
This is an Accepted Manuscript of an article published by Taylor & Francis in the International Journal of Optomechatronics on 11 July 2007, available online:

http://www.tandfonline.com/10.1080/15599610701385479

http://dx.doi.org/10.1080/15599610701385479

This article's supplemental content is available online at the publisher's website: http://www.tandfonline.com/doi/suppl/10.1080/15599610701385479/suppl_file/uopt_a_238436_sup_0001.gif (accessed 2016-06-30)

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Video Ultrasonics by Pulsed TV Holography: a new capability for non-destructive testing of shell structures

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May 25, 2007

Abstract

We present a novel capability of the TV holography technique applied to the non-destructive testing of mechanical parts or structures with the form of a plate or a shell, which consists of the recording of high quality synthetic movies of the spatio-temporal evolution of instantaneous ultrasonic displacement fields of the surface under inspection. Moreover, in the case of narrowband acoustic excitation, movies of the spatio-temporal evolution of the acoustic amplitude and of the total acoustic phase can also be generated. Some examples of the application of the technique to flaw detection in aluminium plates using surface waves are presented. As a previous step for evaluating the context and the advantages of the new capability

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presented, a description of the state of the art with a comparative analysis about non-destructive testing techniques based on optical probing of ultrasound, focused on shell structures, is included in the first part of this work.

Keywords: TV holography, ESPI, Non-destructive testing, Ultrasonic testing, Surface acoustic wave, Lamb wave.
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>diameter of a cylinder-shaped defect</td>
</tr>
<tr>
<td>$e$</td>
<td>depth of the defect measured from the observed surface</td>
</tr>
<tr>
<td>$h$</td>
<td>half-thickness of the plate</td>
</tr>
<tr>
<td>$j$</td>
<td>imaginary unit</td>
</tr>
<tr>
<td>$k_1$</td>
<td>wavevector of the incident acoustic wave</td>
</tr>
<tr>
<td>$k_l$</td>
<td>wavevector of a particular acoustic wave</td>
</tr>
<tr>
<td>$k_l$</td>
<td>wavenumber of a particular acoustic wave</td>
</tr>
<tr>
<td>$N$</td>
<td>number of optical phase-change maps</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
</tr>
<tr>
<td>$t_f$</td>
<td>second illumination instant</td>
</tr>
<tr>
<td>$t_i$</td>
<td>first illumination instant</td>
</tr>
<tr>
<td>$t_n$</td>
<td>time instant of the $n$th optical phase-change map</td>
</tr>
<tr>
<td>$u_1$</td>
<td>instantaneous displacement vector of a surface point due to the incident acoustic wave</td>
</tr>
<tr>
<td>$u_{11}$</td>
<td>instantaneous in-plane displacement of a surface point due to the incident acoustic wave</td>
</tr>
<tr>
<td>$u_{13}$</td>
<td>instantaneous out-of-plane displacement of a surface point due to the incident acoustic wave</td>
</tr>
<tr>
<td>$\hat{u}_{13}$</td>
<td>complex out-of-plane displacement of a surface point due to the incident acoustic wave</td>
</tr>
<tr>
<td>$\hat{u}_{13m}$</td>
<td>complex amplitude of the out-of-plane displacement of a surface point due to the incident acoustic wave</td>
</tr>
<tr>
<td>$u_3$</td>
<td>instantaneous out-of-plane displacement of a surface point due to the total acoustic field</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
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</tr>
<tr>
<td>$\hat{u}_3$</td>
<td>complex out-of-plane displacement of a surface point due to the total acoustic field</td>
</tr>
<tr>
<td>$u_{3m}$</td>
<td>real amplitude of the out-of-plane displacement of a surface point due to the total acoustic field</td>
</tr>
<tr>
<td>$\mathbf{u}_l$</td>
<td>instantaneous displacement vector of a surface point due to a particular acoustic field</td>
</tr>
<tr>
<td>$u_{l3}$</td>
<td>instantaneous out-of-plane displacement of a surface point due to a particular acoustic field</td>
</tr>
<tr>
<td>$\hat{u}_{l3}$</td>
<td>complex out-of-plane displacement of a surface point due to a particular acoustic field</td>
</tr>
<tr>
<td>$u_{l3m}$</td>
<td>real amplitude of the out-of-plane displacement of a surface point due to a particular acoustic field</td>
</tr>
<tr>
<td>$\hat{u}_{l3m}$</td>
<td>complex amplitude of the out-of-plane displacement of a surface point due to a particular acoustic field</td>
</tr>
<tr>
<td>$\mathbf{x}$</td>
<td>position vector</td>
</tr>
<tr>
<td>$x_1$</td>
<td>component of the position vector in the propagation direction of the incident acoustic wave</td>
</tr>
<tr>
<td>$x_2$</td>
<td>component of the position vector in the direction parallel to the plate surface and normal to $x_1$ direction</td>
</tr>
<tr>
<td>$x_3$</td>
<td>component of the position vector in the direction normal to $x_1$ and $x_2$ directions.</td>
</tr>
<tr>
<td>$\mathbf{x}_{10}$</td>
<td>position vector of a particular scattering center</td>
</tr>
<tr>
<td>$\Delta \Phi$</td>
<td>instantaneous optical phase-change</td>
</tr>
<tr>
<td>$\Delta \hat{\Phi}$</td>
<td>complex optical phase-change</td>
</tr>
<tr>
<td>$\Delta \Phi^F$</td>
<td>filtered instantaneous optical phase-change</td>
</tr>
<tr>
<td>$\Delta \Phi_m$</td>
<td>optical phase-change amplitude</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$\varphi_{lm}$</td>
<td>spatial term of the phase of the out-of-plane displacement of a surface point due to the total acoustic field</td>
</tr>
<tr>
<td>$\varphi_{30}$</td>
<td>part of the spatial term of the phase of the out-of-plane displacement of a surface point due to a particular acoustic field and not related to the wave vector</td>
</tr>
<tr>
<td>$\varphi_{lm}$</td>
<td>spatial term of the phase of the out-of-plane displacement of a surface point due to a particular acoustic field</td>
</tr>
<tr>
<td>$\varphi_{m-\omega t}$</td>
<td>total optical phase-change phase</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>laser wavelength</td>
</tr>
<tr>
<td>$\omega$</td>
<td>circular frequency of the acoustic wave</td>
</tr>
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</table>
1 INTRODUCTION

In non-destructive testing (NDT), ultrasonics is one of the classical and most powerful technologies [Birks et al. 1991]. Some reasons for this are:

- Deep-penetration capability of the acoustic waves.
- High degree of interaction of the acoustic waves with the flaws of the material or with inhomogeneities in its elastic properties.
- High speed of propagation of the acoustic waves across the inspected part.
- Directional properties of the ultrasonic waves with possibility of controlling the wavefront geometry.
- Wide bandwidth and high information content capability, allowing fast and massive data acquisition.

