of guided waves in simple aluminum plate can be used to analysis the guided waves in aluminum skin-honeycomb core plate. However, some of energy can leak into the adhesive layer and honeycomb core, guided waves signal would be attenuated to a large extent. Here named as leakage lamb waves.

Figure 2 is the sketch of guided waves in skin-honeycomb core plate. The skin is often thin. When the ultrasonic waves are generated by transmitter, if there is no de-bond fault, some of energy hits the free edge of the plate and reflects back to the transducer in the receive mode, and the other energy would leak into the adhesive layer and honeycomb core. However In the de-bond region, the skin is not adhere to the honeycomb core, so the leakage of transmitted energy is less and the received energy is more. In the case of latter, the amplitude of signal is larger which is an indication of de-bond.

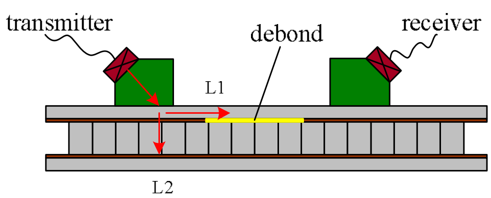


Figure 2 the sketch of guided waves in skin-honeycomb core sandwich plate

2. Experimental setup

Experiments were made in a through-transmission setup (shown in Figure 3) using two variable angle 1.5MHz broadband transducers, one as transmitter of the guided wave and the other as receiver. A Panametrics pulser/receiver OLYMPUS-5800 is used as a pulsing system. The inspected area with this setup is along a line between the two transducers. The signal from the receiving transducer is transferred to the digital oscilloscope TDS5034B.

The specimen used for this study is a piece of aluminum-skin honeycomb core sandwich plate. The skin is approximately 0.5mm thick. The specimen is 240mm× 245mm. The de-bond area is a circular one in the center.

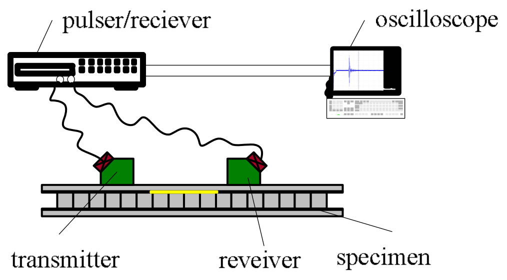
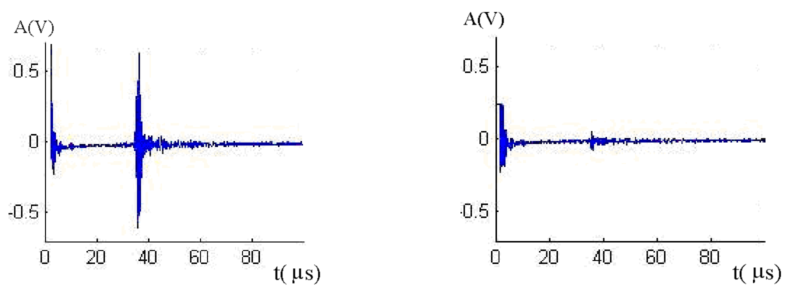


Figure 3 experimental setup

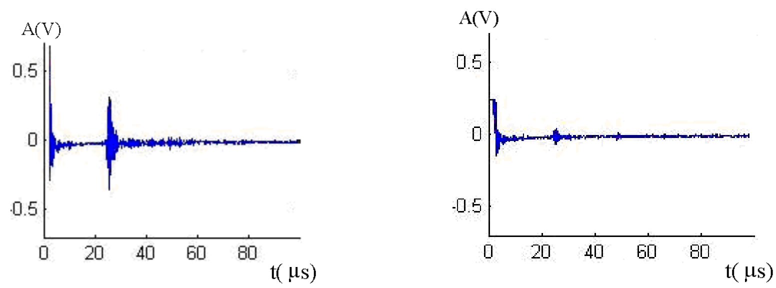
3. Results and discussion

3.1 mode selection

Different guided wave modes have not the same sensitivity to the defects. A guide wave mode, at a given phase velocity and frequency, sensitive to the skin-core de-bond can be found by comparing waves propagation through bonded areas and de-bond areas under the same testing conditions. A high amplitude signal is indicative of a mode traveling primarily in the skin with very little attenuation caused by the adhesive layer and honeycomb. The relative drop in amplitude is a measure of the mode's sensitivity to the de-bond defect at the skin-core interface. In the through transmission setup shown in Figure3, the testing was performed respectively with mode A0 and S0 in the good bond and de-bond areas. Figure 4 shows the measured guided waves signals. The receiver is 120mm away from the transmitter.



