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Non-destructive testing of plates based on the visualisation of Lamb waves by double-pulsed TV holography

Daniel Cernadas, Cristina Trillo, Ángel F. Doval, Óscar López, Carlos López, Benito V. Dorrío, José L. Fernández and Mariano Pérez-Amor


Abstract

We describe a new technique, currently under development, intended to detect the presence of flaws such as cracks and holes in thin-walled mechanical components. This technique combines ultrasonics with optics, both at a low power density, that allows to perform the tests in the non-destructive range. Lamb waves, a kind of surface acoustic waves that propagate in thin plates, are generated to explore metallic samples while double-pulsed TV holography, a whole-field interferometric technique, is used to detect them. This scheme provides maps of the instantaneous surface displacements produced by the waves, where the effects of the flaws can be visualised by contrast against the smooth propagation of the wavefront in defect free plates. Images with reasonable resolution can be achieved almost in real-time. Several examples of detection of typical flaws in plates using the proposed method complete this work.

Key words: Pulsed TV Holography, ESPI, Non-Destructive Testing, Surface Acoustic Waves

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1 Introduction

Many techniques are well-established in the field of non-destructive testing (NDT) to detect flaws in a wide variety of objects, including mechanical parts
and structural components. The most popular of these techniques are based on the use of magnetic particles, dye/fluorescent penetrants, radio & gamma radiography, eddy currents and ultrasonics. All of them can be implemented for routine or massive inspections but, however, each method presents some specific problems as, for example, low inspection speed, lack of resolution, necessity to work close to the inspected area, limited applicability to certain materials or difficulty to automate the inspection tasks.

Ultrasonic techniques show many advantages [1] and that is why we are focusing our attention on them. For instance, ultrasonics present a high sensitivity to many types of flaws and can probe from the surface to significant depths within engineering materials. Most of the ultrasonic waves utilized in practice for NDT are the bulk acoustic waves (BAW). This kind of waves propagate within the volume of elastic bodies and they are classified, in isotropic solids, as longitudinal (P waves) or transversal (S waves). Less usual but of increasing significance in NDT, are surface acoustic waves (SAW), which propagate as guided waves on the surfaces of elastic solids [2]. Within this category, it is worth mentioning Rayleigh and Lamb waves; these last are used in the technique herein presented.

The generation and detection of ultrasound is traditionally performed by means of piezoelectric transducers. This technology offers a high sensitivity, flexibility in what regards the placement and shape of the transducers, a quite wide frequency range and the possibility to be incorporated in automatic NDT systems. However, it also presents important drawbacks, namely: the need of mechanical contact or of a couplant, a limited lateral resolution, the measurements are single-channel (pointwise) —a detector array or a mechanical scanning is needed to acquire information of the whole ultrasonic field—, the phenomenon to measure can be altered due to the contact nature of the method, piezoelectric materials have strong limitations to work in adverse environments —high temperature, corrosive or radioactive—, the position of the transducers may be critical for the detection of a given defect and, finally, it is not suited for inspecting parts whose surface must be kept clean and free of scratches, with complicated topography, difficult access —cavities, stepped surfaces— or small-size.

There are a range of emerging NDT techniques that, combining the high degree of interaction with the flaws offered by the ultrasonic waves with the true remote detection nature of the optical methods, can overcome some of the above mentioned drawbacks. Probably the most popular of these new techniques is the so-called “laser ultrasonics”, in which the acoustic wave is generated by focusing a high-power laser beam on the object surface and subsequently detected with an optical interferometer focused on an adjacent area, which yields an output signal that is proportional to the instantaneous spatial average of the velocity or displacement over this area [3]. Both excitation and
detection are, therefore, remote. Furthermore, since this is a single-channel detection scheme, the acquisition and processing hardware is not shared with any other detection channel which results in a high bandwidth —i.e., a high temporal sampling rate— as well as a high frequency resolution in the sampled signal spectrum. However, laser ultrasonics presents severe limitations to deal with inspection tasks that involve to check for cracks or other flaws along a whole surface in a short time, being the usual solution to perform a scanning over an array of different positions on the object surface repeating the excitation-detection sequence.

