Guided Wave Sensitivity for De-Bond Defects in Aluminum Skin-Honeycomb Core

A. Satour, F. Boubenider, R. Halimi, A. Badidibouda

Abstract**—**Sandwich plates are finding an increasing range of application in the aircraft industry. The inspection of honeycomb composite structure by conventional ultrasonic technique is complex and very time consuming. The present study demonstrates a technique using guided Lamb waves at low frequencies to predict de-bond defects in aluminum skin-honeycomb core sandwich structure used in aeronautics. The numerical method was investigated for drawing the dispersion and displacement curves of ultrasonic Lamb wave propagated in Aluminum plate. An experimental study was carried out to check the theoretical prediction. The detection of unsticking between the skin and the core was tested by the two first modes for a low frequency. It was found that A0 mode is more sensitive to delamination defect compared to S0 mode.

Keywords**—**Damage detection, delamination, guided waves, Sandwich structure.

I. INTRODUCTION

COMPARED to the Conventional materials, the honeycomb composite structures are characterized by high specific strength and stiffness, which increase their use in many fields of application such as aeronautics and astronautics. However, during the manufacture or after use, different defects would appear into. As the most common for the sandwich structure, delamination defect can causes a significant loss of mechanical properties and so the failure of structure. Moreover this kind of defects is invisible and is easily induced during service. There is therefore a need to apply powerful and reliable technique for inspection of these structures. Many defects in composite structures are detected by several techniques such as Shearography [1], Ultrasonic, Radiography [2], Thermograph, and Eddy current [3].

Numerous researchers have developed nondestructive technique based on the Lamb wave propagation to inspect the composite structure [4]-[6]. All these studies showed the potential of guided Lamb waves to discover different defects in such structure. Lamb waves are two-dimensional acoustic waves which can propagate in thin solid plates with free boundaries. Less work was devoted to sandwich structures. It was shown that de-bond between the skin and the core in honeycomb structure can be identified by the s0 Lamb wave [7], [8]. In this paper, a study of low-frequency guided wave sensitivity for de-bonds defects in aluminum Skin-Honeycomb Core is carried out.

II. THEORIES

Lamb wave is one of the guided waves which are induced by free surfaces of plate with finished thickness, and propagates along the directions of length and width. Given the mechanical displacements, two types of motion can propagate in a plate, one symmetric (longitudinal) and the other antisymmetric (flexural) [9].

For an isotropic plate of thickness 2h, the dispersion relation describing symmetrical and anti-symmetrical modes [10] can be written as:

$$(k^2 - q^2)\cos(ph)\sin(qh) + 4k^2 pq\sin(ph)\cos(qh) = 0$$

For symmetrical mode (1)

$$(k^2 - q^2)\cos(ph + \frac{\pi}{2})\sin(qh + \frac{\pi}{2}) + 4k^2 pq\sin(ph + \frac{\pi}{2})\cos(qh + \frac{\pi}{2}) = 0$$

For anti-symmetrical mode (2)

The wave numbers p and q are given by

$$p^2 = \frac{\omega^2}{V_L^2} - k^2, \quad q^2 = \frac{\omega^2}{V_T^2} - k^2$$

where VL and VT are respectively the longitudinal and shear bulk wave velocities of the material, ω is the angular frequency and k is the angular wave number. The numerical resolution of (1) and (2) allows us to obtain the dispersion curves for the aluminum plate (Figs. 1 and 2).

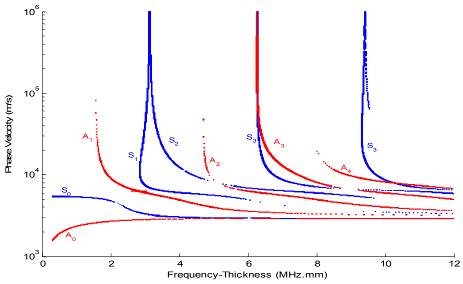

Fig. 1 Phase Velocity Dispersion Curves for an Aluminum Plate

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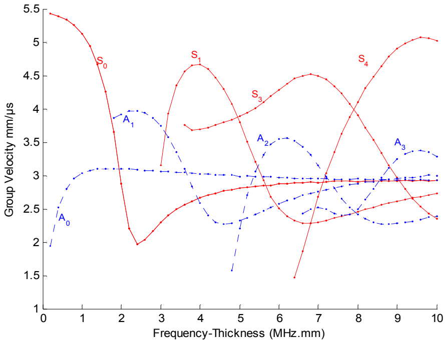


Fig. 2 Group Velocity Dispersion Curves for an Aluminum Plate

III. Mode Selection

For the sandwich structure, it was shown that the dispersion curves at low frequencies are similar to those for free plate [11], [12]. On the other hand, due to complex form of the core (that implies the presence of vacuum inside the sandwich plate), the attenuation increases in the presence of the core.

