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Laser Generation and Detection of Zero-group Velocity Lamb Modes for Plate and Adhesive Disbond Characterization

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Abstract
A non-contact laser based ultrasonic technique is proposed for detecting plate thickness variations due to corrosion and adhesive disbonds between two plates. The method exploited the resonance at the minimum frequency of the S_1 Lamb mode dispersion curve. At this minimum frequency the group velocity vanishes, whereas the phase velocity remains finite. The energy deposited by the laser pulse, generates a local vibration of the plate. This vibration is detected at the same point by an optical interferometer. The spatial resolution is limited by the laser source diameter, *i.e.* to approximately twice the plate thickness. First experiments show the ability to detect a 1.5-µm deep corroded area on the back side of a 0.5 mm thick Duralumin plate. With the same technique we investigate the state of adhesive bonds between Duralumin and glass plates. The S_1-mode resonance is strongly attenuated when plates are rigidly bonded. In the case of small adhesive layers, we observed others resonances, associated with ZGV modes of the multi-layer structure, whose frequencies and amplitudes vary with adhesive thickness.
Keywords: Adhesive disbond, Lamb mode, Zero group velocity, Laser-based ultrasounds

1. Introduction

The use of adhesive bonding, particularly in automotive and aerospace industries, has been motivated by the need for stronger and lighter structures. Compared to other techniques like riveting or screwing, adhesive bonding is easier to process and provides continuous adhesion properties. Moreover, it does not modify the assembled materials like welding. However, manufacturing defects or degradation during service in the lap joint cause failure of the bond-line leading to corrosion of the structure. Then, one factor limiting the use of adhesive bonding is the lack of fast and reliable non-destructive testing (NDT) methods. For the detection of defects in lap-joint, the most popular NDT methods are radiography, eddy current and ultrasonic techniques. Each of them suffers its own disadvantages. Conventional ultrasonic inspection requires a coupling medium (liquid, gel or rubber) for allowing the transmission of the ultrasound into the piece under test [1]. Non-contact ultrasonic techniques using EMAT [2] or air-coupled transducers [3] have been investigated over the years. Laser Based Ultrasonics (LBU) techniques eliminate coupling issues in the generation and detection of elastic waves and have the potential for fast scanning. Owing to its large bandwidth, LBU is an efficient method to study the propagation of Lamb modes in a plate [4].

2. Zero Group Velocity Lamb modes

Lamb modes (frequency f, wavelength λ) are represented by a set of curves giving the angular frequency ω of each symmetric (S) and antisymmetric (A) mode versus the wave number k. Figure 1 shows the dispersion curve of the lower order modes for a

Duralumin plate of thickness d (longitudinal wave velocity V_L = 6.34 km/s and transverse velocity V_T = 3.14 km/s). We have plotted the variations of the frequency thickness product $fd = \omega d/2\pi$ versus the thickness to wavelength ratio $d/\lambda = kd/2\pi$. The A_0 and S_0 modes exhibit free propagation to zero frequency whereas higher order modes admit a cut-off frequency f_c when the wave number k approaches zero. Conversely to other modes, the first order symmetric (S_1) mode exists for small wave numbers at values of fd below its cut-off frequency f_c. The slope of the dispersion curve is negative and the frequency begins to increase at a critical point ($k_0 d$ = 1.58, $f_0 d$ = 2.866 MHz.mm) where the frequency undergoes a minimum and then the group velocity $d\omega/dk$ vanishes. In contrast with the cut-off modes, at this ZGV point, the S_1-mode phase velocity remains finite (V_0 = 11.25 km/s).

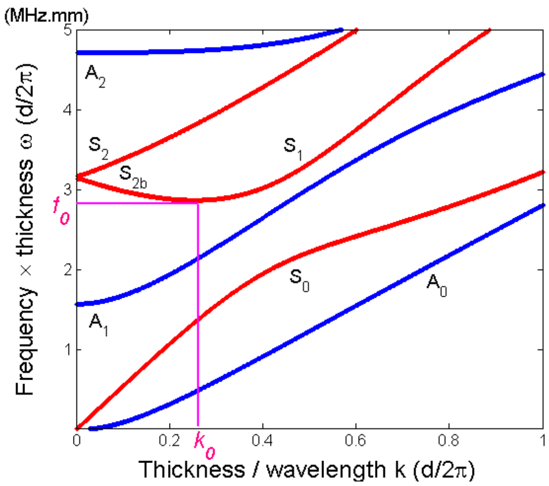

Figure 1. Dispersion curves for a Duralumin plate of thickness d and bulk wave velocities equal to V_L = 6.34 km/s and V_T = 3.14 km/s. Vertical scale: $fd = \omega d/2\pi$, horizontal scale: $d/\lambda = kd/2\pi$.

