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Inspection of laminated composite materials by two ultrasonic techniques

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ABSTRACT

This paper presents some ultrasonic methods to detect and to characterize defects, possibly obtained after damage caused in composite materials. Firstly, artificial defects are located by two piezoelectric transducers. A two-dimensional ultrasonic cartography C-scan, performed section by section, at different positions which took part through the thickness of a carbon fiber-reinforced plastic composite beam, to be analyzed. Next, fundamental symmetric S_0 mode of Lamb waves is used to measure the size of the delamination by scanning over the surface beneath which a delamination lies. A remarkable decrease in the arrival time due to the delamination is detected, and the delamination length can be calculated based on a simple model for Lamb-wave propagation. Furthermore, the delamination edge is located as a sudden decrease in the amplitude. The rate of decrease in amplitude of an individual pulse cycle was detected to vary with the depth of the delamination, being most sensitive to delaminations near the surface of the plate. This is particularly useful when sizing for defects close to the surface, where a normal-incidence pulse-echo ultrasonic method has problems, particularly when the depth of the defect or the back-wall echoes lie within the length of the transmitted ultrasonic pulse. The technique has potential for faster c-scanning of a complete plate than the usual normal-incidence pulse-echo method.

***Keywords**: Ultrasonic C-scan, laminate plate, delamination, Lamb wave*

I. Introduction

Composite laminates are advantageous as structural components for aircraft and spacecraft because of their superior specific strength and stiffness. However, damage detection in composite laminates is difficult due to the anisotropy of the materials and the fact that much of the damage often occurs beneath the top surface. Therefore many researchers have been carried out on the techniques of real time health monitoring to monitor the onset and progress of structural damage during structures operations. Traditional nondestructive evaluation methods using X-ray and ultrasonic waves take long time and require heavy workload. Also these methods cannot be applied to in-service structures. Due to limitations the traditional damage detection methods, new nondestructive evaluation methods such as Lamb wave methods, frequency response methods, and other piezo-based methods for structural health monitoring have been proposed [1-2]. A lot of researches have been carried out on structural damage evaluation in composite and metallic structures using Lamb wave because it has several advantages of application [3–4]. Ultrasonic Lamb waves offer a convenient approach to evaluate composite laminates because they can propagate a long distance and their velocities are sensitive to the in-plane stiffness of laminates.

Many studies have been conducted to detect transverse cracks [5] and delamination [6] using the Lamb wave method. This paper develops a quick and quantitative inspection technique to detect and identify delamination, and evaluate its size and location using Lamb wave velocity and attenuation in composite laminates. We performed this technique and compared the estimated delamination size and location with the data obtained by a conventional C-scan.

II. Lamb waves in plate material

In an infinite solid, a longitudinal or transverse elastic wave can propagate. If this solid is limited by a free surface, the wave will interact with such a boundary. Therefore, a reflection of the wave will occur and conversion of longitudinal modes in transverse modes appears, and vice versa. Once the solid has a flat surface, different reflections on both sides of the solid gives rise to guided waves. These waves are known as one who discovered in 1917 that is to say, Sir Horace Lamb [7].The solutions of the equation of motion must satisfy the boundary conditions, which leads to equations dispersions symmetric Lamb modes (S) and anti symmetric (A).

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$$(k^2-q^2)^2\tan(q\frac{d}{2})+4k^2pq\tan(p\frac{d}{2})=0 \quad \textbf{(1)}$$

$$(k^2-q^2)^2\cot an(q\frac{d}{2})+4k^2pq\cot an(p\frac{d}{2})=0 \quad \textbf{(2)}$$

$$V_P=\frac{V_L}{\sin\theta} \quad \textbf{(3)}$$

The angle of incidence for generating Lamb waves is given by (3), where $\mathbf{V_L}$, is the incidence compression velocity, $\boldsymbol{\theta}$ is the incident angle and $\boldsymbol{V_P}$is the phase velocity of the Lamb waves along the plate. Lamb waves therefore can be generated by mode conversion. The phase velocity for a particular mode depends on the angle of incidence, the incident wave frequency and the thickness of the plate [10]. For a fixed plate thickness and frequency, selected modes of Lamb waves can be obtained by varying the angle of incidence of the transmitter. Figure 1 shows the Lamb wave dispersion curves for the laminate composites used in the experiments described in this paper [9]. There are only the fundamental symmetrical S_0, and asymmetrical A_0 modes. The A_0 mode is dispersive with the phase velocity increasing asymptotically to a constant value near to the Rayleigh wave velocity. The S_0 mode is constant up to about 2MHz×mm where it decreases sharply thereafter and tends to the same constant value as the A_0mode. The non-dispersive S_0 mode from 0 to about 2MHz×mm can be used for defect detection. By choosing an appropriate angle of incidence the S_0 mode can be generated in the plat