Nowadays, ultrasonics holds a privileged position as a high performance NDT branch and becomes increasingly competitive, incorporating the newest transducer technologies and information processing schemes. One of the emergent technologies consists of the optical probing of ultrasound [Scruby and Drain 1990], integrated in a three-step NDT principle (Fig. 1):

(i) the part to be inspected is insonified with an adequate ultrasonic field,

(ii) the interaction of the acoustic wave with the inhomogeneities and flaws of the material gives rise to alterations of the acoustic field (generation of reflected or refracted waves, diffraction or, in general, scattering phenomena), and

(iii) an optical method is used to measure the velocity, displacement, or any other physical quantity associated with the acoustic field.
An ideal NDT method should fulfil the following four requirements, with increasing degree of knowledge about the inspection problem: (i) detection of the existence of flaws, (ii) determination of their location, (iii) their characterization (size, orientation, shape, etc.), and (iv) prediction of their evolution and estimation of the remaining service life of the inspected part or structure.

The detection and measurement of ultrasonic waves by optical means joins the benefits of the worlds of ultrasonics and optics and allows addressing efficiently the former requirements. In particular, some of the benefits added by optics are:

- Remote operation (several metres standoff).
- The detection technique does not alter the acoustic field to measure.
- Avoiding contact- or fluid- coupling of the probing transducer.
- High lateral resolution (limited by the diffraction of the light waves).
- High measurement speed.
- Higher bandwidth than with conventional piezoelectric transducers.
- Possibility to perform inspections in very small or inaccessible areas, inside furnaces or vacuum chambers, on moving parts, etc.

On the other hand, there are also drawbacks that limit the widespread use of these techniques: mainly, a smaller sensitivity than the classical ultrasonics with contact detection by means of piezoelectric transducers, a relative complexity of the inspection equipment, and the purchase and operation costs. Therefore, nowadays these techniques are especially applicable to small, delicate, lightweight, inaccessible or geometrically complicated objects, for which the standard ultrasonic methods are not suitable. Nevertheless, the continuous improvement of the technical performances and economical competitiveness of the photonic technologies leads to an increasing employment of the opto-acoustic methods for industrial NDT tasks.
In this work, we present a novel capability of a well-known optical probing technique, TV holography (TVH), applied to the detection of ultrasonic fields on shell-like parts, that we call Video Ultrasonics by Pulsed TV Holography (VUPTVH). This new capability is the last of a series of developments that our group has done along a decade with successive improvements in the optical and electronic hardware and, especially, in the information processing scheme.

The novelty and main feature of VUPTVH, that distinguish it from our former developments, is that its output has the form of a high-quality movie. To achieve this, two different processing schemes (as explained in subsection 3.3.3) can be applied to a set of optical phase maps that encode the instantaneous ultrasonic field. In order to avoid unnecessary repetition, we have omitted in the present work the details of the measurement of these instantaneous maps and some other specific items of our HTV system already explained in our former works, giving the references instead.

Another point that we wish to highlight is that, for a proper working of the system as a NDT tool, the acoustic subjects are at least as important as the optical ones. For example, a careful selection of the acoustic field parameters (type of wave, frequency, beam geometry, temporization, etc.) must be done. Although a considerable amount of literature dedicated to optical probing of ultrasound has been published since the 90s, only a small fraction deals with whole-field techniques as ours, so the information about both optical and acoustic subjects specific for whole-field detection is scarce and disperse. In consequence, we considered convenient to include an introductory section that briefly reviews the techniques for optical probing of ultrasound directed to the inspection of shell-like parts, in which the specific features and advantages of the whole-field compared to the alternative pointwise techniques are discussed.

The organization of the paper is as follows: section 2 includes a description of the state of the art and a comparative analysis about non-destructive testing techniques based on the optical probing of ultrasound, focused to shell structures. Both optical and acoustical features are considered. In section 3, the essential points of VUPTVH
are explained, with separate subsections dedicated to acoustic (subsections 3.1 and 3.2) and optical (subsection 3.3) subjects. Concerning the acoustic subjects, most of the published works on NDT by optical probing of ultrasound restrict the analysis to only one type of acoustic phenomena (for example, resonant flexural modes, or travelling bulk or surface-guided waves). However, in the results rendered by our system we have identified different phenomena existing simultaneously, as explained in section 4. This led us to make a classification of acoustic phenomena of interest in VUPTVH by making use of more general expressions for the acoustic fields than the ones employed in our previous works. With regard to the optical subjects, the main novel performance of our system reported in this work is the movie generation capability. It is described, along with the corresponding acquisition and processing time, in subsections 3.3.3 and 3.3.5. Other new contributions are the description of the output of our TV holography (TVH) system in terms of the acoustic fields defined in subsections 3.1 and 3.2. Finally, some results that illustrate the capabilities of VUPTVH for NDT of the structural integrity of metallic shell structures are presented in section 4 and the conclusions are exposed in section 5.

\section{NDT BY OPTICAL PROBING OF ULTRASOUND}

\subsection{ULTRASONIC FEATURES}

\subsubsection{SELECTION OF THE ULTRASONIC WAVES FOR NDT}

The geometry and other characteristics of the part to be inspected (for example, anisotropy of the material, or the depth location of the flaws) and of the NDT method (for example, the sensitivity direction of the probing system), restrict the types of ultrasonic waves to be employed. In the present work, we focus our interest in inspecting for flaws in non-polished metallic plates as a first step towards more complicated shell structures.

If the material of the inspected plate is isotropic and homogeneous and its thickness is
much greater than the acoustic wavelengths, the modelling of the medium as a half-space is useful for finding the guided wave solutions [Graff 1975, 311-391], [Rose 2000, 90-100]. In this case, the principal types of waves are (i) bulk waves, of the types dilatational (also known as longitudinal) (L) and distortional (also known as shear) (T), and (ii) surface acoustic waves (SAW), of the Rayleigh type if the boundary is stress-free. In generic, isotropic, homogeneous plates with stress-free boundaries, apart from the bulk L or T waves, the existing types of surface-guided waves are the so called SH and the Lamb ones [Graff 1975, 431-63], [Rose 2000, 101-31 and 241-61], which in the low-frequency end include the flexural waves. Strictly speaking, Rayleigh waves are not possible in finite-thickness plates but instead the very similar quasi-Rayleigh waves, a particular combination of S0 and A0 Lamb modes, can be easily produced [Viktorov 1967, 93-6]. In this work, we will refer to all the surface-guided waves indistinctly as SAW.

For our purposes, i.e., inspecting for flaws in non-polished metallic plates, SAW are of the maximum interest because of the following advantages:

- Less geometric attenuation than bulk waves. This allows the use of the same SAW to interrogate a large section of a structure or part, with a distance of up to tens of metres between the generating and the probing points [Lowe et al. 1998].

- Applicability in a broad range of frequencies, being possible to employ a SAW wavelength larger or smaller than the plate thickness.

- Possibility to measure in-plane as well as out-of-plane material properties.

- The power density profile as a function of depth is mode-dependent, which allows tuning the flaw detection sensitivity peak to a certain location depth or to a given flaw morphology by a proper choice of the excited mode [Rose 2000, 419], [Cho et al. 1997], [Jenot et al. 2001], [Lowe et al. 1998], [Pei et al. 1996].