A very interesting alternative to this approach is to arrange a number of detectors in parallel to obtain an instantaneous map of the displacement field produced by the acoustic wave. When a high spatial resolution is necessary, for example hundreds of samples along each direction on the surface, a practical solution is to use a video camera to acquire the output intensity pattern produced by a whole-field optical technique which is sensitive enough to record the small displacements associated to the wave fields. As these surface displacements are typically of tens of nanometres or even smaller, very special devices and techniques are necessary. To the best of our knowledge, to date only two whole-field optical techniques have allowed to visualize such ultrasonic fields on non specular-finished surfaces, namely: holographic interferometry and TV holography.

Holographic interferometry (HI) techniques have been applied in two basic modes: continuous and transient. In the continuous mode, a hologram recorded with the specimen at rest is then reconstructed while an ultrasonic wave burst is periodically applied to the specimen at the same rate that a video camera integrates and reads the resulting interferograms (usually tens of milliseconds per frame). As the ultrasonic period is typically in the range of microseconds, stroboscopic illumination or detection must be used to avoid the time averaging of the signal within each frame. This approach has been successfully used to detect the displacement fields of Rayleigh waves in real time [4].

In the transient mode, on the other hand, the mechanical state of the specimen is frozen by pulsed laser illumination at two very close instants, generally separated by just a few microseconds, and recorded in the same hologram. The relative displacement of each surface point between the two selected states is then measured by reconstructing both together from the hologram. Some authors have used this method to detect Rayleigh wave displacement fields [5]. The short acquisition time involved in the transient mode presents several advantages with respect to the continuous one: a high immunity to environmental perturbations, a very fine temporal resolution, and the possibility to select the recorded states close enough to the starting time of the excitation to avoid the presence of waves reflected at the edges of the inspected part. This last advantage should not be underestimated, as such reflected waves could
interfere with the incident waves hiding the effects produced by the defects. Hence, operating in the transient mode makes unnecessary to arrange acoustic absorbers in the inspected part. On the other hand, the main hindrance of the transient mode is the experimental complexity associated to the use of a pulsed laser and fast electronics.

Though their performances are remarkable, HI techniques need a photosensitive medium with high spatial resolution to record the holograms, and this fact limits their practical use mainly by economical reasons. Other potential disadvantages (not for all the HI technologies) are: the necessity of darkening the working place, the slow processes of developing and optical reconstruction, and the fragility of holographic equipment.

TV holography (TVH) —i. e., the family of techniques based on the recording of holograms with video cameras and their electronic, either analog or digital, processing [6]—, also called ESPI, has become an attractive alternative to HI since it can overcome some of the above cited limitations. There are also continuous-stroboscopic and transient operation modes in TVH, as in HI, with the same respective principles and advantages. However, TVH presents an intrinsic disadvantage with respect to HI, that is, there is resolvable speckle noise in the output images that degrades the sensitivity. The first results that have been published concerning the detection of ultrasonic waves with TVH were, in our knowledge, limited to the stroboscopic mode, in which the averaging of the signal over an extended time interval allows to discriminate the signal from the noise using standard experimental equipment [7].

We have recently developed a double-pulsed TVH technique to detect surface acoustic waves like Rayleigh and Lamb waves [8], and shown some preliminary results that pointed out its applicability for non-destructive testing [9]. In this paper we report a new technique to detect flaws in thin plates by combining Lamb wave excitation and the aforementioned TVH detection technique. We also present some interesting fringe patterns obtained with our system which show the propagation of these waves on aluminum plates as well as scattering phenomena produced when a flaw is intercepted by the ultrasonic wavefront.