At this zero group velocity (ZGV)-point the energy, which cannot propagate in the plate, is trapped under the source. This sharp and local resonance effect was observed with the first order symmetric (S_1)-Lamb mode. For example, using focussing, air-coupled transducers, Holland and Chimenti [5] found an efficient transmission of airborne sound waves through a thick plate at the S_1-ZGV resonance frequency f_0. This resonance occurs at a frequency smaller than the thickness resonance frequency $V_L/2d$ of the S_1 mode:

$$f_1 = \beta_1 \frac{V_L}{2d}, \qquad \text{with} \qquad \beta < 1. \tag{1}$$

The value of the dimensionless parameter β depends only on the Poisson's ratio ν [6]. A similar result was obtained in the case of a thin tungsten sheet mechanically excited at 45 MHz by an intensity modulated laser diode and detected with an optical interferometer at the same point of a metallic plate [7]. The S_1-ZGV resonance can also be excited by a laser pulse and optically detected in the time domain [8]. Recently, it has been shown that ZGV resonances can be exploited for measuring plate thickness, attenuation coefficient, Poisson's ratio and bulk wave velocities of thin plates [9,10].

In the following, we show that they can be used for detecting very small plate thinning and for investigating the state of an adhesive bond between two plates.

3. Experimental results

Lamb waves were generated by a Q-switched Nd:YAG laser providing pulses having a 20-ns duration and 4-mJ of energy (Fig. 2). The spot diameter of the unfocused beam is equal to 1 mm. Prada et *al* show that for a laser spot diameter equal to half the S_1-ZGV wavelength λ_1, the efficiency of the thermoelastic generation is larger than for other Lamb modes [11]. Numerical simulations show that the optimal conditions are approximately fulfilled when the spot diameter is of the order of twice the plate thickness.

The local vibration of the plate was detected by a heterodyne interferometer equipped with a 100-mW frequency doubled Nd:YAG laser [12]. This interferometer is sensitive to any phase shift along the path of the optical probe beam. The calibration factor (10 nm/V) for mechanical displacement normal to the surface and the sensitivity (0.1 nm) were constant over a large detection bandwidth (50 kHz-40 MHz). Signals detected by the optical probe were fed into a digital sampling oscilloscope and transferred to a computer. In all experiments the source and detection points are superimposed. The laser energy absorption heats the air in the vicinity of the surface and produces a variation of the optical index along the path of the probe beam. The resulting phase shift induces a very large low frequency voltage, which saturates the electronic detection circuit. This spurious effect is eliminated by interposing a high-pass filter having a cut-off frequency equal to 1 MHz.

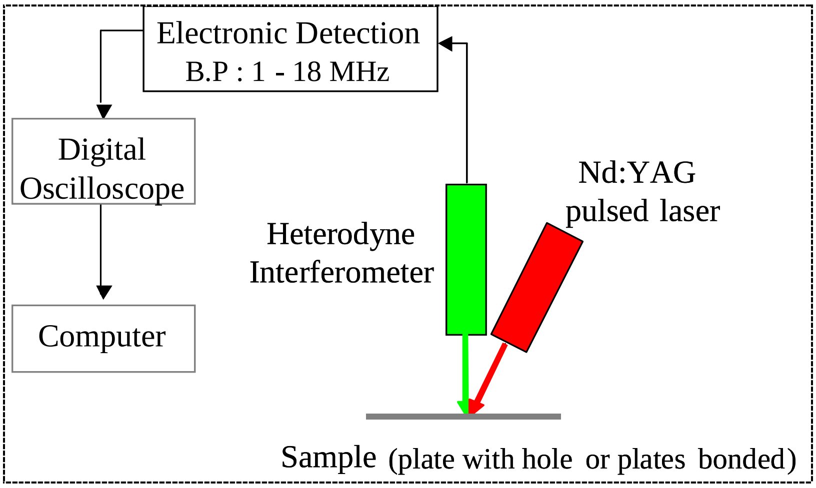

Figure 2. Experimental set-up.