- If a whole-field probing technique is employed, the full field of view can be covered with a sufficiently long acoustic wavetrain, thus allowing the inspection of this area
in a single snapshot picture.

When using SAW for non-destructive testing, there are several questions to address about the desired characteristics of the waves: single-mode vs. multimode, narrowband vs. broadband, high vs. low dispersion working point. A brief discussion about these questions has been done in [Fernández et al. 2007].

2.1.2 GENERATION OF ULTRASOUND

Ultrasound can be generated by different methods: the classical one, with contact, employing piezoelectric or similar transducers and, more recently developed, non-contact methods like laser, electromagnetic acoustic transducers (EMAT), air-coupled devices, and others. Laser is the only truly remote generation method, with a standoff of several metres.

Among the contact methods for generating SAW, the angle beam transducer (also called prismatic coupling block or wedge transducer) is one of the most appropriate. Its remarkable features are [Rose 2000, 94-6, 200-23 and 416-9]:

- It allows launching very directional, nearly plane guided waves.
- Very good control of the temporal profile of the launched acoustic wave, including the frequency and the wavetrain envelope.
- Good efficiency, with acoustic amplitudes of the order of several nanometres in metals.
- It allows a certain degree of selection of the generated guided modes (although multimode fields are unavoidable in general, especially for a short coupling length).

The non-contact methods allow overcoming several limitations like the need to adapt the transducers geometry to that of the inspected part, the need of coupling fluids and the need to maintain extremely clean the surface to be inspected, contributing to an easier automation of the inspection process.
Acoustic waves can be generated by irradiating the sample surface with a laser pulse. Various types of waves having different amplitudes may appear, depending on the optical power density distribution at the surface and on the medium properties [Scruby and Drain 1990, 320], [Davies et al. 1993]. The ablation regime (also known as plasma regime) can be reached when the power density is high enough; its effect is similar to a mechanical impulse and, in this case, mainly L and T waves as well as SAW are generated. The same types of waves are generated for lower power densities (thermoelastic regime), although their amplitudes are much lower than in the ablation regime. Laser generation of SAW can be improved by selecting adequate spatial and temporal irradiance distributions on the part surface, being even possible to generate narrowband SAW [Huang et al. 1992], [Yamanaka et al. 1993], [Kenderian et al. 2003], [Edwards et al. 1992], [Murray et al. 1997].

2.1.3 INTERACTION OF ULTRASOUND WITH MATERIAL FLAWS

In general terms, the interaction of ultrasound with defects gives rise to new acoustic waves, which can be explained by mechanisms such as reflection, diffraction, scattering or mode conversion [Graff 1975, 394]. In ultrasonic NDT, the usual aim is to locate and characterize the existing flaws into a given volume (the part or structure under inspection), given a spatial and temporal sampling of the acoustic field in a region of the volume boundary (i.e., at the inspected part surface). This leads in a natural way to the statement of the problem as an inverse problem. In the majority of practical cases, the subject is rather involved.

Usually, classical books [Graff 1975, 394-430], [Auld 1990, vol. II, 190-201] include the treatment of the direct problem (i.e., given the medium and flaw characteristics and the incident wave, then calculating the scattered field) by standard analytical methods, but only simple geometries and wave schemes admit solutions in closed form.

Other approach consists of the numerical simulation of the direct problem under selected conditions about the launched acoustic waves and the material characteristics
and flaws. The available tools include, among other, the finite element method (FEM) [Lowe et al. 2002], [Sato et al. 2003], [Hassan and Veronesi 2003], [Samartín et al. 2004], [Alleyne and Cawley 1992], the boundary element method (BEM) [Rose 2000, 308-34], [Cho et al. 1997], and the local interaction simulation approach (LISA) [Agostini et al. 2003]. The numerical simulation approaches allow managing complex geometries and wave schemes but, in general, are heavy and time-consuming methods not always indicated to solve the inverse problem for extracting the flaw features. It is worth to be aware of that 3D models are necessary for properly describing the ultrasound-flaws interaction in NDT realistic situations. This fact leads to the need of powerful machines to perform massive computation tasks.

Other approaches establish an analytical relationship between the flaws and the acoustic field that allows to solve the inverse problem (usually, by applying numerical techniques). For example, in [Mast and Gordon 2001], the measurement of the out-of-plane 2D surface displacement field of a plate provides massive input data to solve the inverse scattering problem by deconvolution of an appropriate Green function. In [Wang and Huang 2004], the knowledge of the displacements of the scattered field at the plane surface of an elastic solid allows, by backpropagation of elastic waves, to extract the locations, dimensions and shapes of the existing cracks embedded in the material. In [Cheng and Resch 1995] an acoustic scattering model for a distribution of cracks based on generalized reciprocity theory and Kino’s scattering formalism is developed and, subsequently, the numerical evaluation of the reflection coefficient of Rayleigh waves is performed. In [Diligent et al. 2002] an analytical model based on mode superposition for scattering problems in plates, and its application for predicting the reflection coefficient of Lamb waves from a through-thickness hole, is presented combined with FEM simulation of the scattering and also with experimental data. Other works based on modal decomposition relate the reflected and transmitted waves to the properties of specific types of flaws [Shkerdin and Glorieux 2004], [Castaings et al. 2002].
2.2 OPTICAL PROBING OF ULTRASOUND

Among the existing optical techniques for probing ultrasound on opaque surfaces, we highlight the following:

2.2.1 POINTWISE TECHNIQUES

2.2.1.1 Optical beam deflection (OBD)  It is based on recording the deflection of a light beam after its reflection on the specimen surface on which the ultrasound is propagating. This technique has a pointwise character, that is, there is only one measuring channel in such a way that the information about the state of the illuminated area (whose size is comparable or smaller than the ultrasonic wavelength) is integrated in a unique signal. Several variants have been reported that use different methods to record the beam deflection: knife-edge [Scruby and Drain 1990, 66-73], [Jen and Hartmann 1996], optical fibre bundle [Williams and Dewhurst 1995], [Murfin et al. 2000], or single optical fibre [Lu et al. 2001]. Due to its single-channel nature and to its low sensitivity when inspecting optically rough surfaces, OBD is not a competitive technique for our purposes of inspecting for flaws in non-polished metallic plates.

