Laser Ultrasonic Inspection of Plates Using Zero-Group Velocity Lamb Modes

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***Abstract*—A noncontact laser-based ultrasonic technique is proposed for detecting small plate thickness variations caused by corrosion and adhesive disbond between two plates. The method exploits 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 resonance of the plate. This vibration is detected at the same point by an optical interferometer. First experiments show the ability to image a 1.5-μm deep corroded area on the back side of a 0.5-mm-thick duralumin plate. Because of the finite wavelength of the S_1- zero group velocity (ZGV) mode, the spatial resolution is limited to approximately twice the plate thickness. With the same technique we investigate the state of adhesive bonds between duralumin and glass plates. The S_1-Lamb mode resonance is strongly attenuated when plates are rigidly bonded. In the case of thin adhesive layers, we observed other resonances, associated with ZGV modes of the multi-layer structure, whose frequencies and amplitudes vary with adhesive thickness. Experiments were carried out on real automotive adhesively bonded structures and the results were compared with images obtained by X-ray radiography.**

I. Introduction

The use of adhesive bonding, particularly in the automotive and aerospace industries, has been motivated by the need for stronger and lighter structures. Compared with other techniques like riveting or screwing, adhesive bonding is easier to process and provides continuous adhesion properties. Moreover, it does not distort assembled materials like welding does, and it allows the joining of dissimilar materials. The most common use is the lap joining of two metal plates such as aluminum and steel. The thickness of the adhesive layer is in the range of 0.1 to 0.5 mm and the metal sheets are typically 0.5 to 2 mm thick. However, manufacturing defects in the lap joints or degradation during service can cause failure of the bondline, leading to corrosion of the structure. One factor limiting the use of adhesive bonding is the lack of fast and reliable non-destructive testing (NDT) methods [1]. For the detection of defects in lap-joints, the most popular NDT methods are radiography, eddy current, and ultrasonic techniques [2]. Over the last few decades, various NDT ultrasonic methods have been developed [3]–[5]. Conventional ultrasonic testing requires a coupling medium (liquid, gel, or rubber) for allowing the transmission of the ultrasound into the piece under test [6]. Noncontact ultrasonic techniques using EMATs [7] or air-coupled transducers [8] have been investigated. Laser based ultrasonic (LBU) techniques eliminate coupling issues in the generation and detection of the elastic waves and have the potential for fast scanning. In this technique, elastic waves are generated by a pulsed laser and detected by an interferometric optical probe [9]–[11].

The overall quality of a joined region depends on the adhesion between the layer and the metal sheets as well as the cohesive strength of the adhesive layer. These problems are beyond the scope of this paper, which is primarily focused on the detection of voids, disbonds, and layer thickness variations. It has been shown that LBU is an efficient method for studying the dispersive propagation of Lamb modes in a plate [12]–[14]. The method proposed here does not use propagating Lamb modes. It exploits the local resonances of the structure that appear at frequencies where the group velocity of some modes vanishes. At these particular points of their dispersion curves, the acoustical energy of the corresponding zero group velocity (ZGV) modes is trapped in the source area without any transfer to the adjacent plate medium. The resulting local resonance is sensitive to the plate material properties [15] and to the surface state. The objective of this paper is to show that these ZGV modes can be used for detecting small plate thinning flaws and for investigating the integrity of an adhesive bond between two plates. Compared with techniques using propagating Lamb modes [16], this method has the advantages that it is localized and more sensitive.

II. Zero Group Velocity Lamb Modes

Guided waves (frequency f, wavelength λ) propagating in a homogeneous isotropic plate are either symmetric or antisymmetric [17]. For each family, the angular frequency $\omega = 2\pi f$ and the wave number $k = 2\pi/\lambda$ satisfy a secular or frequency equation [18], [19]. When the faces of the plate are free of traction, no energy leakage occurs. Then, for any real k, the secular equation yields an infinite number of real roots in ω. The dispersion curves of these symmetric (S_n) or antisymmetric (A_n) propagative Lamb modes are represented by a set of branches in the (ω, k) plane. When the wave number approaches zero, the fundamental modes A_0 and S_0 exhibit free propagation to zero frequency, whereas high-order modes exhibit a finite limit. At these cut-off frequencies f_c, corresponding to a thickness resonance of the plate, the group velocity V_g

