A New Lamb-Wave Based NDT System for Detection and Identification of Defects in Composites

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Abstract

Ultrasonic testing is one of the most applied and powerful method for inspecting carbon fibre reinforced polymers (CFRP) for wide range of internal defects. For sandwich composites, pitch-catch technique, that utilise guided (Lamb) wave are most effective in detecting the common defects such as crushed cores, disbond and delamination. Popular commercial instrument could detect the presence of these defects but it is not able to give crucial information about the defects, which include types of the defects, the exact location of the defects, and the depth of the delamination. This information will be important for determining if and how the composite repair can be carried out. Conventional instrument gives yes or no result. In this paper, we present an enhanced Lamb wave based method which not only able to detect the defect but also able to distinguish different types of defects in the sandwich composites. The key novelty in our method is a modified excitation signal designed for address the dispersion effect in the low frequency range. The response to the material was based on phase shift against the excitation signal. The approach was implemented in a portable system that comes with a special probe. This probe, embedded with a position sensor, can directly scan on the composite surface to obtain and record C-scan type of defect map without using an x-y stage.

Keywords: Ultrasonic Testing, Lamb Waves, CFRP, Inspection

1. Introduction

As composites are being increasingly used in commercial aircrafts, new inspection technologies have to be developed to meet the industry demands for airworthiness and flight safety. Examples of the commonly found defects in composite materials include delaminations, disbond, crushed core, and heat damage. In the case of delaminations, there is a separation between one ply to another, which can be caused by improper construction of the laminate or from heat exposure. A composite structure can also be found in laminate-core-laminate form, whose core is made of fibreglass or Nomex in a honeycomb shape. The adhesive between the laminates and the core can also be improperly applied or damaged from various conditions, which causes the laminate layers to be disbonded from the core. This condition can clearly cause a loss of strength of the structure. In another form of internal defect, a crushed core can happen when the aircraft structure is hit by an object. However, this damage cannot be seen from the outside and therefore an inspection process that can penetrate the depth of the core is desirable.

A fast inspection technique is a so called “coin tap” testing method, which the inspection conductor tap the suspected areas lightly with a hard and blunt tool to obtain an indications of the underlying structure from the sound of the tap [1]. Other methods include thermograph, non-linear spectroscopy, X-radiography, and eddy current measurements, and ultrasonic waves. Among these techniques Lamb wave methods have recently re-emerged as a reliable way to locate damage in the composite
components [2]. Current commercial instrument utilizes Lamb wave could detect the presence of these defects but it is not able to give crucial information about the defects, which include types of the defects, the exact location of the defects, and the depth of the delamination. This information will be important for determining if and how the composite repair can be carried out. In the following sessions we present an enhanced Lamb wave based method which not only able to detect the defect but also able to distinguish different types of defects in the sandwich composites.

2. Theoretical Background

Lamb waves are guided waves which propagate in thin structures such as plates. They interact with the boundaries by way of reflection and refraction in the combination of longitudinal and shear waves. Lamb wave can either by symmetric or anti-symmetric depends on plate thickness, phase velocity, wave numbers. The characteristic equations of the two modes [3] can be expressed in Equations (1) and (2).

\[
\frac{\tan(qh)}{\tan(ph)} = \frac{4k^2qp}{(k^2 - q^2)^2} \quad \text{for symmetric modes}\quad (1)
\]

\[
\frac{\tan(qh)}{\tan(ph)} = \frac{(k^2 - q^2)^2}{4k^2qp} \quad \text{for anti-symmetric modes}\quad (2)
\]

In these equations,

\[
p^2 = \frac{\omega^2}{c_L^2} - k^2 \quad q^2 = \frac{\omega^2}{c_T^2} - k^2 \quad k = \frac{\omega}{c_p}
\]

where \( c_L \) is the velocity of longitudinal modes, \( c_T \) is the velocity of the transverse mode, \( c_p \) is the phase velocity, \( k \) is the wave number, \( \omega \) is the wave circular frequency of the propagating wave and \( h \) is plate thickness.

Solving these two equations with known material properties gives the dispersion curves, which is a plot of phase velocity against frequency or frequency-thickness. The dispersion curves can be used to explore the various wave modes that are expected for a given excitation frequency and material thickness. In a Lamb wave, at least two wave modes can be observed; the symmetrical mode \( S_0 \) and the asymmetrical mode \( A_0 \) as illustrated in Figure 1.

The dispersion curves illustrate two distinct velocity dispersion characteristics of Lamb waves. Firstly, the velocity dispersion in a single mode is due to the frequency dependency of a single Lamb wave mode. Different frequency components in a single Lamb wave mode travel at different speeds, thus the wave packet spreads as it propagates. Secondly, the velocity dispersion among multiple modes exists due to different modes travelling at different speeds at each given frequency [4].

The Lamb wave inspection method is very promising for the detection of defects in the composites. In conventional ultrasonic methods based on the reflection or scattering by defects, the smallest defect detectable is dependent on the wavelength. Low frequencies are incapable of detecting small defects, while high frequency signals have high attenuation. On the other hand, the defect detection capability of the Lamb wave inspection method does not simply depend on the reflection of waves by the defects,
but also on the interaction between the waves and the defects. The presence of a defect changes the peak amplitude corresponding to a particular Lamb wave mode, which is typically exploited in the popular Lamb wave based NDT tools, and also may cause frequency shift of the wave [5].