2 Principles of the technique

2.1 Characterization of the ultrasonic wave field

Lamb waves are a particular class of SAW that propagate in plates limited by two stress-free parallel boundaries. We will restrict the theoretical treatment to plane plates and will suppose that the wavefronts are sufficiently smooth
to neglect the variations along the coordinate perpendicular to the sagittal plane, which is the plane perpendicular to the free boundaries that contains the propagation direction (this means to ignore diffraction effects). In these conditions, the displacements produced by the Lamb waves have components only in the sagittal plane, and the wave can be considered like a superposition of P and S waves guided by the plate. Except for very special values of the angles of incidence, each reflection of a P wave in the boundary generates two reflected waves, a P and a S ones, and the same is true for the reflection of S waves.

Let us define the axes $x_1$ parallel to the propagation direction and $x_3$ perpendicular to both free surfaces of the plate, it is possible to write the expressions of the displacements along these axes corresponding to a given family of modes of Lamb waves as [10]

$$u_1 = (i \xi C_1 \cos k_3 x_3 - \kappa_3 C_2 \cos \kappa_3 x_3) \exp [i (\xi x_1 - \omega_M t)] \quad (1)$$

and

$$u_3 = (-k_3 C_1 \sin k_3 x_3 + i \xi C_2 \sin \kappa_3 x_3) \exp [i (\xi x_1 - \omega_M t)] \quad (2)$$

where $C_1$ and $C_2$ are two complex constants, $k \equiv (k_1, k_2, k_3)$ and $\kappa \equiv (\kappa_1, \kappa_2, \kappa_3)$ are the wavevectors corresponding to the longitudinal and transversal bulk elastic waves associated with these Lamb modes, respectively, $\xi = k_1 = \kappa_1$ is the modulus of the wavevector associated to a given Lamb mode propagating in the direction of $x_1$, $\omega_M$ is the angular frequency of the mode, $t$ is the time and $i$ is the imaginary unit.

The modes given by (1) and (2) are called symmetrical modes, since $u_1(-x_3) = u_1(x_3)$ and $u_3(-x_3) = -u_3(x_3)$ and, therefore, the displacement is symmetric with respect to the plane $x_3 = 0$.

It is also possible to demonstrate the existence of another class of modes, with the corresponding displacements along $x_1$ and $x_3$ given by

$$u_1 = (i \xi D_1 \sin k_3 x_3 - \kappa_3 D_2 \sin \kappa_3 x_3) \exp [i (\xi x_1 - \omega_M t)] \quad (3)$$

and

$$u_3 = (k_3 D_1 \cos k_3 x_3 - i \xi D_2 \cos \kappa_3 x_3) \exp [i (\xi x_1 - \omega_M t)] \quad (4)$$

where $D_1$ and $D_2$ are two complex constants. In these modes, the displacement verifies $u_1(-x_3) = -u_1(x_3)$ and $u_3(-x_3) = u_3(x_3)$; thus, they are known as antisymmetrical Lamb modes.

These two classes of modes can propagate independently each from the other. Only a discrete number of modes exist for a given thickness of the plate and a
given value of \( \omega_M \), and each one has its particular value of \( \xi \). This takes us to a relevant characteristic of Lamb waves: they are dispersive, i.e., their phase and group velocities depend on the angular frequencies of the modes that are present and on the thickness of the plate. In figure 1(a) and 1(b), we illustrate the displacement produced across the section of the plate by the propagation of harmonic symmetrical and antisymmetrical modes respectively.

Lamb waves can be used in NDT to detect surface and subsurface flaws in materials by analyzing the behaviour of the waves scattered by these defects. But at present it does not exist any general theory of surface waves scattering and one has to resort to numerical simulations to understand the effects produced by the flaws, habitually by using 2D models that give incomplete information. Furthermore, it would be useful to have a mathematical model of inversion powerful enough to detect and characterize an unknown kind of flaw from the measured scattering pattern. In any case, actual data from experiments are necessary to feedback the numerical work. So, the proposed study requires a high degree of specialization in several branches of science and technology, for which an interdisciplinary research team is desirable.