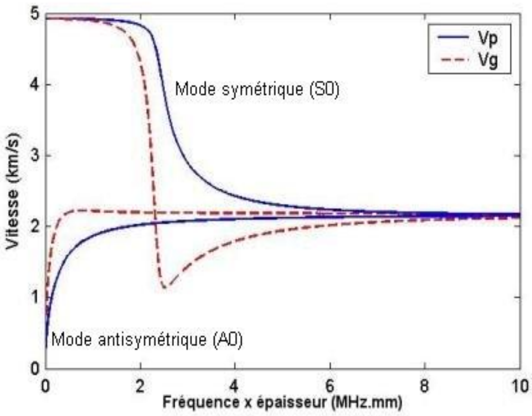

Fig 1. Dispersion curves for an 8 layer laminate composite

III. Experimental procedures

The material studied was carbon/epoxy (*Epocast 50-A1/9816*) composite laminates with stacking sequences of [0°,90°,45°,-45°]$_S$. This composite plate (*400 mm×400 mm*) was made of eight plies of woven fiber carbon. The average thickness of the cured plate was 2.3 mm. The thickness of the plies inside the cured plate was 0.27 mm. Artificial defects (delamination 20mm×30mm) were inserted between the adhesive film and the substrate. Each of the included defects simulates a different type of flaw that could appear on the assembly line. Some pieces of Teflon film, peel ply or separated film were inserted between 2ed/3ird ply and between 4th/5th before bonding. Figure (2) shows a typical specimen dimension with the tow simulated delamination sizes.

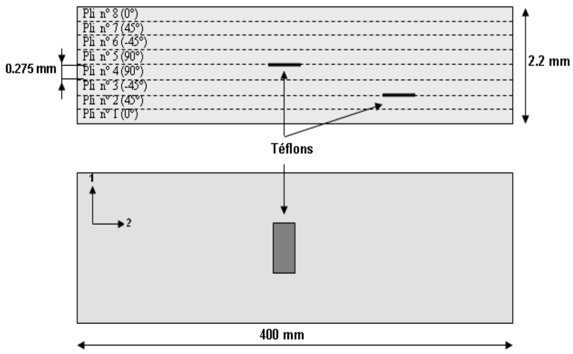

Fig 2. Typical location and size of delaminations

III.1.Interaction of S_0 mode with delamination

Figure (3) illustrates the experimental set-up for Lamb wave generation and detection. A variable-angle-beam transducer consisting of a broadband transducer element (0.5 MHz, Panametric) and a Perspex wedge (ABWX-2001, Panametric) was used as the ultrasonic transmitter to excite Lamb waves. In order to generate a pure S_0 mode, the angles of incidence were determined by Snell's law as (3) [9]. Both the transmitter and receiver were mounted on the surface of the laminate via a coupling gel, separated with a distance of 100mm.A pulse generator (5800Pr OLYMPUS), is used to provide electrical power in pulsedurationof5µs. The detected signals were amplified and transferred to a digital oscilloscope (TDS 3054, Tektronix), which carried out 100 averages to improve the signal-to-noise ratio.

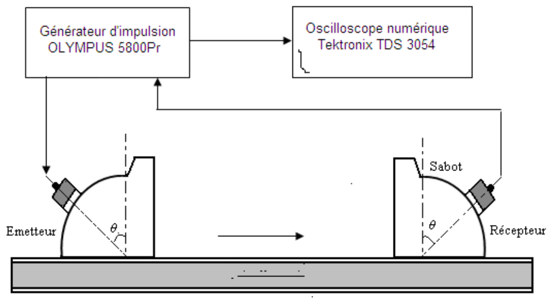

Fig 3: S_0 Lamb wave mode generation and detection.

The transmitter and receiver were then positioned at a defect-free area adjacent to where a delamination was situated. We obtain a reference signal which corresponds to theS_0 Lamb mode in an area. Then again take the signal obtained with two artificial delaminations. From time signals were can draw the corresponding frequency spectra.