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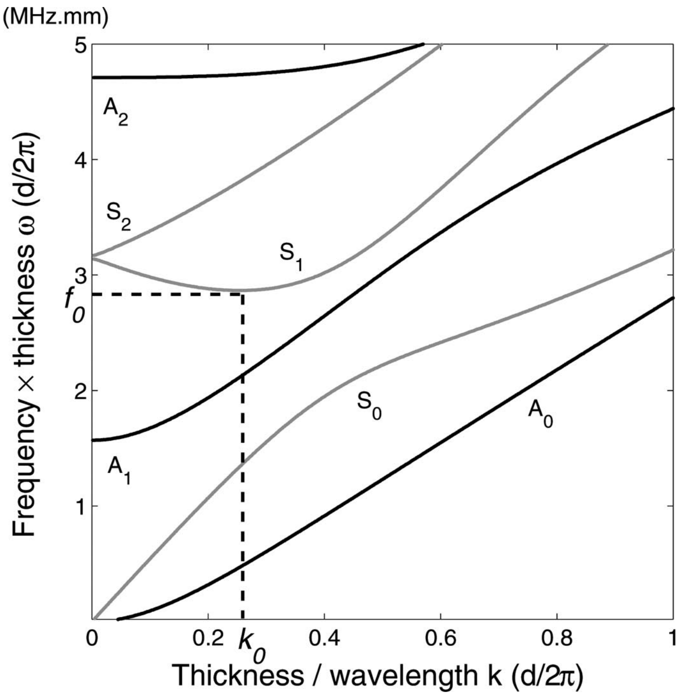


Fig. 1. Dispersion curves for Lamb waves propagating in a duralumin plate of thickness d and velocities $V_L = 6.34$ km/s and $V_T = 3.14$ km/s. Vertical scale: $fd = \omega d/2\pi$, horizontal: $d/\lambda = kd/2\pi$. The dashed lines indicate the position of the S_1-ZGV mode.

$= d\omega/dk$ vanishes, whereas the phase velocity $V = \omega/k$ becomes infinite.

Fig. 1 shows the dispersion curve of the lower-order Lamb modes for a duralumin plate (AA2024 composition 93.5% Al, 4.4% Cu, 1.5% Mg, and 0.6% Mn by weight) of thickness d (longitudinal wave velocity $V_L = 6.34$ km/s and transverse velocity $V_T = 3.14$ km/s, measured by the pulse-echo technique). The variations of the frequency thickness product $fd = \omega d/2\pi$ versus the thickness to wavelength ratio $d/\lambda = kd/2\pi$ show that for some Lamb modes, the group velocity $V_g = d\omega/dk$ vanishes, whereas the phase velocity $V = \omega/k$ remains finite. For the first order symmetric (S_1) mode, a minimum occurs at the finite wave number k_0 and at a frequency f_0 smaller than the thickness resonance frequency: $f_c = V_L/2d$. In contrast with the cut-off modes, at this ZGV point, the phase velocity remains finite ($V_0 = 11.25$ km/s)

For wave numbers smaller than k_0, the S_1-Lamb mode exists at frequencies smaller than f_c. In this region, the slope of the dispersion curve is negative. The frequency begins to increase at a point ($\lambda_0 = 3.98d$, $f_0 d = 2.866$ MHz·mm) where it undergoes a minimum. This ZGV-Lamb mode exhibits a specific behavior: the acoustic energy, which cannot propagate in the plate, is trapped under the source. Using focused, air-coupled transducers, Holland and Chimenti [20] observed a sharp and local resonance corresponding to the minimum frequency f_0 of the S_1-Lamb mode:

$$f_0 = \beta \frac{V_L}{2d}, \quad \text{with } \beta < 1, \tag{1}$$

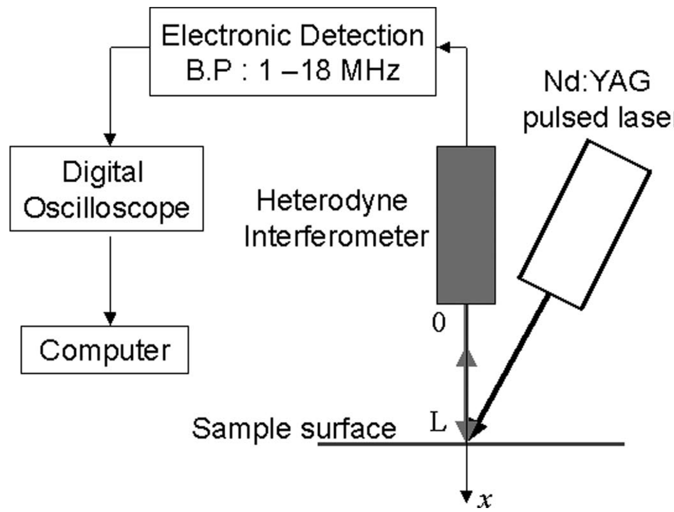


Fig. 2. Laser-ultrasonic setup.

where β is the shape factor introduced by Sansalone and Carino [21]. Gibson and Popovics showed that the value of the dimensionless parameter β depends only on the Poisson's ratio ν [22]. If the material parameters are known, the plate thickness d can be deduced from the measurement of ZGV resonance frequency, as in the impact echo method used in civil engineering.