### 2.2 Generation of the Lamb wave fields

In this work, we generate Lamb waves on aluminium plates by the standard method of the prismatic coupling block (see figure 2), that we have chosen on account of its reliability, repeatability and simplicity. In addition, this method permits an easy control of the main parameters of the Lamb waves it produces. The setup essentially comprises a piezoelectric crystal that generates bulk P waves into a wedge, made of a plastic material and acoustically coupled to
Fig. 2. Scheme of the generation of SAW by the prismatic coupling block method. A piezoelectric crystal generates longitudinal P waves that propagate in the wedge. As this waves reach the interface between the wedge and the plate with a critical angle, they are transformed into Lamb modes.

the surface of the part to be inspected. The angle of the wedge as well as the selection of its material are critical and depend on the elastic constants of the part. The generation of SAW with this method is, basically, a consequence of the frustrated total internal reflection of the P waves produced by the piezoelectric transducer on the interface wedge-test surface [11]. The piezoelectric crystal is excited by a generator that periodically emits bursts of high-voltage pulses synchronized with an external trigger signal. The number of pulses per burst can be programmed from 1 to 99; the nominal frequency of the pulses within each packet, $f_M$, is also selectable to match the crystal resonance. In our case, we worked at $f_M = 1.0$ MHz.

From a previous independent measurement, using a point speckle Michelson interferometer, we know that the surface waves produced with our wedge sys-
tem on an aluminium slab (Rayleigh waves) have out-of-plane amplitudes in the range of 10 nm [12]. We can expect similar amplitudes, that are near the current sensitivity limit for the detection of displacements by pulsed TVH [9], for Lamb waves.

It is also possible to generate surface waves on an object from a remote location by using high-power laser pulses, but some inconveniences would have to be solved before this method can be extensively used. The main problem of the laser generation is that it is a broadband impulse (tens of MHz bandwidth), and many surface wave modes (along with other bulk waves) are generated. For the testing purposes, a narrow-band excitation is desirable. On the other hand, to match the TVH sensitivity, the amplitude of the displacements should be as large as possible, preferably in the range of tens of nanometres. One can generate elastic waves with lasers using any of two different regimes: ablation and thermoelastic. Ablation could be the most adequate generating regime because it produces waves of higher amplitudes than the thermoelastic one. However, it requires a protection against damage on the laser impact zone, which is generally achieved by the interposition of a target of suitable material acoustically coupled with the surface under inspection. On the other hand, such a protection is not necessary in the thermoelastic regime but it is very difficult to select the optimal laser power density to generate waves of a reasonable amplitude without taking the risk of accidentally entering the ablation mode and damaging the surface under test. These difficulties would have to be overcome before a fully remote NDT tool based on our technique can be implemented; so, in this stage of development we have preferred to use a well known and controllable Lamb wave generation technique.

2.3 Detection of the Lamb wave fields

To visualize the instantaneous displacement field of the ultrasonic waves, we have implemented a technique that is a variant of the double-pulse single-exposure TVH technique [13]. A detailed description of our detection technique can be found in reference [8], nevertheless, we will point out its most relevant aspects in connection with the application herein presented. Figure 3 shows a diagram of our double-pulsed TVH system. We have arranged this experimental setup to detect only the instantaneous out-of-plane component $u_3$ of the surface displacement, by choosing the adequate illumination and observation geometry. This configuration is preferable to geometries with other sensitivities because it renders images with the best signal-to-noise ratio. With the chosen sensitivity, the optical object phase difference field associated to any particular state of the sample surface is given, as function of the image
coordinates, by the expression

$$\phi_o (x', t) = -\frac{4\pi}{\lambda} u_3 (x', t)$$ \hspace{1cm} (5)$$

where $x' = (x'_1, x'_2)$ is the position on the image plane, $t$ is the time and $\lambda$ is the wavelength of the laser.

In particular, the displacement produced by the surface waves can be locally described as

$$u_3 (x', t) = u_{30} (x', t) \cos (\varphi_o + k'_M \cdot x' - \omega_M t)$$ \hspace{1cm} (6)$$

where $u_{30}$ is the amplitude, $\varphi_o$ and $k'_M$ are the mean values in the considered region of the initial phase and of the wavevector (scaled to the image plane) and $\omega_M = 2\pi f_M$ is the angular frequency of the SAW.