Fig. 3 shows the temporal signal and the spectrum measured on a 0.49-mm thick Duralumin plate. The detected signal is dominated during first 10 µs by slow oscillations associated to the A_0 mode. After a ringing effect at a higher frequency associated to the S_1-ZGV Lamb mode is observed. The measured resonance frequency (5.86 MHz) is very closed to the expected one (f_1 = 5.84 MHz) given by Eq.1 with V_L = 6.34 km/s, d = 0.49-mm and β = 0.903.

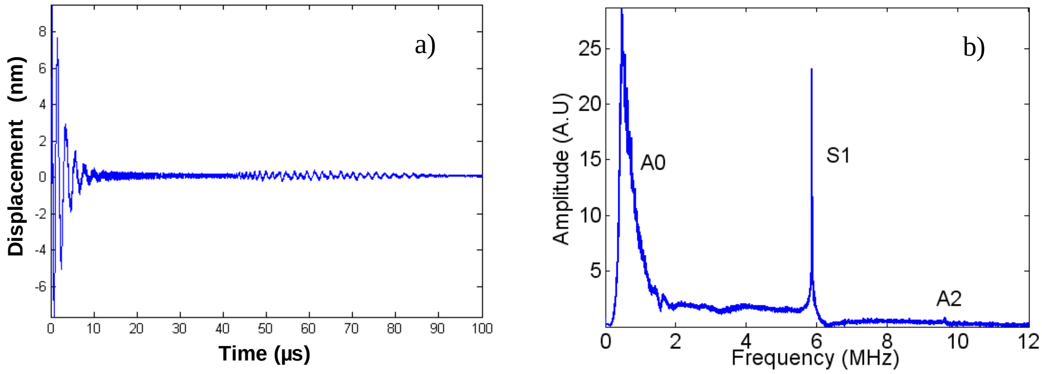

Figure 3. (a) Normal displacement and (b) spectrum generated by the absorption of the YAG-laser pulse on a 0.49-mm-thick Duralumin plate and detected at the same point by an optical heterodyne interferometer.

3.1 Analysis of a corroded area

The back face of the plate was corroded by exposure to a H_3PO_4–C_2H_5OH solution. The corrosion speed of this mixture is assumed to be the same that for aluminium: 0.05 µm/min. The exposure time was 30 min, so that the local plate thinning was expected to be 1.5 µm. A 15×15 mm^2 C-Scan image by 0.2 mm-step with superimposed source and detection points was made after corrosion. Due to surface roughness of the plate and the smooth profile of the wash, the acquisition time was limited to 40 µs. The image of thickness d, deduced from the frequency f_1 of the S_1-ZGV mode resonance, is plotted in Fig. 4b, revealing a quasi-circular wash with a maximum depth of 1.5 µm. In comparison with Fig. 4a, we observe a good spatial resolution and a slow decreasing slope on the edges of the wash. These results, close to the expected values both in depth and space, confirm the potential applications of this method for measuring very small relative plate thickness variations (< 0.1 µm) due for example to early corrosion.