A similar result was obtained in the case of a thin tungsten sheet excited at 45 MHz by an intensity modulated laser and detected with an optical interferometer at the same point on the plate [23]. The S_1-ZGV resonance can also be excited by a laser pulse and optically detected in the time domain [24]. Recently, it has been shown that the local resonance spectrum of an unloaded elastic plate is entirely governed by the ZGV Lamb modes [25] and that these resonances can be exploited for measuring the Poisson's ratio ν, the bulk wave velocities, and the attenuation coefficient of thin plates [15], [26].

In the experiments, 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). As the efficiency of the thermoelastic generation is greater than for other Lamb modes, for a source diameter equal to half the S_1-ZGV wavelength $\lambda_0 \approx 4d$, the optimal conditions are approximately fulfilled when the spot diameter is of the order of twice the plate thickness [27]. Thus, plates of thickness in the millimeter range can be investigated with an unfocused beam of diameter equal to 1 mm.

The local vibration of the plate was detected by a heterodyne interferometer of the Mach-Zehnder type, equipped with a 100-mW frequency-doubled Nd:YAG laser (optical wavelength $\Lambda_0 = 532$ nm). Signals detected by the optical probe were fed into a digital sampling oscilloscope and transferred to a computer. This interferometer is sensitive to any phase shift along the path of the optical probe beam reflected by the moving surface [28]. The contribution $\Delta\phi_u$ caused by the local vibration of the plate is proportional to the component u of the mechanical displacement normal to the surface:

$$\Delta\phi_u = \frac{4\pi}{\Lambda_0} u. \qquad (2)$$

In all measurements, the source and detection points are superimposed. The laser energy absorption heats the air in the vicinity of the surface and produces a variation Δn of the index along the optical path of the probe beam ($0 < x < L$). The resulting phase shift,

$$\Delta\phi_n = \frac{4\pi}{\Lambda_0} \int_0^L \Delta n(x) \mathrm{d}x, \qquad (3)$$

induces a very large low-frequency voltage, which saturates the electronic detection circuit. This spurious thermal effect is eliminated by interposing a high-pass filter having a cut-off frequency equal to 1 MHz. This filtering also eliminates the low-frequency components of A_0 mode. 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 (1 to 18 MHz).

Fig. 3(a) is a typical example of signal detected on a 0.49-mm duralumin plate at the same point as the emission. Besides the low-frequency spread spectrum corresponding to the A_0 Lamb mode, the prominent feature of the spectrum in Fig. 3(b) is a very sharp peak at 5.87 MHz. From (1) and with $\beta = 0.903$ for duralumin ($\nu = 0.337$), it was found that this value is very close to the resonance frequency $f_0 = 5.85$ MHz predicted for the S_1-ZGV Lamb mode. The resonance frequency was determined from the position of the maximum with an accuracy better than 1 kHz, and no significant change was observed from one experiment to the other.

In a homogeneous plate, the spatial resolution is equal to half the S_1-ZGV wavelength λ_0 i.e., to about twice the plate thickness d. In practice, this feature is also limited by the plate thickness variations in the source area and the acquisition time. The group velocity vanishes exactly at the ZGV point, i.e., for the frequency thickness product $f_0 d_0$. Because of small thickness variations, $\Delta d = d - d_0$, propagating Lamb waves are launched with a finite group velocity. If the acquisition time Θ is too large, the energy spreads out laterally from the interrogation point and the spatial resolution is reduced. In the vicinity of the ZGV point, the dispersion curve can be approximated by a parabola [26]

$$\omega d = \omega_0 d_0 + \delta V_{\mathrm{T}} \, (kd - k_0 d_0)^2, \qquad (4)$$

where the dimensionless coefficient δ only depends on the material's Poisson's ratio ν. The group velocity $V_{\mathrm{g}} = 2\delta V_{\mathrm{T}} \, (kd - k_0 d_0)$ can be expressed as:

$$V_{\mathrm{g}} = 2 \, (\delta V_{\mathrm{T}})^{1/2} \, (\omega d - \omega_0 d_0)^{1/2}. \qquad (5)$$

At the minimum frequency: $\omega_0 = \pi\beta V_{\mathrm{L}}/d_0$, variations V_{g} in the group velocity are caused by variations Δd in the plate thickness according to