2.2.1.2 Surface grating diffraction  It is based on recording the diffraction pattern created after reflection of a laser beam onto the travelling phase grating formed on the specimen surface by the passage of the acoustic wave [Scruby and Drain 1990, 63-5], [Rogers et al. 2000], [Rogers 1998]. This technique only works if the surface is optically smooth and if the illuminated area contains an appreciable number of acoustic wavelengths, a fact that leads to a practical range of ultrasonic frequencies of typically hundreds of MHz for most materials. These two constraints preclude its use in our case. Although it is usually employed under a pointwise detection scheme, a particular imaging configuration allows recording simultaneously the power distribution of the acoustic waves across the whole illuminated area [Zuliani et al. 1973].
2.2.1.3 **Laser velocimetry** There are many variants gathered under this general denomination, all of them basing their principle of measurement on optical interferometry. The magnitude that carries the information is the phase or frequency of the light scattered from a point of the specimen surface on which a laser beam impinges. The extracted signal is proportional to a given component of the instantaneous displacement or velocity of the illuminated area of the specimen, usually the out-of-plane component, although there are specific designs that are sensitive to the in-plane one. These techniques reach a high sensitivity (the most sensitive optical methods are the interferometric ones) and have demonstrated to be a very valuable tool to probe ultrasound in practical situations including both smooth and rough surfaces, so that complete NDT systems are commercially available. A rough classification of laser velocimeters may be done as follows [Scruby and Drain 1990, 76-222], [Murfin et al. 2000], [Dewhurst and Shan 1999]:

- **Two beam interferometers**: include the Michelson and Mach-Zehnder configurations, with a smooth reference beam under homodyne or heterodyne detection schemes, and also differential and time-delay interferometers, which use as a reference beam the speckled object beam scattered from the specimen surface.

- **Multiple beam interferometers**: mainly, the Fabry-Pérot configuration.

- **Adaptive interferometers that employ photorefractive effects**: phase conjugation, self-diffraction –especially, two-wave mixing [Delaye et al. 2000]– and photo-induced electromotive forces.

2.2.1.4 **Ultrashort pulse pump-probe** These techniques make use of very short stress pulses, generated by thermoelastic deformation of the surface irradiated by an ultrashort optical pulse, that propagate across the specimen and are subsequently detected by another optical probing pulse after a controlled delay. The detection principle is usually the change in the specimen optical reflectivity [Thomsen et al. 1986], [Rossignol et al. 2005], [Vollmann et al. 2002], although the change in the surface slope
(OBD) [Wright and Kawashima 1992] and interferometric detection [Hurley and Wright 1999] have also been reported. The fine achievable temporal resolution (of the order of picoseconds), lateral resolution (of the order of micrometres) and the specific and expensive equipment needed make these techniques especially adequate for characterizing microstructures and thin films in laboratory, but not well suited for macroscopic industrial inspection where the temporal and spatial scales are much larger.

2.2.1.5 Limitations of pointwise methods The aforementioned pointwise detection methods render a time story of the interrogated point. This scheme is adequate if one desires a high bandwidth (which means a high temporal sampling rate) along with a high frequency resolution in the spectrum of the sampled signal (which means a large number of samples), because the acquisition and processing hardware is fully dedicated, not shared with any other channel. Moreover, the scanning of the probe allows the inspection of the whole specimen to get a measure of its structural integrity. For example, one of the most popular opto-acoustic approaches, included under the generic term ”laser ultrasonics” [Scruby and Drain 1990], combines pointwise ultrasound detection by optical means (usually, by laser velocimetry) with ultrasound generation by another laser beam focused onto the specimen surface, being both laser beams automatically scanned across a selected area to perform the inspection of the specimen volume under that area in a fully remote way. The scanning allows also extracting information about the spatial distribution of the acoustic amplitude (that is, the acoustic displacement amplitude field) by sequential acquisition in successive experiments following a repetitive generation-detection scheme [Clark et al. 2000], [Knuttila et al. 2000]. Nevertheless, difficulties arise to obtain, by scanning, a precise knowledge of the relation among the amplitudes of different points of the same acoustic field and among their temporal responses. This is the case when one is interested in the phase of a stationary acoustic displacement field or in the instantaneous displacement field. These difficulties are related to the lack of repeatability from one experiment to the following (due, to a great extent, to ultrasound coupling inconsistenc-
cies) and to the slow measuring rate (that imposes long-term stability requirements to
the acoustic field and to the experimental setup).

2.2.2 WHOLE-FIELD TECHNIQUES

To overcome the difficulties mentioned in 2.2.1.5, an attractive approach to is to parallelise
the detection by arranging a set of detectors that performs a spatial sampling of an
optical image whose irradiance contains information of the acoustic field at a given time
interval. Probably, the most practical way to implement such a scheme is to employ a
video camera as the optical detector. The actual difficulty to realise this approach is
how to generate the optical image, that is, to find a whole-field optical method sensitive
enough to the fast and subtle displacements associated to the ultrasonic waves. Optical
have demonstrated to be feasible methods for specular specimen surfaces whilst two
approaches based on the recording of holograms have succeeded this challenge for surfaces
of non-specular finish: holographic interferometry and TV holography.

2.2.2.1 Holographic interferometry  Holographic interferometry (HI) techniques
[Collier et al. 1971] are based on the interferometric comparison of two or more optical
wavefronts scattered from the specimen surface, corresponding each to a different me-
chanical state. This allows extracting the map of the optical phase-difference between
successive states, which is proportional to a certain component of the surface displace-
ment (usually, the out-of-plane one). In order to allow the comparison, at least one
of the wavefronts is frozen and stored in a hologram by some appropriate temporal
treatment of the illumination-recording process, and then reconstructed and superim-
posed to the other wavefronts. Apart from the classical and tedious photographic emul-
sions [Shiokawa et al. 1975], [Gagosz 1974, 78-83], [Aleksoff 1974, 247-63], [Vest 1979,
224-5 and 242-4], [Henning and Mewes 1995], [Fällström et al. 1989], real-time recording
media like thermoplastic film [Pohl et al. 1992], [Schroeder and Crostack 1996], bacteri-
orthodopsin [Blackshire et al 2002], [Blackshire and Duncan 2004] or photorefractive crystals [Telschow et al. 1999], [Telschow et al. 2003], [Delaye et al. 2000], [Lemaire et al 2000] have been employed, allowing a much higher refreshing rate (up to tens of Hz for photorefractive media, although at the expense of a large light power demand).

### 2.2.2.2 TV holography

TV holography (TVH) techniques [Doval 2000], also known as electronic speckle pattern interferometry (ESPI), use the image sensor of the video camera as a recording medium and employ a configuration of image hologram. At least, one hologram is recorded for each mechanical state to be compared. However, there is not optical reconstruction of the recorded holograms but instead their intensity distribution is electronically processed to render the optical phase-difference map at the specimen surface, losing the three-dimensional character of HI and introducing extra noise due to the necessity to resolve the speckle in the recorded intensity distributions [Mast and Gordon 2001], [Trillo et al. 2003a], [Trillo et al. 2003b]. The main advantages of TVH over HI are easier use, real-time display of results and lower light power needed, being possible to maintain a refreshing cadence (limited by the camera and associated electronics) of tens of Hz with megapixel resolution and, not less important for its spreading in industrial applications, lower cost of the equipment.

### 2.2.2.3 Additional advantage of holographic techniques

In addition to the aforementioned advantages common to the optical measurement methods, in holographic techniques (HI as well as TVH) the field of view is easily selectable over a wide range by changing the imaging optics (zooming capability).