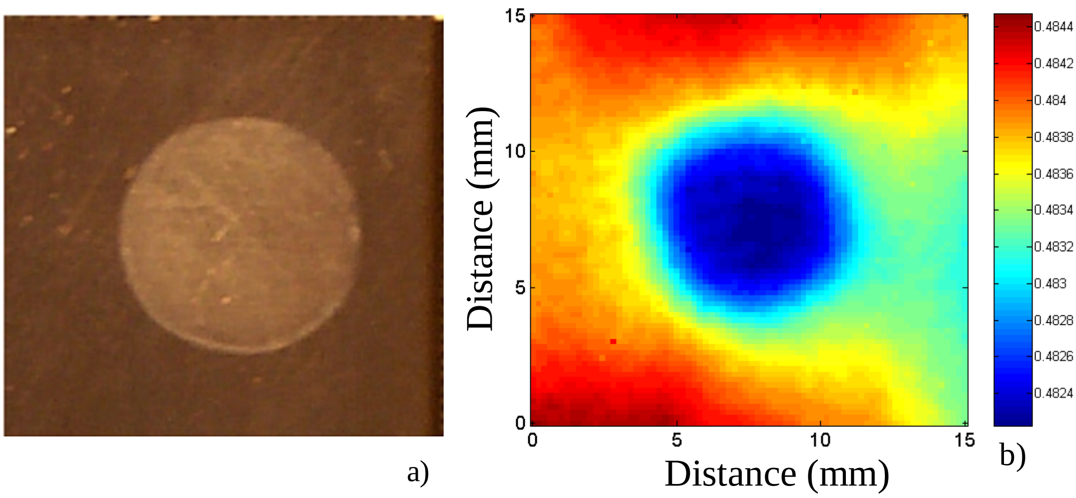

Figure 4. (a) Photography of corroded area ; (b) thickness d (mm) of S_1-ZGV Lamb mode.

3.2 Analysis of an adhesive disbond

First experiments were carried out on a 0.5 mm thick Duralumin plate bonded with a 0.2 mm thick epoxy layer to a 2 mm thick glass plate. The thickness of the joint was controlled by interposing a rigid film between the two plates. In the centre, an air bubble was imprisoned, the shape of which was not controlled. The air bubble and a dendrite can be observed on figure 5a. In order to obtain more precision about the shape of the bubble, we integrate the signal only during the first 7.5 µs. Fig. 5b is an amplitude C-scan image (30×30 mm^2 by 0.25 mm step) of the S_1-mode resonance in the frequency range 5.8 - 6.4 MHz. The spatial resolution (1 mm) is of the size of the laser spot. The ZGV resonance disappears when the two plates are rigidly bonded. A 25-dB amplitude contrast is observed when the source and detection points lie on a disbonded area. The attenuation of the S_1-mode resonance is due the presence of the thick (0.2 mm) epoxy layer. The comparison between the two views in Fig.5, shows that this laser ultrasonic method based on the local resonance of the S_1-ZGV Lamb mode, gives a valuable information with a large contrast on adhesive disbonds.

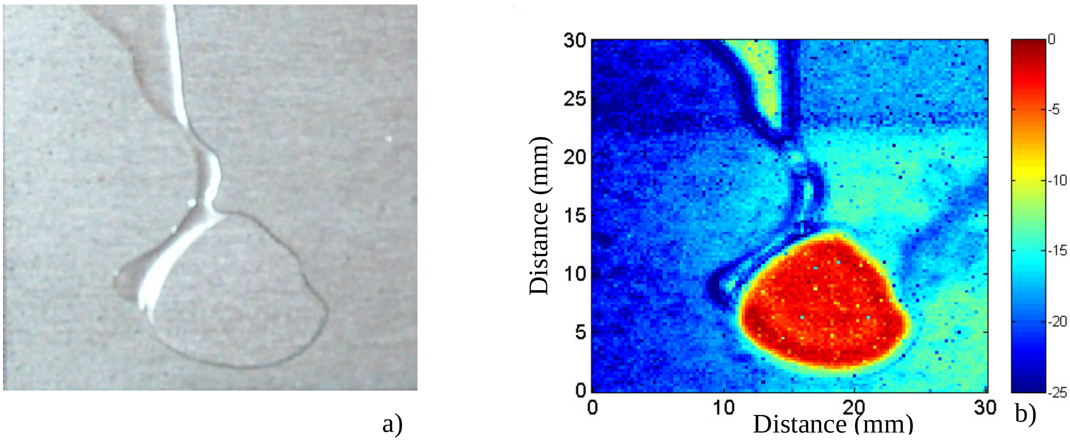

Figure 5. (a) Photography of disbond area ; (b) Amplitude (in dB) of S_1-ZGV Lamb mode.