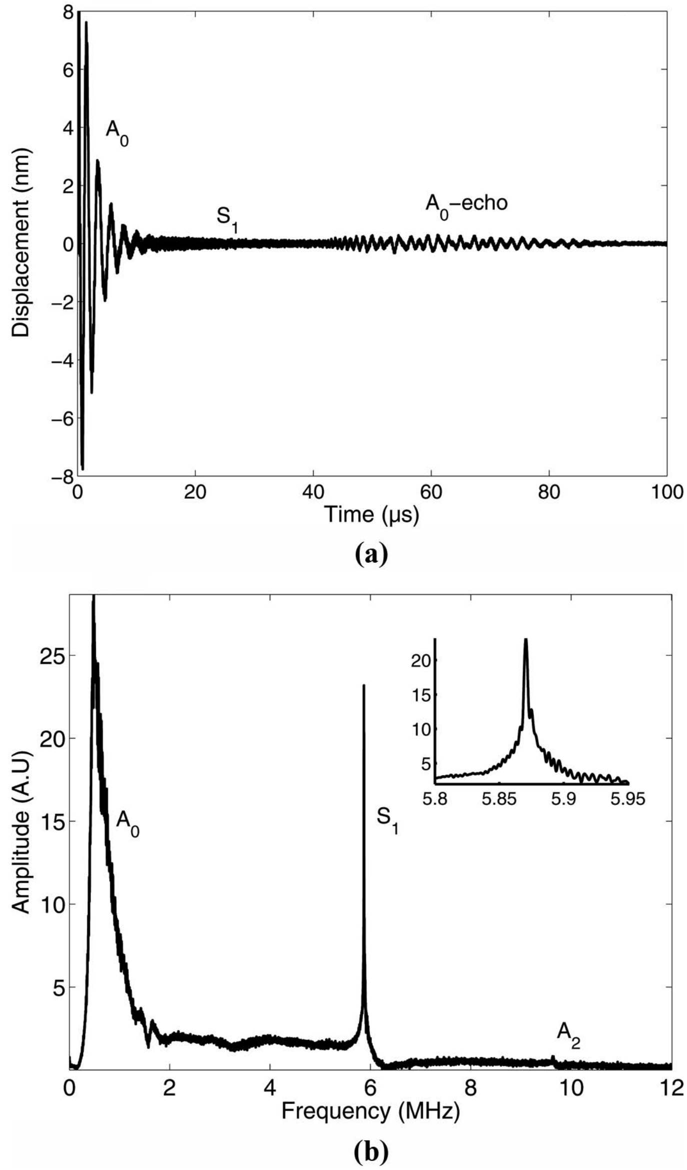


Fig. 3. Normal displacement (a) generated by the Nd:YAG-laser pulse on a 0.49-mm-thick duralumin plate and detected at the same point by an optical heterodyne interferometer. (b) Frequency spectrum.

$$V_{\mathrm{g}} = 2 \, (\pi\delta\beta V_{\mathrm{L}} V_{\mathrm{T}})^{1/2} \left| \frac{\Delta d}{d_0} \right|^{1/2}. \qquad (6)$$

For duralumin or steel plates used in the experiments ($d_0 = 0.5$ mm, $\nu \cong 0.34$, $\beta \cong 0.9$, and $\delta \cong 0.3$), the relative plate thickness variations $\Delta d/d_0$ in the source area can be estimated as 0.5×10^{-4}. Thus $V_{\mathrm{g}} \cong 60$ m/s and the acquisition time Θ must be limited to $d_0/V_{\mathrm{g}} \cong 8$ μs to achieve a spatial resolution equal to 1 mm. However, reducing the acquisition time too much enlarges the resonance peak and thus reduces the accuracy of the frequency and thickness measurements. Thus, the choice of this parameter is a trade-off between these constraints. Experimentally, best results are obtained with values in between 5 and 50 μs.