### 2.2.2.4 Temporal treatment of holographic techniques

Concerning the temporal treatment, three generic schemes can be applied in HI as well as in TVH:

a) Continuous or time-average. This scheme is only adequate for stationary (i.e., periodic in time) ultrasonic fields but can be applied to both standing waves and
travelling waves. A hologram is recorded while the specimen is insonified, and the optical irradiance modulated by the acoustic field is time averaged within each video frame. In a special configuration named photorefractive dynamic holography, homodyne or heterodyne phase modulation of the reference beam is applied which allows raising the sensitivity to subnanometre level maintaining a high immunity to perturbations of frequency not similar to the ultrasound frequency. Moreover, it allows extracting the acoustic displacement amplitude and phase and also the instantaneous acoustic displacement field in quasi-real time (several maps per second). This technique was successfully employed to analyse SAW in crystals and metals [Telschow et al. 1999], [Telschow et al. 2003]. Another configuration, namely frequency translated holography, combines homodyne phase modulation with spatial filtering to extract the acoustic displacement amplitude, allowing simultaneously to discriminate travelling waves moving in one direction from those moving in the opposite one and from standing wave patterns (Shiokawa et al. 1975), (Blackshire et al. 2002), (Blackshire and Duncan 2004). However, properly working of the spatial filtering requires that the acoustic displacements of the specimen surface form a well-defined phase grating (ideally, the acoustic wave should be plane with many cycles in the field of view), and the tailoring and alignment of the spatial filter may be critical to avoid missing or introducing artificial information in the output.

b) Stroboscopic. This scheme is adequate for stationary ultrasonic fields and also for transient events that are shorter than the integration time of the video camera and can be accurately repeated, so its repeated excitation at regular intervals generate a periodic signal. As the ultrasonic period (of the order of microseconds) is much shorter than the integration time of the camera (typically, tens of milliseconds), a stroboscopic illumination or detection system is employed to freeze the acoustic field avoiding the time averaging of the ultrasonic signal within each video frame. In one of the real-time usual variants, a hologram is recorded corre-
sponding to a reference state with the specimen at rest and, afterwards, new states are acquired corresponding to the propagation of an ultrasonic wave across the specimen surface [Schroeder and Crostack 1996]. In another real-time variant, two different states of the vibration cycle are acquired and compared one against the other [Mast and Gordon 2001]. These two references report the measurement of the instantaneous acoustic displacement field of ultrasonic SAW, although it would be also possible, in principle, to extract also the acoustic displacement amplitude and phase maps by employing a refinement of the basic method [Doval et al. 2000], [Doval et al. 1994], [Valera et al. 1992]. Among the advantages of the stroboscopic scheme, we can highlight its practically instantaneous presentation of the acoustic fields, similarly to the photorefractive dynamic holography but with a much lower laser power. One of its main drawbacks is its high susceptibility to optical phase changes in the band of the video frame rate (tens of Hz) and higher frequencies, for which a good isolation against environmental perturbations (seismic vibration, air currents, acoustic noise, temperature gradient, etc.) must be provided. Realistic values of the minimum measurable displacement are of the order of one nanometre.

c) Pulsed. This is the only scheme adequate for transient measurands. Two mechanical states of the specimen separated by a short time interval (typically of the order of microseconds) are frozen by two respective light pulses and recorded each in a hologram. Electronic processing of the holograms (preceded by optical reconstruction in IH) allows to recover the optical phase-difference at each point of the field of view, which is proportional to a given component of the acoustic displacement between the two compared states. Specific advantages of this temporal treatment (in contrast to time-average or stroboscopic schemes) are:

- True transient analysis capability with acquisition of a snapshot picture of the surface displacement.
- High temporal resolution (of the order of the pulse duration, about 10 nanosec-
onds).

- High immunity to environmental perturbations.

- High flexibility in the temporization of the events: laser firing and ultrasound generation. This allows recording the holograms before the ultrasonic waves reflected or scattered by the specimen boundaries affect the area under inspection, thus avoiding the use of acoustic absorbers and improving the fidelity of the measurements.

This combination of characteristics makes pulsed holographic techniques a powerful measurement tool, suitable to freeze and capture 2D dynamic displacement fields of opaque surfaces in a variety of circumstances including small, delicate, sensitive to scratching, very thin, lightweight or moving objects, restricted-access zones (furnaces, vacuum chambers, tanks, the bottom surface of holes), and other difficult NDT tasks. Several authors have employed pulsed IH to visualize and even to extract quantitative data of instantaneous displacement fields of transient vibrations of mechanical components and of SAW [Gagosz 1974, 78-83], [Vest 1979, 224-5 and 242-4], [Pohl et al. 1992], [Fällström et al. 1989], [Henning and Mewes 1995]. However, to the best of our knowledge, only our group has reported the detection of SAW by pulsed TVH [Cernadas et al. 2002], [Trillo et al. 2003a], [Cernadas et al. 2006]. Moreover, we developed a specific phase evaluation technique that renders quantitative data of transient SAW, namely the instantaneous out-of-plane acoustic displacement field and also the out-of-plane acoustic displacement amplitude and phase fields, with a minimum measurable displacement of the order of one nanometre [Trillo et al. 2003b].

2.2.2.5 Shearography  One of the most popular variants of TVH for industrial NDT is speckle-shearing interferometry, also named shearography, which employs common-path illumination-detection geometry where the role of the reference beam is played by a du-
licate of the object beam laterally displaced. This offers a certain degree of immunity (although not as complete as with pulsed techniques) to environmental perturbations even with long exposure times. Shearography has been successfully employed for measuring instantaneous SAW displacement fields [Bard et al. 1998], [Taillade et al. 2000]. However, it presents several handicaps compared to standard HI and TVH: (i) its output is more noisy because the reference beam is also speckled, (ii) shearography does not render the map of a given component of the surface displacement as in HI and TVH, but its output is rather the map of the difference of the displacement component between points separated by the shearing vector [Doval 2000]. Even in the simplest case of small shear, in which the displacement difference can be approximated by its spatial derivative, the relationship between the measured data and the material structure and flaws is more complex than in HI and TVH [Mast and Gordon 2001], and (iii) the shearing direction and magnitude limits the optimum sensitivity to only some acoustic wave propagation directions and wavelengths. For fields propagating in other directions, sensitivity decreases with the angle between the shearing vector and the wave vector. For example, for the standard linear shear, cylindrical waves scattered from defects would be detected predominantly in the shearing direction. Hence, optimum shearing vector selection requires a previous knowledge of the acoustic wave vector.

2.2.2.6 Conclusion From the former considerations it seems that, among all the holographic techniques, the pulsed TVH ones hold possibly the greatest potential for probing of ultrasound in industrial NDT tasks.

3 VIDEO ULTRASONICS BY PULSED TV HOLOGRAPHY

In this section, we will briefly describe the VUPTVH technique and the associated self-developed prototype to apply this technique. As stated in the introduction, it
has been developed by our research group along the last decade, with successive improvements in the optical and electronic hardware and, especially, in the information processing scheme. Some parts of the current system have been incorporated from former prototypes already explained elsewhere [Trillo et al. 2003b], [Trillo et al. 2006], [Trillo and Doval 2006], [Cernadas et al. 2002], for which the details will not be repeated here.

The use of VUPTVH for NDT is based on the same three-step working principle explained in the introduction: (i) generation of ultrasound in the part to inspect, (ii) interaction ultrasound-flaws and (iii) probing by TVH of the ultrasonic displacement field at the part surface.