The modes selected are the longitudinal mode S0 (symmetrical) and the flexural mode A0 (antisymmetric) in the field of low frequencies.

The displacement inside the plate thickness informs us about the sensitivity of Lamb mode to a surface or bulk defect. The mechanical displacement is the vectorial sum of longitudinal (along axis OX) and transverse (along axis OZ) displacement. For the aluminum skin of sandwich composite the reports/ratios of the out –of-plane displacement (uz) over the in-plane displacement (uz) at the border of plate are calculated for each frequency-thickness product. From Fig. 3 it can be seen that for the low products f.d, the S0 mode has displacements whose principal components are longitudinal. When the product f.d increases, the normal components of displacements take importance and the mode loses its longitudinal prevalence. For A0 mode, the various evolutions of the ratio (uz/ux), according to the product f.d, inform us about the surface' state: transverse displacement is prevailing whatever the product f.d. for the low products f.d, displacement becomes frankly transverse. These results, confirm in fact, the movement of this flexural mode.

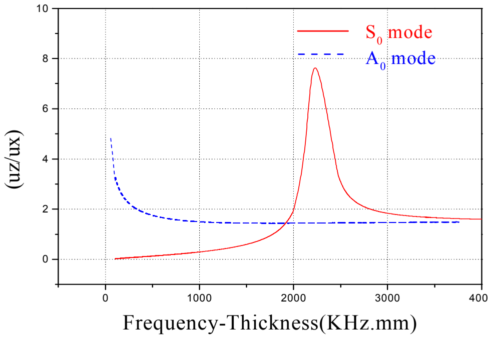


Fig. 3 Evolution of the reports/ratios of uz/ux displacements at the border of the plate (Z=d) with the product frequency-thickness for the S0 mode and A0 mode

IV. Experiments

The composite structure: skin-core, core with honeycomb, is largely used in aeronautics (Fig. 4); this structure is made up with two aluminum skins and aluminum honeycomb core. The plate used for experiments was provided by the aeronautical structures and composites service, this service has the plates of large extent, intended for the repair of the aeronautical structures. In the latter, separation between the plate and the core is produced using a technique based on the heat transfer principle between a thermal source and the plate via a full steel cylinder. Part of material underwent a heating to create a not stuck surface (between the skin and the core). The C-Scan cartography of the part including defect is shown in Fig. 5.

The ultrasonic technique using guided wave consists in the launch of an elastic wave in the material. A part of the energy which propagates in the skin will be absorbed by the core and, to control the quality of the sticking between the skin and the core, it is sufficient to compare the reflected or transmitted signal by unstuck material and a signal when the plate and the core are stuck well.

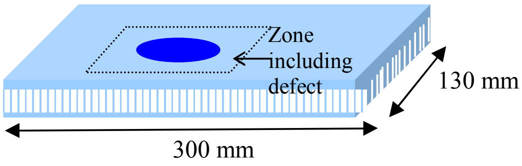


Fig. 4 The composite skin-Honeycomb core plate

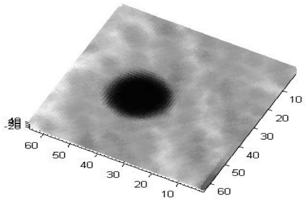
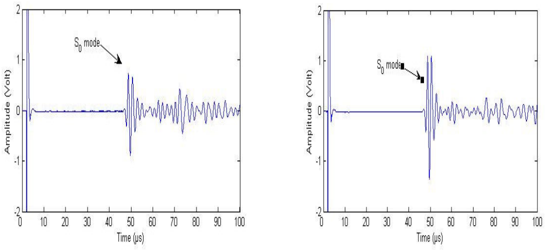


Fig. 5 Through transmission C-scan of debonding defect

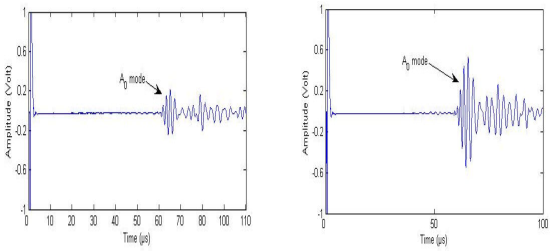
For the sandwich structure, it was shown that the dispersion curves at low frequencies are similar to those for free plate. On the other hand, due to complex form of the core, the attenuation increases in the presence of the core, furthermore sandwich composites are no homogenous and anisotropic materials, so, the attenuation of ultrasonic waves increases very much at high frequencies [7]. In our work the two fundamental modes were generated in the sample at 500 KHz, and the sensitivity to separation skin-honeycomb was compared between the two first modes (A0 and S0 modes). Experiments were made in a pitch-catch setup using two variable angle 500 KHz 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.