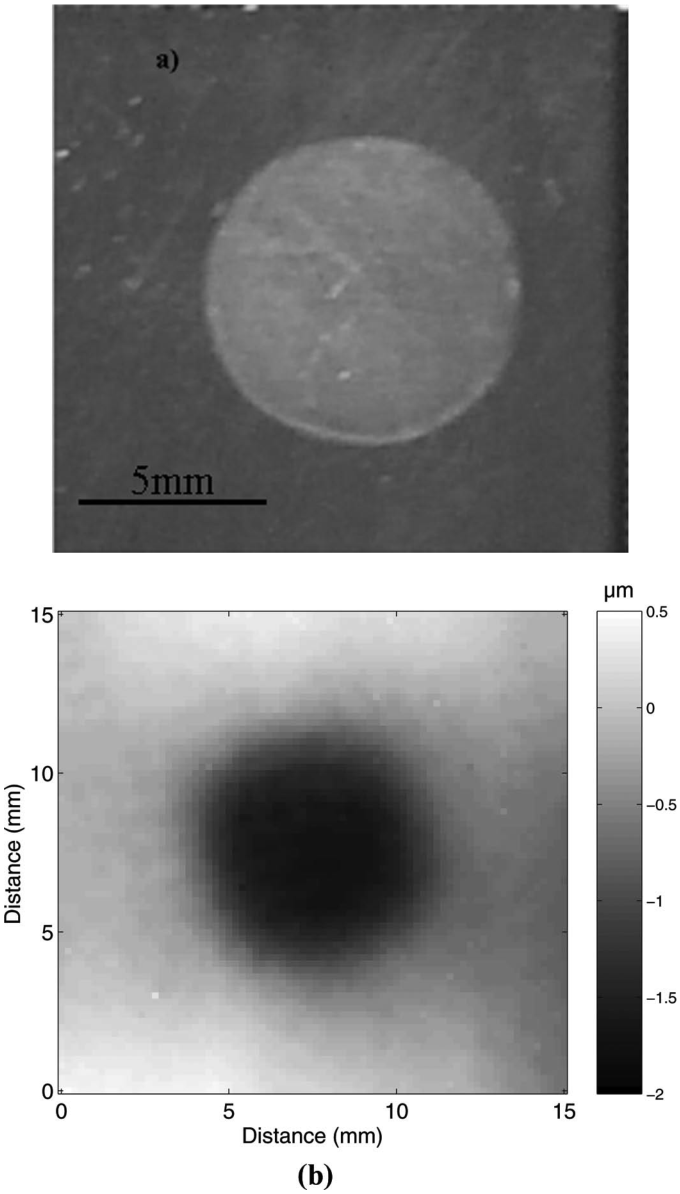


Fig. 4. Detection of plate thinning. (a) Photograph of the corroded area, (b) C-scan image of variations (μm) of the plate thickness.

In the following section, we demonstrate the ability of this technique to image an area with very shallow corrosion on the backside of a duralumin plate.

III. Detection of a Corroded Area

In the case of a low-loss material such as duralumin, the quality factor Q can be very large ($Q > 10^3$) provided that the acquisition time is sufficient ($\Theta > Q/f_0$). This very sharp peak allows us to measure small plate thickness variations from the shift of the ZGV resonance frequency:

$$\Delta d = -d_0 \frac{\Delta f_0}{f_0}. \tag{7}$$

The back face of the duralumin plate was corroded by exposure to a H_3PO_4–C_2H_5OH solution [Fig. 4(a)]. The corrosion speed of this mixture (0.05 μm/min on aluminum) is assumed to be the same for duralumin. The exposure time was 30 min, so that the local plate thinning was expected to be 1.5 μm. The chemical etching did not modify the material parameters in the bulk of the plate. Thus, the resonance frequency variations only depends on the thickness variations.

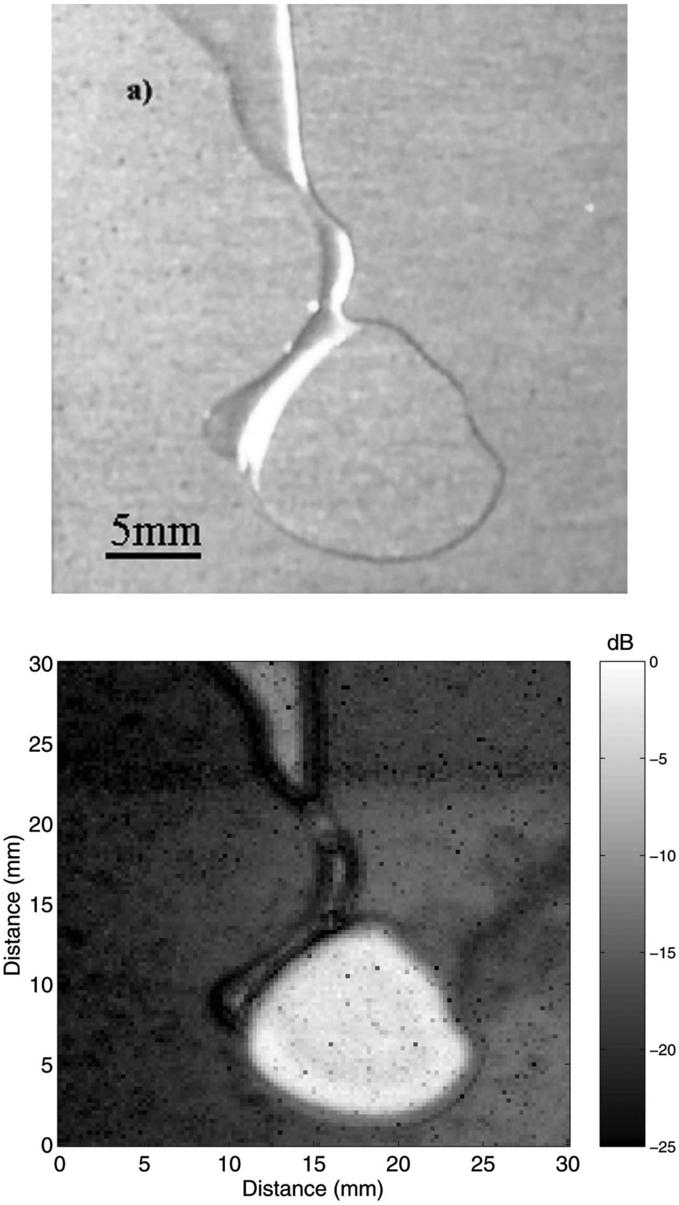
A 15 × 15 mm C-scan image using a 0.2-mm step of the plate with superimposed source and detection points was made after corrosion. The detection of the surface displacement was performed on the side opposite to the corroded area. The rms surface roughness of the plate, estimated to be 0.2 μm from optical measurements, is smaller than the thickness variations. Because of the smooth profile of the trough, the acquisition time was limited to 40 μs, and the noise was reduced by averaging 100 signals. The image of thickness variations Δd, deduced from the frequency variations Δf_0 of the S_1-ZGV mode resonance, is plotted in Fig. 4(b), revealing a quasi-circular trough with a maximum depth of 1.5 μm. In comparison with Fig. 4(a), a 0.5-μm depression can be observed on the right edge of the trough. This depression can be ascribed to a continuous thickness variation of the sound plate (before etching). The spatial resolution (0.5 mm) is slightly smaller than the source beam diameter and the depth resolution is better than 0.5 μm.