In order to test this method in a non-destructive configuration, two 0.5-mm thick plates of Duralumin were bonded with a 0.2-mm thick epoxy layer and a disbonded arbitrary area. Fig. 6.a represents C-scan image (20×20mm^2 by 0.25mm step) of the amplitude variations in the frequency range 5.95 - 6.2 MHz. The presence of an air bubble is detected by the attenuation of the *S*1-ZGV Lamb mode resonance, with a 25-dB contrast ratio. We don't observe close to half frequency the resonance corresponding to the sum of the two plates. A non-negligible component of transverse displacement is probably affected by the presence of the thick viscoelactic layer.

In previous experiments we observe that the S_1-ZGV Lamb mode resonance disappears when plates are rigidly bonded by a thick epoxy layer. Now, we analysed the influence of a thin adhesive layer thickness. In this experiment, we have bonded a 0.5-mm thick Duralumin plate to a 1.08 mm thick glass plate with a variable thin layer of cyanolite. The thickness varies from 0 to 40 µm over a distance of 60 mm. Fig. 6.b represents the spatial Fourier transform in the frequency range 0.5 - 7 MHz obtained by integrating the signal on the first 15 µs. Abscissa lower than 20 mm and larger than 75 mm correspond to a zone without glue. In presence of thin layer of glue, we observe three supplementary resonances close to 1.5, 3 and 5 MHz the frequency of which decreases linearly with the thickness glue increase. For the three resonances, the frequency variation is close to 0.3 MHz and the decrease is inversely proportional to the joint thickness. Around the S_1-ZGV Lamb mode resonance, we observe multiple resonances whose variations in amplitude are thickness joint dependent.

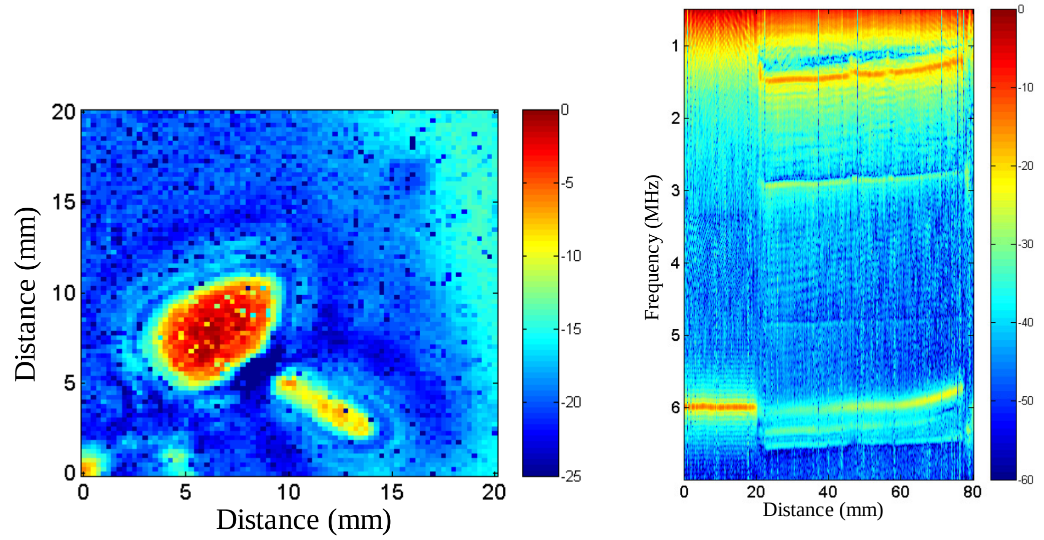

Figure 6. (a) Amplitude (in dB) of S_1-ZGV Lamb mode for two 0.5-mm thick Duralumin plates rigidly bonded and (b) Spatial Fourier transform (in dB) with variable thickness glue (0.5-mm thick Duralumin and 1.08-mm thick glass plates).

In order to understand the existence and the frequency response in this multilayer sample, numerical calculations of dispersion curves including Duralumin, glass and glue parameters must be performed.

4. Conclusions

We have demonstrated that a laser ultrasonic system can be used to generate and to detect at the same point the resonance of the S_1-ZGV Lamb mode in various plate-like structures. By scanning the sample relative to the laser beams, it has been shown that it is possible to image very small plate thinning and adhesive disbond in epoxy glue layers. This non contact system provides comparable results to a conventional immersion ultrasonic system. Further work is presently carried on in order to extend the investigation to the degradation of real bonded lap joints.

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