3.1 GENERAL DESCRIPTION OF THE ULTRASONIC FIELDS FOR VUPTVH

In subsection 2.1.1, the suitability of SAW for NDT of shell-like structures was justified. In our case, we have used Lamb waves, including the particular case of quasi-Rayleigh waves, in aluminium plates a few millimetres thick as depicted in Fig. 2, generated by the wedge method. Our generating system (Fig. 3) consists of a piezoelectric element (PZT) attached to a wedge of plastic material and the corresponding driver, that produces high-voltage tone-bursts with the possibility of selecting both the number of cycles and the central frequency in the range of a few MHz. In a near future, we expect to implement also generation by laser.

From the illumination-observation geometry (Fig. 3) it can be seen that the sensitivity vector of our TVH system is approximately parallel to the observation direction. This means that we only measure the out-of-plane component of the surface displacement vector. Therefore, in the current configuration, the interesting Lamb modes are those with an appreciable out-of-plane component at the object surface. It is possible also to make the system sensitive to the in-plane components by changing the illumination-
observation geometry or by tilting the inspected part a large angle (for instance, 45 degrees); these variants will be explored in future developments.

With respect to the temporal behaviour, we classify the fields in two categories:

a) Broadband: the fields are intrinsically transient and there is not a clear temporal periodicity but, instead, the time waveforms at each point consist of isolated pulses with very few cycles or, when dispersive effects appear, chirped or similar waveforms formed by an oscillatory signal of variable period and amplitude. Apart from the components of the guided ultrasonic waves (i.e., travelling waves and non-propagating evanescent modes), transient vibration patterns excited by the former may also appear, due to vibrational eigenmodes of the material structure (for instance, resonant flexural or torsional modes). A generic description of a broadband field cannot be too restrictive, so we will employ the most general expression of a scalar field depending on space and time:

\[ u_{l3} = u_{l3}(x,t) \] (1)

where \( u_{l3} \) is the out-of-plane component of the instantaneous acoustic displacement vector \( \mathbf{u}_l \) at the plate surface point \( x = (x_1, x_2, h) \) (Fig. 2), the first sub-index \( (l) \) denotes which particular wave we are referring to (for example, \( l = 1 \) for the incident wave) and the second sub-index (3 in this case), denotes the cartesian component.

b) Narrowband: the fields have some kind of temporal periodicity and their representation in terms of a central circular frequency \( \omega \) is of convenience. In this way, the out-of-plane component \( u_{l3}(x,t) \) at the plate surface can be described in terms of the complex acoustic field \( \hat{u}_{l3}(x,t) \), whose spatial dependence is included in the complex acoustic amplitude \( \hat{u}_{l3m}(x,t) \):

\[
u_{l3}(x,t) = \text{Re} [\hat{u}_{l3}(x,t)] = \text{Re} [\hat{u}_{l3m}(x,t) \exp (-j\omega t)] = \text{Re} (u_{l3m}(x,t) \exp \{j [\varphi_{l3m}(x,t) - \omega t]\}) \] (2)
where, due to the narrowband character of the wave, the acoustic amplitude \( u_{l3m}(x, t) \) and the spatial acoustic phase term \( \varphi_{l3m}(x, t) \) at each point must vary slowly in time compared to the wave period \( 2\pi/\omega \) except, perhaps, at the front and trailing edges of the wavetrains, where large amplitude and phase excursions may take place in a time interval comparable to the period. Into this scheme, we can differentiate two basic behaviours:

b.1) Travelling waves: neglecting dispersion, \( \hat{u}_{l3}(x, t) \) can be described for each single mode as follows:

\[
\hat{u}_{l3}(x, t) = u_{l3m}(x, t) \exp \left\{ j \left[ k_l(x) \cdot x + \varphi_{l30}(x, t) - \omega t \right] \right\}, \quad \text{travelling wave}
\]

where the acoustic phase \( \varphi_{l30}(x, t) \) must vary slowly in time compared to the wave period \( 2\pi/\omega \) and in space compared to the wavelength \( 2\pi/k_l \) except, perhaps, at the front and trailing edges of the wavetrains. In most cases, the coexistence of several travelling waves of the same central frequency gives rise to spatial variations of the amplitude, i.e., interference or standing wave patterns, although in our case it would be more appropriate to speak of quasi-standing wave patterns because of the temporal dependence of the envelope of the wavetrains.

b.2) Quasi-stationary patterns: can be described as follows:

\[
\hat{u}_{l3}(x, t) = u_{l3m}(x, t) \exp \left\{ j [\varphi_{l30}(x, t) - \omega t] \right\}, \quad \text{quasi-stationary pattern}
\]

where the acoustic phase values of each pattern, \( \varphi_{l30}(x, t) \), are at each instant restricted to two discrete values whose difference is \( \pi \) and also must vary at each point slowly in time compared to the wave period \( 2\pi/\omega \), except at the phase discontinuities where the jump of \( \pi \) rad between neighbouring points may suffer a spatial shift along time. Similarly to the broadband case, quasi-stationary patterns may appear due to evanescent waves or to eigenmodes.
Other oscillatory phenomena that can be included into this category are the coupled vibrational eigenmodes, which can be described as a superposition of two or more pure vibrational eigenmodes at the same frequency and whose difference of phases $\varphi_{l30}(x,t)$ is not 0 or $\pi$, resulting that the phase of the superposition, $\varphi_{3m}(x,t)$, has a continuous variation across the spatial coordinates.

To enhance the capability of VUPTVH to detect isolated flaws like cracks and voids, a single-mode narrowband incident plane wavetrain in the form of a tone-burst of constant amplitude and a number of cycles between 5 and 30 is quite adequate. In a first approximation, ignoring diffraction and dispersive effects, the expression (3) applies to this case with a wavevector, $k_l$, constant and parallel to the $x_1$ axis.

3.2 EXPRESSIONS FOR THE INTERACTION OF ULTRASONIC WITH MATERIAL FLAWS

In subsection 2.1.3, different treatments of the scattering of ultrasound by material flaws were indicated. In our case, for solving the inverse problem we have at our disposal, as the directly measured data, a set of 2D instantaneous acoustic displacement maps of the plate surface, recorded in successive instants of the ultrasound propagation. The development of a model that relates this information of the scattered field to the flaw localization and characteristics is out of the scope of this paper. Nevertheless, we will write here generic equations of the different classes of possible ultrasonic fields for a better understanding of the obtained maps. Also, we will consider in these equations (Fig. 4) the existence of scattering centres at the specimen surface that are point sources of the scattered waves. The distribution of scattering centres is intimately related to the positions of the flaws embedded in the plate material. Specifically, for surface-breaking and near-surface flaws of size comparable to or smaller than the SAW wavelength, a cylindrical scattered SAW seems to emanate from a scattering centre located approximately at the projection of the
flaw on the specimen surface. This fact provides an easy procedure to get a first indication of the existence and location of flaws without solving the inverse problem. Following the same classification of section 3.1, the fields expressions are:

a) Broadband: if the material works in the linear regime, the resultant field can be regarded as a superposition of the incident and scattered fields, including travelling and evanescent waves and transient vibration patterns. The total out-of-plane instantaneous acoustic displacement at the plate surface can be written, from (1), as

\[ u_3(x, t) = \sum_l u_{3l}(x - x_{l0}, t), \quad \text{broadband field} \quad (5) \]

where the summation extends to all the existing waves and vibration patterns and we have written the spatial dependence of the \( l \)-th wave with respect to the coordinates \( x_{l0} \) of the scattering centre that generates that wave.