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%) due, for example, to early corrosion. This method is much more sensitive than those using propagating Lamb modes.

IV. Detection of an Adhesive Disbond

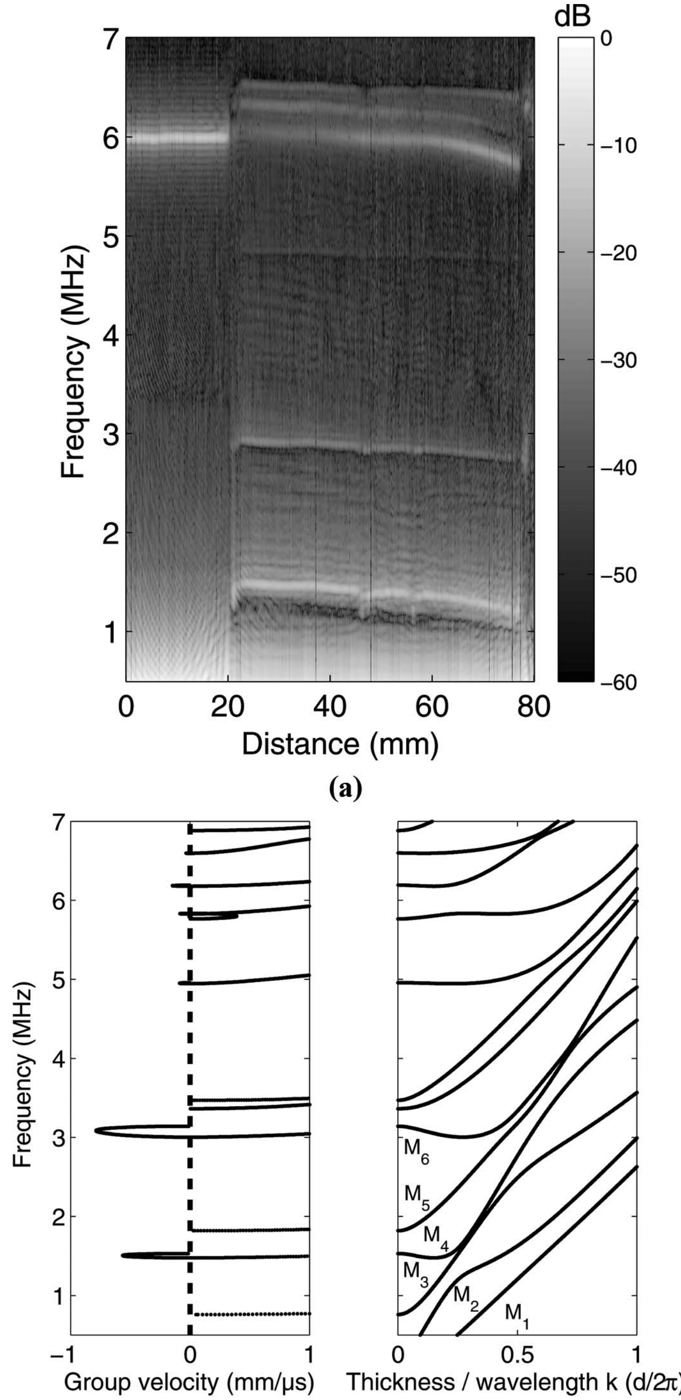
The first experiment was carried out on a 0.5-mm duralumin plate bounded with a thick (0.2 mm) epoxy layer to a 2-mm-thick glass plate. The thickness of the joint was controlled by interposing a rigid film between the two plates. In the center, an air bubble was entrapped, the shape of which was not controlled. The air bubble and a dendrite can be optically observed in Fig. 5(a). The laser source spot and the detection point are superimposed on the duralumin plate. According to the previous considerations and to improve the spatial resolution, we integrate only the first 7.5 μs of the signal. Fig. 5(b) is an amplitude C-scan image (30 × 30 mm using a 0.25 mm step) of the S_1-mode resonance in the frequency range 5.8 to 6.4 MHz.