(a) (b)



(c) (d)

Figure 4 sample data at f=1.5MHz ,(a) sample signal from de-bond area with A0 mode, (b) sample signal from good bond area with A0 mode, (c) sample signal from de-bond area with S0 mode, (d) sample signal from good bond area with S0 mode

The amplitude and attenuation of mode A0 and S0 are shown in table 1. It can be seen from the table 1 that mode A0 is more sensitive than mode S0 due to its more attenuation under same condition.

Table 1 sensitivity comparison between guide wave mode A0 and mode S0

mode	amplitude (V)		relative drop
	de-bond	good bond	
A0	1.244	0.129	89.6%
S0	0.666	0.118	82.2%

The sensitivity to the defect of guided waves mode is determined theoretically by their wave structures. The displacements of guided waves in thin plate are described by the following expressions (1) and (2) [6].

$$U_s = Ak\left(\frac{ch(mz)}{sh(mh)} - \frac{2mn}{m^2+n^2}\cdot\frac{ch(nz)}{sh(nh)}\right)$$
$$W_s = -Am\left(\frac{sh(mz)}{sh(mh)} - \frac{2m^2}{m^2+n^2}\cdot\frac{sh(nz)}{sh(nh)}\right) \quad (1)$$

$$U_a = Bk\left(\frac{sh(mz)}{ch(mh)} - \frac{2mn}{m^2+n^2}\cdot\frac{sh(nz)}{ch(nh)}\right)$$
$$W_a = -Bm\left(\frac{ch(mz)}{ch(mh)} - \frac{2m^2}{m^2+n^2}\cdot\frac{ch(nz)}{ch(nh)}\right) \quad (2)$$

where , z——the distance from the particle to middle plane of the plate

U_s——in-plane displacement of the symmetric modes
U_a——out-of –plane displacement of the anti-symmetric modes
W_s——in-plane displacement of the symmetric modes
W_a——out-of –plane displacement of the anti-symmetric modes

A , B—— arbitrary constants

$m = \sqrt{k^2 - k_l^2}$, k_l is wave number of longitudinal wave

$n = \sqrt{k^2 - k_t^2}$, k_t is wave number of transverse wave

k——wave number of Lamb waves

For the aluminum skin of skin honeycomb core sandwich plate, the wave structure of A0 mode and S0 mode guide waves are shown in Figure 5 according to the expression (1) and expression (2) when fd (frequency thickness product) is 0.75MHz-mm, which shows the in-plane (solid line) and out-of-plane (dashed line) displacement profiles across the thickness of the plate.

It can be seen in Figure 6 that for the guided wave signal of mode S0 the in-plane displacement is lager than out-of-plane displacement which results that the leakage energy into adhesive layer and honeycomb core is less; for the guided wave mode A0, there are more energy that would be leaked into the adhesive layer and honeycomb core due to more out-of-plane displacement. So when the aluminum skin aluminum honeycomb core plate has de-bond fault in the surface, the guided wave signal of mode A0 is more sensitive to inspect the defect.

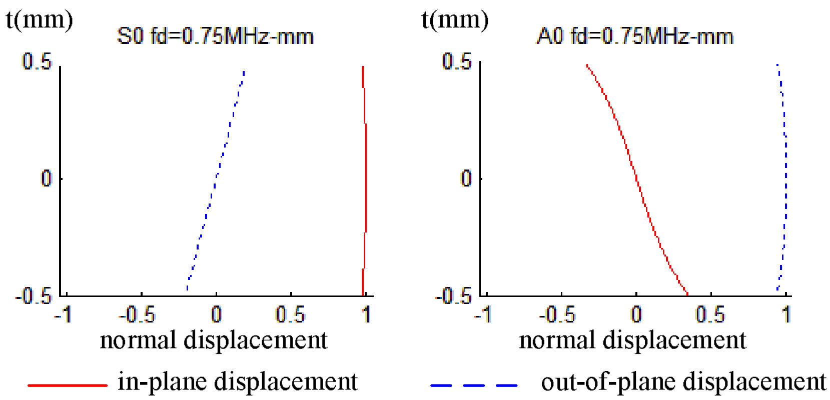
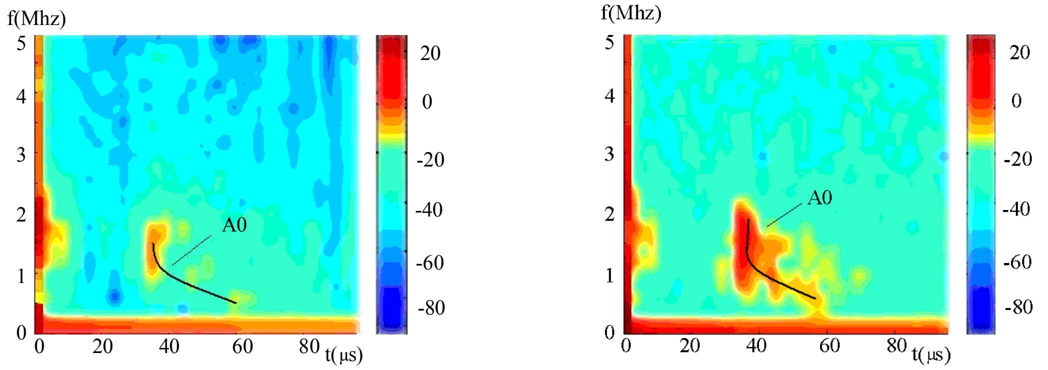