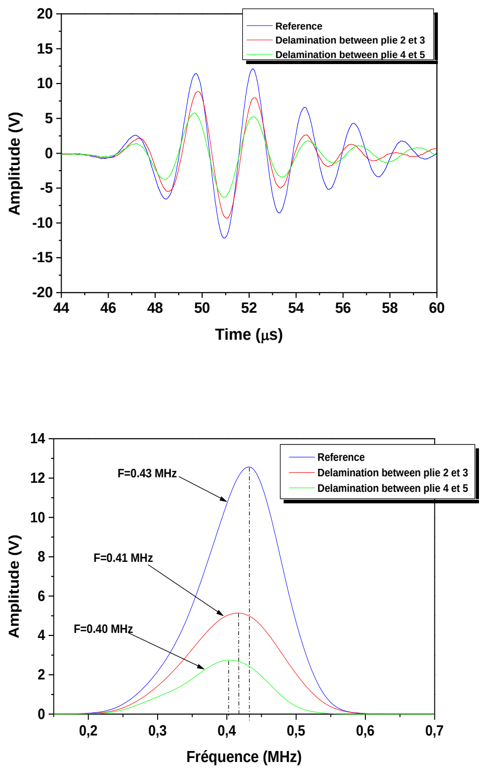

Fig 4: Waveform detected of two different delaminations

When Lamb wave incident meeting a defect delamination near the surface (between the second and 3rdfolds), it is possible to observe a decrease in amplitude of the received signal and a shift frequency to the left. This reduction is due to the separation of the wave front to delamination, and a major portion of energy is drawn by thicker sections of the laminate. The signal is taken just above a shallow delamination (between4th and 5thplies), a significant decrease in amplitude was noted.

In order to detect and identify delamination, and evaluate its size and location, a new method using Lamb wave velocity and attenuation was developed [8]. The method illustrated in *Figure 5*, consists in comparing the signal amplitude inspecting delamination. The transmitter– receiver system is moved in a line parallel to the Y axis containing the major axis of the delamination. The objective inspection area within the plate was 110 mm long and 200 mm wide. Experimental results of the transition of the normalized maximum amplitude of the earliest wave packet are provided in *Figure 6*. A sudden change (decrease) in the maximum amplitude of the earliest wave was observed in the presence of the delamination, and the lower amplitude was maintained even beyond the delamination. We could therefore estimate the detectable delamination length about 27 mm. These experimental results show the feasibility of foam damage detection using Lamb waves. However, we could detect and identify the delamination and estimate its size and linear location.

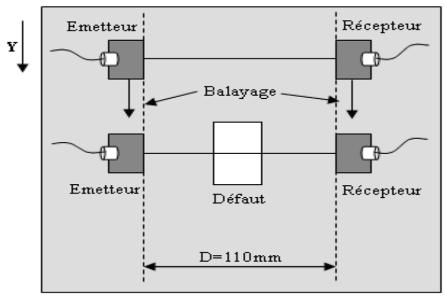

Fig 5. Schematic representation of line-scanning method

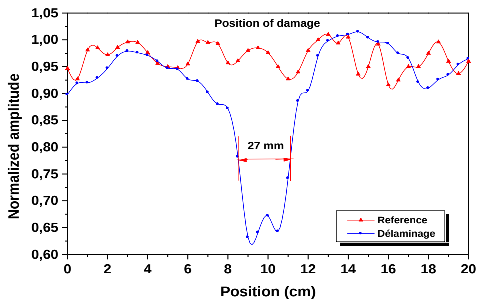

Fig 6. Normalized amplitude measurements

III.2. Comparison with C-scan results

We performed a conventional C-scan to validate the present method. Two piezoelectric transducers (9.5 mm diameter with a center frequency of 5 MHz) were positioned face to face. The distance between the two devices is about 4 cm. The composite plate was placed on a XY motorized table. The receiver transducer measures the transmitted signal through the plate and the maximum of the amplitude was stored by a computer. The inspection area was 90 mm 90 mm, including the delamination, and was scanned in steps of 2 mm. *Figure 7* presents the C-scan image depicting the delamination. We confirmed that the delamination was nearly rectangular15 mm long and 25 mm wide mm so we demonstrated that the present method accurately evaluated the size and location of delamination.

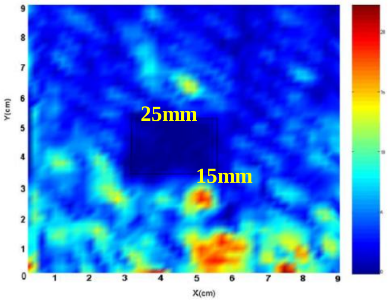

Fig 7.C-scan image of delamination

IV. Conclusions

This work has intended to establish the feasibility of monitoring damage in composite laminates by the use of Lamb waves. The first results induce important remarks. The propagation of ultrasound by the Lamb wave technique is possible. Using the maximum and minimum values of the received amplitude and arrival times of the transmitted S_0 mode along the Y direction, we were able to identify the delamination and quantitatively evaluate it size and linear location by measure the transition of the maximum amplitude of the earliest wave packet in a line including the major axis of the delamination. A sudden drop in the amplitude was clearly observed, and we were able to determine the location of the delamination edge. The decrease in signal amplitude is very sensitive to delaminations near to the surface of the plate. This is particularly useful when sizing for defects close to the surface, where the normal incidence pulse-echo ultrasonic method has problems, particularly when the depth of the defect or the back wall echoes lie within the length of the transmitted ultrasonic pulse. A conventional C-scan validated this method, and we confirmed our method has great potential for quick inspection of impact-induced delamination in composite structures. However, the propagation mechanisms have to be modelized, in order to confirm the hypothesis formulated about the waves propagation in composite laminate.

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