The spatial resolution (0.5 mm) is of the size of the YAG laser spot. The ZGV resonance disappears when the two plates are rigidly bounded. A 25-dB amplitude contrast is observed when the source and detection point lie on a disbond area. The attenuation of the S_1-mode resonance is due to the sound absorption by the thick (0.2 mm) epoxy layer. The comparison between the two images in Fig. 5 shows that this ultrasonic method based



(b)

Fig. 5. Detection of an adhesive disbond between a 0.5-mm duralumin plate bonded with a 0.2-mm-thick epoxy layer to a 2-mm-thick glass plate. (a) Photograph of the disbonded area, (b) amplitude (in dB) of the S_1-ZGV Lamb mode.



(b)

Fig. 6. Fourier transform (in dB) of the signal measured on a structure composed of a 0.5-mm-thick duralumin plate and a 1.08-mm-thick glass plate bounded with a variable thickness layer. (b) Group velocities and dispersion curves computed with the software Disperse for the same structure rigidly bonded with a 40-μm-thick adhesive layer.

on the local resonance of the S_1-ZGV Lamb mode, gives valuable information with a large contrast on adhesive disbonds.

In the previous experiment, we observed that the S_1-ZGV Lamb mode resonance disappears when plates are rigidly bounded by a thick epoxy layer. Now, we analyze the influence of a thin adhesive layer. In this experiment, a 0.5-mm thick duralumin plate was bonded to a 1.08-mm-thick glass plate with a variable layer of cyanolite. The layer thickness varies by from 0 to 40 μm from the 20 mm to 75 mm abscissa.

Fig. 6(a) represents the Fourier transform in the frequency range 0.5 to 7 MHz obtained by integrating the signal on the first 15 μs. In the bonded zone (20 mm $< x <$ 75 mm), we observe additional resonances close to 1.5, 3, 5, and 6 MHz, the frequency of which decreases linearly as the adhesive thickness increases. For these resonances, the frequency variations are similar and close to 0.3 MHz.

Using the software Disperse (v. 2.0.16, Imperial College London, London, UK), we have calculated the disper-

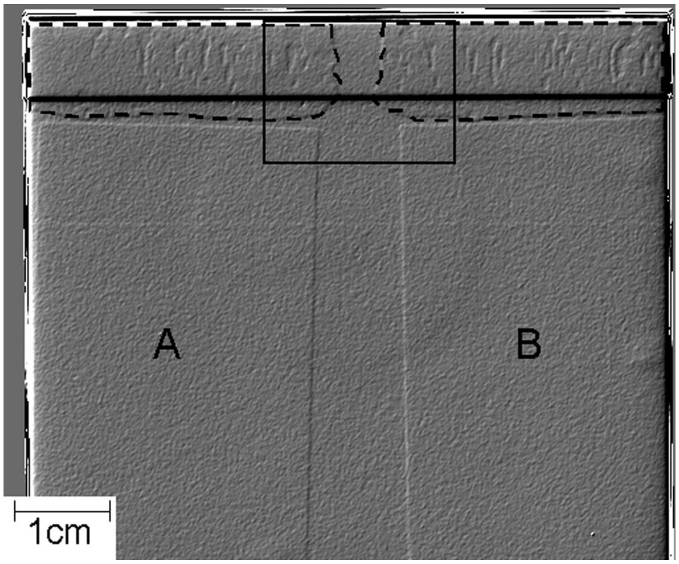


Fig. 7. X-ray radiograph of the tested automotive part showing the void artificially created in the middle of the lap joint and the unbound zones A and B, where an intermediate sheet separates the two steel plates of the car-door. The double lines on the left come from the edge of the sample.

TABLE I. Material Parameters Used for the Simulation.

	Duralumin	Epoxy	Glass
V_L (km/s)	6.34	2.61	5.64
V_T (km/s)	3.14	1.1	3.28

sion curves for a structure composed of a 0.5-mm-thick duralumin plate and a 1.08-mm-thick glass plate rigidly bonded with a 40-μm-thick adhesive layer. Fig. 6(b) shows the group velocities and the frequency dispersion curves versus the total thickness to wavelength ratio. Numerical values used for the simulation are given in Table I.

In the low-frequency range, the behavior of the first six modes is similar to that of the first three symmetric and antisymmetric Lamb modes of a homogeneous plate of the same thickness. It corresponds to dilatational and flexural vibrations of the whole structure. For example, similar to the S_1-Lamb mode, the fourth mode M_4 exhibits a minimum at a frequency $f_0 \cong 1.5$ MHz. Another pronounced ZGV mode appears at the minimum frequency (about 3 MHz) of the sixth mode, equivalent to the A_2-Lamb mode. The comparison with Fig. 6(a) shows that each resonance experimentally observed corresponds to a ZGV mode existing in this structure, i.e., to the crossing of the group velocity curve with the zero vertical axis in Fig. 6(b). In practice, a negative group velocity has no physical meaning: the energy always propagates from the source (pulsed laser) to the receiver (optical interferometer). In fact, between the cut-off and ZGV frequencies, two modes exist with opposite phase velocities: backward propagation occurs [25]. The representation used has the advantage of showing the zero crossings corresponding to the ZGV frequencies.