b) Narrowband: supposing again that the material works in the linear regime, the resultant field can be regarded as a superposition of the incident and scattered fields, including travelling waves and quasi-stationary patterns, all excited by the incident wave (and, in consequence, with the same central frequency). The total out-of-plane instantaneous acoustic displacement at the plate surface can be written, from (2)-(4), as:

\[ u_3(x, t) = \text{Re} \left[ \hat{u}_3(x, t) \right] = \text{Re} \left( u_{3m}(x, t) \exp \left\{ j \left[ \varphi_{3m}(x, t) - \omega t \right] \right\} \right) = \text{Re} \left( \sum_l u_{3lm}(x, t) \exp \left\{ j \left[ k_l(x) \cdot (x - x_{l0}) + \varphi_{30}(x, t) - \omega t \right] \right\} \right), \quad \text{narrowband field} \quad (6) \]

where \( k_l(x) = 0 \) for quasi-stationary patterns and the conditions that must fulfil the functions \( u_{3lm}(x, t) \) and \( \varphi_{30}(x, t) \) were given along with the expressions (2)-(4). Expression (6) is quite general, applicable to single- and multimode ultrasonic fields of the Rayleigh and Lamb types coexisting with waves scattered by flaws, including
the case of mode conversion, recorded along time intervals short enough to neglect dispersive effects.

3.3 PROBING OF ULTRASOUND BY VUPTVH

The optical probing system is depicted in Fig. 3. Basically, it is a self-developed double-pulsed TVH system with specific phase evaluation techniques.

3.3.1 FIRST EVALUATION STAGE

In a first evaluation stage, the optical phase-change field $\Delta \Phi (x, t)$ is obtained by the spatial Fourier transform method (SFTM), [Saldner et al. 1996]. In these conditions, the output of the system is a 2D map that renders, at each point of the field of view, the difference between the out-of-plane displacements corresponding to the two mechanical states defined by the illuminating laser pulses. Details of the practical implementation and some examples of the system output can be found in [Trillo et al. 2003b], [Trillo et al. 2006]. This measurement scheme can be particularized to the ultrasonic temporal behaviour:

a) Broadband: this is the most general case. Taking into account expression (5) and denoting the illumination instants as $t_i$, $t_f$, the directly measured quantity is an optical phase-change of the form

$$\Delta \Phi (x, t_i, t_f) = -\frac{4\pi}{\lambda}[u_3(x, t_f) - u_3(x, t_i)] + \text{noise} \left(\Delta \Phi\right)$$

where $\lambda$ is the laser wavelength in the medium surrounding the plate (usually air) and the unavoidable noise of the whole measurement process has been simply considered as an additive term without any attempt to characterise it. Firing the first laser pulse with the object at rest, it results

$$\Delta \Phi (x, t) = -\frac{4\pi}{\lambda} u_3(x, t) + \text{noise} \left(\Delta \Phi\right), \quad \text{instantaneous optical phase-change}$$
b) Narrowband: taking into account expressions (6) and (7) and separating the illumination instants by an odd number of semiperiods:

\[ t_f = t_i + (2q + 1) \frac{\pi}{\omega}, \quad q = \text{small integer (typically, } q = 0 \text{ or } 1) \quad (9) \]

it results

\[ \Delta \Phi (x, t_i, t_f) = \frac{4\pi}{\lambda} \text{Re} \left( \sum_l \{ u_{l3m} (x, t_i) \exp[j \varphi_{l30} (x, t_i)] + 
+ u_{l3m} (x, t_f) \exp[j \varphi_{l30} (x, t_f)] \} \exp \{ j [k_l (x) \cdot (x - x_{l0}) - \omega t_i] \} \right) + 
+ \text{noise} (\Delta \Phi) \quad (10) \]

The expression (10) can be approximately substituted by

\[ \Delta \Phi (x, t) \approx \frac{8\pi}{\lambda} \text{Re} \left( \sum_l \{ u_{l3m} (x, t) \exp[j \varphi_{l30} (x, t)] \} \times 
\times \exp \{ j [k_l (x) \cdot (x - x_{l0}) - \omega t] \} \right) + \text{noise} (\Delta \Phi) = 
= \frac{8\pi}{\lambda} u_3 (x, t) + \text{noise} (\Delta \Phi), \quad \text{instantaneous optical phase-change} \quad (11) \]

where we have employed the fact that the acoustic amplitude \( u_{l3m} (x, t) \) and the acoustic phase \( \varphi_{l30} (x, t) \) at each point must vary slowly in time compared to the wave period \( 2\pi/\omega \) except, perhaps, at the front and trailing edges of the travelling wavetrains or at the quasi-stationary pattern phase discontinuities. In these points, (11) may fail but (10) should be employed instead.

### 3.3.2 SECOND EVALUATION STAGE

Whenever an incident narrowband travelling wave is employed, a second evaluation stage that takes advantage of the periodicity of the signal can be applied to the output (11) of the first stage. We have devised two variants:

a) Spatial evaluation: this variant [Trillo et al. 2003b] is based on the spatial periodicity of the signal. For its practical realization, we have used a single-mode incident
plane wavetrain in the form of a tone-burst of smooth envelope. Once obtained
the optical phase-change map (11) corresponding to the instantaneous acoustic dis-
placement at a given instant \( t \), it can be interpreted as a superposition of different
spatial carriers (the different existing travelling waves), each modulated in ampli-
tude and phase. Therefore, a second application of the SFTM allows recovering the
complex optical phase-change field at the instant \( t \):

\[
\Delta \hat{\Phi} (x, t) = \frac{4\pi}{\lambda} \hat{u}_3 (x, t) + \text{noise} (\Delta \hat{\Phi}) = \\
\frac{4\pi}{\lambda} \sum_l u_{3m} (x, t) \exp \{ j [k_l (x) \cdot (x - x_{l0}) + \varphi_{3m} (x, t) - \omega t] \} + \text{noise} (\Delta \hat{\Phi}) = \\
\frac{4\pi}{\lambda} u_{3m} (x, t) \exp \{ j [\varphi_{3m} (x, t) - \omega t] \} + \text{noise} (\Delta \hat{\Phi}) ,
\]

complex optical phase-change (12)

which is, apart from the noise, proportional to the complex acoustic field (incident
plus scattered) at the instant \( t \). The modulus and the argument of \( \Delta \hat{\Phi} (x, t) \) are,
respectively, the optical phase-change amplitude \( \Delta \Phi_m (x, t) \) and the total optical
phase-change phase \( \varphi_m (x, t) - \omega t \):

\[
\Delta \Phi_m (x, t) = \text{mod} \left[ \Delta \hat{\Phi} (x, t) \right] = \frac{4\pi}{\lambda} u_{3m} (x, t) + \text{noise} (\Delta \Phi_m) ,
\]

optical phase-change amplitude (13)

\[
\varphi_m (x, t) - \omega t = \text{arg} \left[ \Delta \hat{\Phi} (x, t) \right] = \varphi_{3m} (x, t) - \omega t + \text{noise} [\varphi_m (x, t) - \omega t] ,
\]

total optical phase-change phase (14)