Figure 5 wave structure for various points on the S0 mode and A0 mode of guide waves in aluminum plate

3.2 Time frequency analysis and mode conversion

Guided waves signal is characterized by dispersion. The velocities of signals with different frequencies will vary with their frequencies. During the process of propagation, the frequencies of signals will also be changed and mode conversion will possibly occur. Short time frequency transform (STFT) analysis can be used to analysis the frequency change and mode conversion. The STFT of signal in Figure 4 (a) and (b) is shown in Figure 6. The length of NFFT is 256, sample frequency is 50MHz, and the Hanning window is chosen as window function. The number of samples in each segement of overlaps is 128。

From the Figure 6, it can be seen the main mode in the signal is A0. But the frequency range varies with defects. The frequency changeable range is from 0.3MHz to 2.3MHz with de-bond and from 0.9MHz to 1.8MHz with good bond. It indicates that when guided waves encounter de-bond defect, the frequency of signal had will be changed due to defect. Some frequency component would be leak into the adhesive layer and honeycomb core. Mode conversion is hardly found in this condition. However, mode conversion would be observed in many occasions, for example in the inspection of large aluminum plate. In this case which mode is more sensitive to the defect can be found by analyze mode conversion.



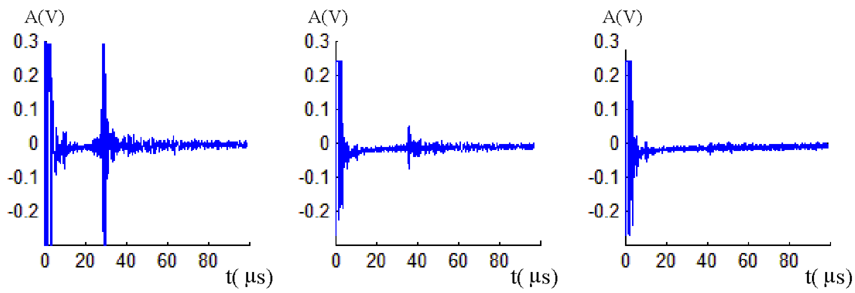
(a) the STFT of guided waves signal in good bond field

(b) the STFT of guided waves signal in de-bond field

Figure 6 the STFT of guide waves signal

3.3 best line scan distances

The purpose of line scan is to obtain the high efficiency. The longer is the scan line, the quicker is inspection. The longest length of scan line can be found by test the amplitude of signal in different position in good area. Selection in good area not in de-bond area is because the signal for the latter is sure to be larger than the former. The guide wave signals in different positions are shown in Figure 7.



(a) (b) (c)

Figure 7 sample data at different position with different modes in good bond area, (a) sample signal received from the receiver at 100mm away from the transmitter with mode A0, (b) sample signal received from the receiver at 120mm away from the transmitter with mode A0, (c) sample signal received from the receiver at 140mm away from the transmitter with mode A0

The group velocity can be calculated from the time delay shown in Figure 7(a) and (b). The flight time difference of guided waves in the distance 100mm and 120mm is 6.54us, so the group velocity of A0 mode is 3058m/s which is consistent with the group velocity shown in Figure 1(b).

From Figure 6, it can be seen that the signal is too small to distinct it when the propagation distance is 140mm in the good bond area. So 120 mm length is the best distance in guided wave inspection line scan of specimen. Comparing with traditional ultrasonic, suppose the scan step distance is 0.5mm, the point –by –point scan times is 240 in inspection of 120mm length line, while guide waves line scan times is only 1 to inspection the same length. Obviously guide wave line scan method has much advantage over the traditional ultrasonic method.

4. Conclusion

Guided waves based on results show that the detection of skin - honeycomb core sandwich structure de-bond is possible. Guide wave mode A0 is more sensitive than mode S0 to de-bond defect in the aluminum skin – aluminum honeycomb core specimen structure. Amplitude is a potential signal feature that could be considered for classifying good and bad areas. Mode conversion is hardly found in the testing. Compared to conventional methods, guided waves line scan inspection is fast and reliable.

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