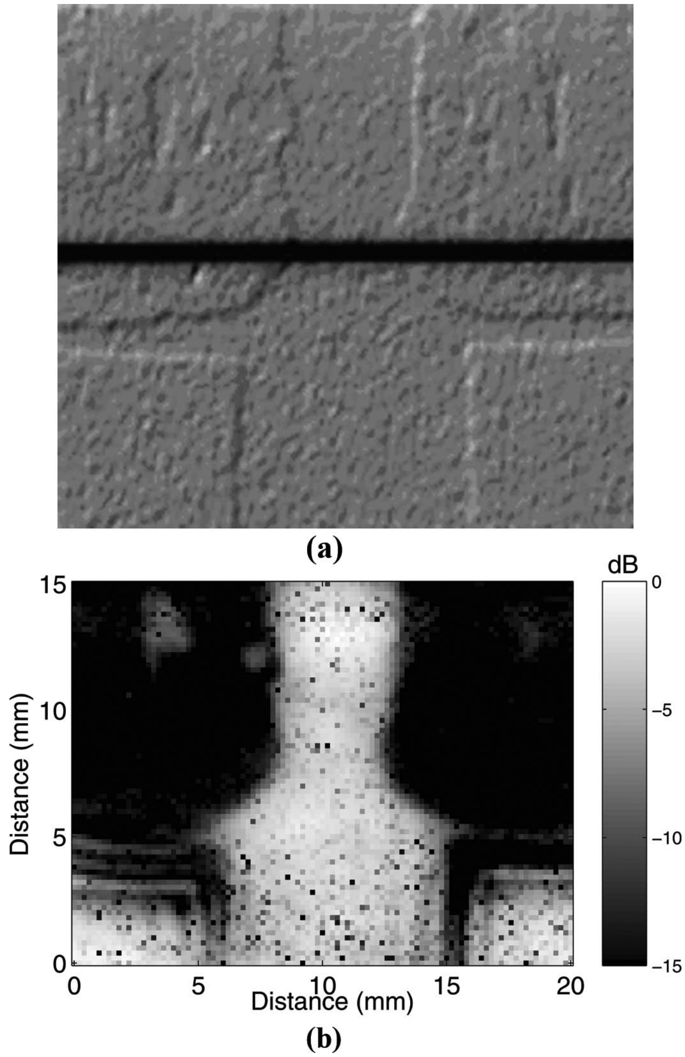


Fig. 8. Expanded view of the X-ray radiography (a) compared with the C-scan (b) of the amplitude at the resonance frequency of the S_1-ZGV mode.

V. Evaluation of the Method on an Automotive Assembly

To evaluate the proposed method, we carried out experiments on real automotive adhesively bonded structures. Tests were performed on a hem flange joint of a car-door. The thickness of the two steel plates is 0.65 mm and the nominative thickness of the adhesive epoxy layer is 0.3 mm. Fig. 7 is a X-ray radiography of the assembly, showing the bonded regions inside the contour dashed line. A 4-mm wide void was artificially created in the middle of the lap joint. In the rectangular zones A and B, an intermediate sheet was included to maintain a constant spacing between the two metal plates. The inspected zone is delimited by the solid line square.

In Fig. 8, the expanded view of the X-ray radiography is compared with the C-scan of the amplitude at the resonance frequency of the S_1-ZGV mode. This resonance frequency varies from 4.25 to 4.30 MHz according to the thickness variations of the steel plates and the acquisition time is limited to 15 µs. A good correlation was observed between the two images. The local vibration measured on the laser-excited metal sheet is localized in the unbound zones, i.e., the void and the parts of zones A and B in the lower corners in Fig. 8(b). In the sound lap joint, the ZGV resonance disappears. The spatial resolution (0.5 mm) is enhanced by the large amplitude contrast (20 dB).

VI. Conclusion

This paper investigates the possibility of using local resonances at the minimum frequency points of guided mode dispersion curves for the inspection of plate-like structures. 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-zero group velocity (ZGV) Lamb mode in a plate. By scanning the sample relative to the laser beams, it has been shown that it is possible to image very shallow corrosion corresponding to a relative plate thinning as small as 0.1%. This method of detecting early corrosion is much more sensitive than those using propagating Lamb modes or conventional pulse echo measurements in the megahertz range. With ultrasound inspection by acoustic microscopy, such sensitivity would require an operating frequency in the gigahertz range, which is not realistic because of plate material attenuation.

With the same noncontact technique, we investigate the state of an adhesive bond between plates. Experiments were carried out on a car-door sample. A good correlation was observed between images obtained by X-ray radiography and by resonance of the S_1-ZGV Lamb mode. The ZGV resonance method is appropriate for the inspection of a large sample. Moreover, this technique has the advantage of operating when access is limited to one side of the piece under test. In the case of a small adhesive layer, we observed several resonances, all associated with ZGV modes of the multi-layer structure. These modes can potentially be used for thickness measurement of the adhesive layer.

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