A pulsed laser with a pulse duration of a few tens of nanoseconds or shorter is necessary to freeze the ultrasonic field, since the nature of the phenomenon to measure is very fast. We employ a twin cavity Q-switched Nd:YAG pulsed laser with a second harmonic generator, emitting 25 double pulses per second of visible light at a wavelength $\lambda = 532$ nm. The frequency doubling duplicates the sensitivity of the interferometer with respect to the primary infrared emission of the laser and also allows an easy and safer alignment. The laser output
Fig. 4. Triggering of both cavities’ laser pulses relative to an ultrasonic burst. The small boxes show the position of a wave packet for the two triggering instants.

is split into the reference and object beams; this last is expanded by a negative lens and illuminates the surface to be tested. The light scattered from it and the reference beam are coherently superimposed by a beam combiner and imaged onto the photosensitive surface of a CCD camera. This is a fast progressive scanning interline-transfer camera that can record two independent images, separated down to 1 µs from each other, with a full spatial resolution of 1280 × 1024 pixels; it is also thermoelectrically cooled and digitizes the data with a resolution of 12 bits, therefore yielding a very low noise-floor. Two high-precision digital delay generators, supported with custom designed synchronization electronics, control the triggering of the laser flash lamps and Q-switches, of the camera integration period and of the ultrasonic wave generator.

A key point of our technique is to record two primary correlograms, one for each laser light pulse, with a very short time lapse. Each primary correlogram stores information about the state of the dynamic deformation of the observed surface at a given instant $t_n$ ($n = 1, 2$), and they can be represented by [6]

$$I_n = g I_o [1 + V \cos (\psi_p - \phi_{r,n} + \phi_{o,n})]$$

(7)

where $I_n = I_n (x')$ is the primary correlogram corresponding to the pulse of cavity $n$ ($n = 1, 2$), $g = g (\lambda)$ is the spectral sensitivity of the camera, $I_o = I_o (x')$ is the local central value of the intensity, $V = V (x')$ is the local visibility, $\psi_p = \psi_p (x')$ is the random phase difference of the interfering speckle patterns, $\phi_{r,n} = \phi_r (t_n)$ is the reference phase difference and $\phi_{o,n} = \phi_o (x', t_n)$ is the object phase difference as defined in equation (5).

The recording of both correlograms must be separated by the minimum odd number of half periods of the SAW that our experimental system allows, in order to maximize the displacement of the surface between correlograms (see figure 4) while maintaining the effect of environmental noise as low as possible.
According to the frequency of the SAW \((f_M = 1.0 \text{ MHz})\) and to the minimum separation between frames allowed by our camera \((1 \mu\text{s})\), the correlograms are separated by three half periods in our experiments, thus

\[
t_2 = t_1 + \frac{3\pi}{\omega_M}
\]

(8)

It is necessary to produce a secondary correlogram from the two primary correlograms to obtain observable fringes that reveal the displacement of the surface between light pulses. The secondary correlograms are then generated by subtraction and full-wave rectification, to maximize the sensitivity to small displacements [14], and follow the equation

\[
\tilde{I}_{fw} = |I_1 - I_2| = 2gI_oV \left| \sin \left( \psi_p + \tilde{\phi}_o - \tilde{\phi}_r \right) \right| \sin \frac{\Delta\phi_o - \Delta\phi_r}{2}
\]

(9)

where \(\tilde{\phi}_o = \tilde{\phi}_o(\mathbf{x}')\) is the mean object phase difference, \(\tilde{\phi}_r\) is the mean reference phase difference, \(\Delta\phi_o = \Delta\phi_o(\mathbf{x}')\) is the change of the object phase difference and \(\Delta\phi_r\) is the change of the reference phase difference between the two light pulses.