3. Pitch-Catch Method

The inspection of the composites laminates is by means of the pitch-catch technique using a pair of piezoelectric probes as a transmitter and a receiver (Figure 2). The transmitter excites the material and the response is picked up by the receiver after it passes through a short distance in the material. The presence of structural defects and the changes material property will result in more and sometimes less vibration energy transmitted to the receiver. It also affects the wave propagation speed due to the mode change and thus the time of flight of the transmitted vibration. This change in amplitude and time delay of the received signal provides an indication of the presence of a defect in the composite material.

The excitation signal of the new method utilizes a swept mode of a wideband frequency for the reason that different material conditions are more sensitive to different frequencies. The signal typical is a linear chip wave with the frequency decreases within a range of 40 kHz in the frequency lower than 50 kHz over a short period of time. The decreasing frequency mode allows more distinctive frequencies in the excitation signal, which otherwise would be compromised by the dispersive nature of the Lamb wave travelling in anti-symmetric mode Figure 1. The response of the excitation wave after it passes through the materials is computed for the phase shift over a range of frequency (Figure 3). Such processed response is proven more stable and repeatable than if the response is computed in term of the magnitude, which is often the case for the state-of-the-art system.

4. Identification of defects

The detection of the defects is by way of referencing instead of measuring the response of the signal to the material. The method of identifying the defects is by way of direct comparison of the test results obtained from a reference board with known defects. The general procedure for defect identification is shown in Figure 4. The responses collected from the inspection are compared with the phase shift profile in real time during the actual inspection. The defect type is determined based on the best match of the profile with the tolerance set in the teaching phase.
The methods described above have been implemented in a portable system called PiCaScanner (Figure 5). It consists of a laptop, a DAQ unit and a pitch-catch probe embedded with a position transmitter. With PiCaScanner, the inspection area can be defined before the actual inspection using a position transducer and encoder imbedded with a position encoder/sensor the actual inspection area on the aircraft is mapped on to the screen of the NDT system. The position transducer and encoder allow the linear coordinates of the probe relative to a defined frame on the aircraft surface to be determined. The area is then gridded with a user-chosen numbers of uniform rows and columns to form the display panel. Each of the grid boxes is to display the inspection result of the corresponding points on the actual aircraft surface. In the actual inspection operation, the user scans the inspection area with the probe and the processed results are displayed bit by bit in the grid boxes. The results of the inspections are illustrated with colours corresponding to the defect types assigned during the teaching stage.

### 5. Demonstration

**Test Samples**

One of the test specimen used is an inch thick carbon fiber honeycomb panel manufactured to the standards set by the Commercial Aircraft Composite Repair Committee (CACRC) [6]. The panels, called Composite Honeycomb Reference Standards (CHRS) is made of laminates lay up on both sides of the honeycomb core. The laminate material is either glass fibre or carbon fibre fabric. The core of every panel consists of two types of materials namely Nomex and fiberglass. The CHRS panels come with different laminate thickness ranging from 3 to 12 plies. Figure 6(a) shows an example of carbon fibre laminates panel.

Four types of defects are artificially fabricated into the specimen (Figure 6(b)). These include a machined core in which a flat bottom hole of about 0.25 inch milled out of the honeycomb core, a pillow insert in which a layer of tissue are held together between two layers of polyamide film tape and inserted into the interface layer. Figure 6(c) shows a schematic diagram of the defects depicted in a cross-section of the panel.
Test results

Here we present the capability of the PiCaScanner in distinguishing defects of different types. If we take CHRS panel as a reference panel and the locations of every type of defects are known, we can acquire the responses of the lamb wave for each of the defect types and assign them with a colour. As we scan the panel with the probe, the types of the defects as well as the location of the defects are recorded and displayed. A map similar to the C-scan is thus obtained as shown in Figure 7. It can be seen that PiCaScanner is able to distinguish the core types (Nomex is indicated in pink and fibreglass in blue), the machine core (disbond between laminate and core, coloured in yellow), pillow insert (delamination in the laminates marked in orange), potted core (crushed core displayed in light blue), and splice core (crack in the core doted in red). The shapes of the individual defects, as shown in the figure are not so accurately represented. This is mainly due to the pixel size setting and the speed of the scanning. Smaller pixel size and slower scanning speed will allow a more accurate representation for the shapes and locations of the defects. The total scan time for the area (200 mm by 100 mm) for the one displayed in Figure 7 is about 15 min.

To scan an area of an actual part say the nose cone of an aircraft (Figure 8), the position transducer of the PiCaScanner is first attached on the aircraft. After the area (within the sensing range of the transducer) is defined using the probe, the area can then be scanned manually until the same area mapped on the laptop is covered with colour.
6. Conclusions

An enhanced Lamb-wave based method has been developed. It is able to detect and distinguish the types of typical defects in the honeycomb composites, including the delaminations, disbonds, crushed core, and crack. The method is implemented in a potable NDT system which comes with position transducer. With it, the area of interests can be rapidly scanned and the defects information recorded without the need of setting up an x-y stage on the areas of inspections. The development of the easy-to-use system is able to provide more information about the material conditions which would allow better decision making in the repair and maintenance operations.

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