Figs. 6 and 7 show the signals acquired from bonded zone (sample including defect) and de-bonded zone (sample without defect) at 500 KHz when the samples were excited with S0 mode and A0 mode respectively. For both modes it can be observed a significant change in the signal amplitude when the delamination defect is introduced. Fig. 8 exhibits the Comparison of through transmission signals and the amplitude frequency spectra for the damaged plate and the perfect plate, for the two modes. It can be seen that there is two principal phenomena due to presence of separation between the skin and the core: reduction in the amplitude of the signal and dispersion of the wave. The first is more remarkable. It is important to note that the dispersion of the wave translated by the change of the frequency spectrum in presence of de-bonding defect is more significant when we used the A0 mode; indeed the A0 mode is very dispersive at lower frequencies. In practice it is sufficient to exploit the attenuation phenomena. We calculated an amplitude ration which can define the mode's sensitivity. It is given by the difference in amplitude between the healthy area and the defective area compared to signal amplitude in defective area.



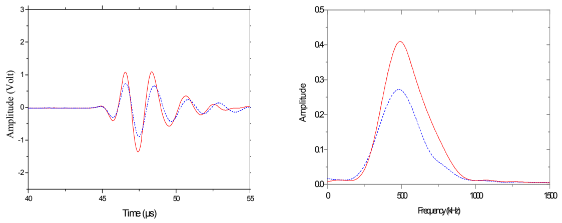
(a) (b)

Fig. 6 S_0 mode responses at 500 KHz (a) Signal from bonded zone, (b) Signal from debonded zone

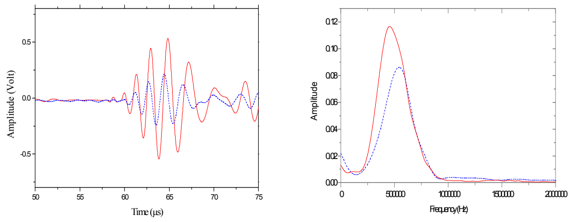


(a) (b)

Fig. 7 S_0 mode responses at 500 KHz (a) Signal from bonded zone, (b) Signal from debonded zone



(a)



(b)

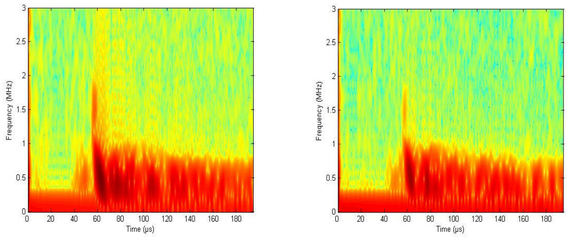
Fig. 8 Comparison of the through transmission signals and the amplitude frequency spectra for the damaged plate (dash line) and the perfect plate (solid line), (a) for the S0 mode (b) for the A0 mode

TABLE I
UNITS SENSITIVITY OF THE S_0 AND A_0 MODES TO DE-BONDING DEFECT

Mode	Frequency (KHz)	Amplitude Ratio
S_0	500	**33.4%**
A_0	500	**57.54 %**

Table I shows that A0 mode is more sensitive to delamination defect compared to the S0 mode. This result confirm in fact, that the sensitivity of wave to de-bonding defect in sandwich structure depend on the out-plane displacement of the wave at boundary of skin. Indeed, at f=500 KHz, the A0 mode has a component of out-plane displacement that is larger to that corresponds to s0 mode (Fig. 3).

In order to have more information about the A0 guided mode signals, the short time frequency transform analysis (STFT) was used. In principle if one part of skin is not stuck with the core, ultrasonic energy will be slightly leak in the core, and the frequency range of signal will be changed. The STFT of signal in Figs. 7 (a) and (b) is shown in Fig. 9. It can be seen that when the de-bonding defect is introduced in sandwich plate, the frequency of signal will be changed. This explains that some frequency component would be leak into the honeycomb core.



(a) (b)

Fig. 9 STFT of guided waves signals (a) in healthy area and (b) in defective area

V. CONCLUSION

The aim of the present work was to study the sensitivity of low frequency guided lamb waves to de-bonding defect in aluminum skin-honeycomb structure. The separation between the skin and the core was created by a technique of heating. The size and exact form of defect were estimated through the

C-scan cartography. The theoretical study of plate's vibrations enabled us to plot the velocity dispersion curves and displacement of various modes which can propagate in aluminum skin. Interaction of S0 and A0 Lamb modes with de-bonding defect was examined in the field of low frequencies. The analysis of guided wave signals provided several observations. The guided wave excited in sandwich plate is propagated in the skin and it is leaked in the core. Reduction in the amplitude of signal presents the indicative factor of de-bonding defect. Finally the results show that A0 mode is more sensitive than S0 mode to de-bond defect in the aluminum skin-honeycomb core structure.

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