Let us define the local average brightness as \(B = \langle \tilde{I}(\mathbf{x}') \rangle\), with \(\langle \cdot \rangle\) the spatial average in the neighbourhood of \(\mathbf{x}'\). The changes of \(B\) create a pattern of clear and dark fringes that can be easily noticed in the display, and that for full-wave rectification has the expression

\[
B_{fw} = \frac{4}{\pi} g \langle I_o V \rangle \left| \sin \frac{\Delta\phi_o - \Delta\phi_r}{2} \right|
\]

(10)

By combining equations (5), (6) and (8) and assuming that the amplitude of the SAW, \(u_{30}\), is constant in time, one obtains that the local average brightness represents

\[
B_{fw} = \frac{4}{\pi} g \langle I_o V \rangle \left| \sin \left\{ \frac{4\pi}{\lambda} u_{30}(\mathbf{x}') \cos \left[ \varphi_o + k'_M \cdot \mathbf{x}' - \omega_M t_1 \right] + \frac{\Delta\phi_r}{2} \right\} \right|
\]

(11)

If the TVH system is set slightly over the quadrature point by selecting a small positive value for \(\Delta\phi_r\), thus maintaining the value of the argument of the sine function in (11) positive in every point [8], and \(u_{30} \ll \lambda\), the local average brightness can be approximated by

\[
B_{fw} \approx B_0 + 16g \langle I_o V \rangle \frac{u_3(\mathbf{x}', t_1)}{\lambda}
\]

(12)
Fig. 5. (a) Long burst of Lamb waves propagating from right to left in a defect free zone of a 3.0 mm thick aluminium plate. The actual dimensions of the field of view are 75 mm × 61 mm and the shadow barely visible on the right side is the wedge of the wave generator. (b) Long burst identical to (a), but propagating over a subsurface defect consisting in a 6 mm diameter flat bottomed bore, drilled on the opposite side of the plate, with a depth 1.5 mm less than the plate thickness. The circular mark represents the projection of the hidden bore. The distortion of the wavefronts produced by the defect becomes evident.

being \( B_0 \) a constant. So, the local average brightness (i.e., grey level) \( B_{fw} \) of the output image is approximately proportional to the instantaneous ultrasonic displacement at each point.

3 Experimental results and discussion

The observation of the perturbations experienced by the fields of elastic deformation when the incident waves are scattered by the defects is, essentially, the operating principle of our flaw-detection scheme. It is, therefore, highly advisable to characterize the displacement fields on defect-free samples before proceeding with the flaw-detection tests.

Figure 5(a) shows a secondary correlogram where we can observe a map of the out-of-plane component of the relative displacement between two instants, separated 1.5 \( \mu s \) (three half periods), produced by an unperturbed SAW. The image was recorded from a defect free zone of a 3.0 mm thick aluminium plate. In this case, the SAW is a Lamb wave because the slab thickness is of the same order of magnitude than the wavelength; if the sample had been much thicker than the wavelength, we would have generated Rayleigh waves instead. In any case, we have verified experimentally that we were actually generating Lamb waves, since the ultrasonic field was visible in both faces of the plate. The interpretation of this correlogram is straightforward: according to equation (12), the average grey level at each point is approximately proportional to the instantaneous absolute out-of-plane ultrasonic displacement at this point.
There is only a significant error in the zones corresponding to the first and last fringe of each burst, due to the non stationary nature of the measurand \cite{8}. The number of pulses of the burst that can be seen in the figure is long enough to cover the entire inspected area but, at the same time, the measurement has been synchronized to be complete before the wavefront reaches the edges of the part, thus avoiding the occurrence of undesired reflected waves that could interfere with the primary one.

In figure 5(b), on the other hand, we can see a secondary correlogram showing a long burst of Lamb waves that propagates on another zone of the same plate where a major defect is present: a 6 mm diameter flat-bottomed bore perpendicularly drilled from the opposite side to the observed surface and with a depth of one half the thickness of the plate. Observing both images in this figure, it becomes apparent that the presence of the bore produces noticeable effects in the fringes.

Figure 6 presents a sequence of secondary correlograms taken at intervals of 3 µs, which shows in detail the evolution of a short burst of Lamb waves comprising eight pulses that propagates on the same zone of the plate pictured in figure 5(b). In figure 6(a) we can see that the fringes still keeping their original curvature (concave as seen from the source). Then in figure 6(b) the fringes begin to suffer a perturbation in their curvature in a zone situated near the projection of the actual position of the bore. The further evolution of the perturbed fringes is shown in figures 6(c-f). Even the presence of a retro-reflected wave originated at the position of the bore is observable. From this analysis, it is evident that the possibility to select the number of pulses, according to a particular situation, provides this inspection method with a remarkable flexibility.

An example of flaw detection of a superficial groove open to the opposite face of a plate is shown in figure 7. In the first images of the sequence [figures 7(a) and 7(b)] we can see the incident Lamb wave as it approaches to the projection of the hidden defect. In figure 7(c) and 7(d) we see both the transmitted and reflected waves, which reveal the presence of the groove. We have marked the actual position of the projection of the groove in figure 7(d).

Figure 8 presents another example of the possibilities of our double-pulsed TVH method. A sequence of secondary correlograms recorded at 3 µs intervals show the interaction of a Lamb wave burst, just four pulses long, with a slit open to both sides of an aluminium plate with a thickness of 3.5 mm. The slit appears vertical in the images and its actual dimensions are 30 mm × 0.7 mm. In this case, several phenomena result from the presence of the defect: a strong reflection [figures 8(e) and 8(f)], interference between the incident and reflected waves [figure 8(d)] and diffraction from the tip of the slot [figures 8(d) and 8(e)].
Fig. 6. Sequence of secondary correlograms corresponding to a Lamb wave burst of eight pulses, propagating from right to left over the same bore of figure 5(b). The elapsed time between two consecutive images of the sequence is $3.0 \mu s$. It is seen the evolution of the perturbation produced by the defect and the generation of a backward propagating reflected wave. The field of view is also the same as in figure 5(a).

4 Conclusions

A novel method combining Lamb-wave ultrasonic excitation and optical detection by double-pulsed TVH has been proposed for the non-destructive testing of plates and, in general, thin-walled mechanical parts. The main advantages of this technique are the capability of whole-field remote measurement with
Fig. 7. Sequence of flaw detection with a burst of Lamb waves. (a) Incident waves emerging from the source, (b) wavefront reaching a defect located on the opposite face of the plate, (c) and (d) transmitted and reflected waves (the vertical line is the position of a groove made on the opposite free surface). The images were recorded with intervals of 3.75 µs. The field of view is 93 mm × 74 mm, the thickness of the plate 3.5 mm and the dimensions of the groove are: 36.8 mm length, 0.7 mm width and a depth of 0.6 mm less than the plate thickness.

With high temporal resolution, almost real-time visualization and, due to the short temporal gap between both exposures, high immunity to environmental perturbations. Furthermore, the actual implementation of the technique renders a great flexibility in the temporization of the events: the triggering of the laser pulses—which establish the two mechanical states to be compared—and the generation of the ultrasonic wave, comprising the starting time and the duration of the burst. This flexibility makes possible to inspect a wide area of the test piece before the ultrasonic field undergoes reflections from the edges or discontinuities like rivets, steps, etc.

The results obtained to date show that this technique holds a great potential to detect different types of flaws and that it is suitable to be adapted for industrial inspection outside the laboratory.
Fig. 8. Sequence showing the evolution of a Lamb wave burst of four pulses incident obliquely on a slit (vertical in the figure and of dimensions 30 mm × 0.7 mm). Each image is separated 3 µs from the preceding one. A very clear phenomenon of reflection can be seen and also the diffraction produced at the lower tip of the slit. The darkest rectangular shadow appearing in the lower right corner of each image is the wedge of the wave generator. The actual size of the field of view is 75 mm × 61 mm.

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