The acoustic amplitude \( u_{3m} (x, t) \) and the total acoustic phase \( \varphi_{3m} (x, t) - \omega t \) can be
obtained (apart from the noise) by simply re-scaling the optical phase-change correspond-
ing quantities using (13) and (14). Also, the real part of \( \Delta \hat{\Phi} (x, t) \), that we denominate
filtered instantaneous optical phase-change \( \Delta \Phi^F (x, t) \), gives a band-pass filtered render-
ing of the instantaneous acoustic displacement field \( u_3(x,t) \):

\[
\Delta \Phi^F(x,t) = \text{Re} \left[ \Delta \hat{\Phi} (x,t) \right] = \frac{4\pi}{\lambda} \text{Re} \left( u_{3m}(x,t) \exp \{ j [\varphi_{3m}(x,t) - \omega t] \} \right) + \text{noise} \left[ \Delta \Phi^F \right] = \frac{4\pi}{\lambda} u_3(x,t) + \text{noise} \left[ \Delta \Phi^F \right], \quad \text{filtered instantaneous optical phase-change} \quad (15)
\]

The main advantage of the field \( \Delta \Phi^F \) is that it is less noisy than \( \Delta \Phi \) because of the filtering process in the SFTM evaluation. However, care must be taken to select an appropriate filtering window to avoid eliminating useful information and to avoid introducing artifacts that can be mistaken for acoustic signals.

b) Spatio-temporal evaluation: this variant [Trillo and Doval 2006] makes use of both the spatial and temporal periodicity of the signal. A sequence of \( N \) (typically, \( N = 64 \)) optical phase-change maps (11) is acquired with increasing delay times \( t_n \) (with \( n = 1, 2, ..., N \)) between the ultrasound generation and the initial illumination instant, in successive experiments following a repetitive generation-detection scheme. The time interval between two consecutive maps is selected short enough compared to the acoustic period to ensure the Nyquist sampling condition. We have then spatial periodicity at a given instant across each map and temporal periodicity at a given point across the series of maps. Then a three-dimensional (3D) Fourier transform, followed by a filtering and an inverse 3D Fourier transform, renders a set of \( N \) complex amplitude maps of the acoustic field (incident plus scattered), corresponding to successive instants \( t_n \) of the acquisition procedure. From each complex field \( \Delta \hat{\Phi}(x,t_n) \), the three fields, \( \Delta \Phi_m(x,t_n), \varphi_m(x,t_n) - \omega t_n \) and \( \Delta \Phi^F(x,t_n) \) (with \( n = 1, 2, ..., N \)) are obtained in the same manner than in case (a). This technique allows a noise filtering even better than the spatial evaluation variant because the temporal narrowband character of the acoustic fields is taken into account in the filtering process, although it requires a larger data acquisition time and a more powerful data processing equipment. Another advantage of the spatio-temporal evaluation, in opposition to the spatial evaluation, is that quasi-stationary patterns
as those described by (4) can be recovered even in the absence of spatial carrier because the temporal periodicity is still present and sampling takes place along several (typically, 16) complete vibration cycles.

3.3.3 SYNTHETIC MOVIE GENERATION

Our technique allows to generate high quality synthetic movies of any of the following fields: the instantaneous optical phase-change, $\Delta \Phi (x, t)$, given by equations (8) or (11), the optical phase-change amplitude, $\Delta \Phi_m (x, t)$, the total optical phase-change phase, $\varphi_m (x, t) - \omega t$, and the filtered instantaneous optical phase-change, $\Delta \Phi^F (x, t)$. For this, $N$ maps of the instantaneous optical phase-change are obtained corresponding to increasing delay times $t_n$ (with $n = 1, 2, ..., N$) between the ultrasound generation and the initial illumination instant. The data are acquired in successive experiments under repeatability conditions. Once obtained this set of maps, for generating a movie of $\Delta \Phi (x, t_n)$, the maps are treated as digital images and they are arranged with a video editor like the frames of a standard movie. In addition, for obtaining the other three maps, two alternatives can be followed:

a) Movie generation by individual processing of the maps: from each instantaneous optical phase-change map recorded at the time $t_n$, the corresponding $\Delta \Phi_m (x, t_n)$, $\varphi_m (x, t_n) - \omega t_n$ and $\Delta \Phi^F (x, t_n)$ maps are obtained by spatial evaluation. Afterwards, the maps are arranged with a video editor like the frames of a standard movie.

b) Movie generation by global processing of the set of maps: by applying the spatio-temporal evaluation to the whole set of $N$ instantaneous optical phase-change maps, three sets (of $N$ maps each) of the fields $\Delta \Phi_m (x, t_n)$, $\varphi_m (x, t_n) - \omega t_n$ and $\Delta \Phi^F (x, t_n)$ are obtained. Afterwards, like in method (a), the maps are arranged with a video editor. This procedure renders better results than alternative (a) in terms of noise for the same reason stated in 3.3.2, but takes more computation time and uses more
3.3.4 NOISE CONSIDERATIONS

A critical aspect of the VUPTVH system is the noise. Taking into account that the acoustic displacements to measure are of the order of a few nanometres, different sources of noise need to be controlled, which imposes severe requirements to the whole system, especially to the laser and image acquisition hardware. An estimation of the main contributions to the system noise was made in [Cernadas et al. 2002]. Also, information processing procedures like the employment of differential phase evaluation algorithms [Trillo et al. 2003b] and the numerical cancellation of the phase mismatch between the laser cavities, made by a technique similar to that reported in [Trillo et al. 2006], contribute to the quality of the measurements.

3.3.5 ACQUISITION AND PROCESSING TIME

To obtain a single instantaneous optical phase-change map $\Delta \Phi (x, t)$, four primary correlograms (i.e., the images as recorded by the camera) are employed following the aforementioned phase mismatch cancellation procedure. The acquisition time is of the order of 1 second although the ultrasonic field can be effectively frozen because the exposure time is just 20 nanoseconds and the pulse-to-pulse interval is approximately 1 microsecond. The processing time for the first evaluation stage –that yields a single instantaneous optical phase-change map $\Delta \Phi (x, t)$– is about 3.2 seconds for a map size of $1024 \times 1024$ pixels (Fig. 5), and about 1.7 seconds for a map size of $1024 \times 512$ pixels (Fig. 7(a)).

The second evaluation stage in the spatial variant requires about 1.1 seconds to calculate a complex optical phase-change map $\Delta \hat{\Phi} (x, t)$ from a single $\Delta \Phi (x, t)$ map of size $1024 \times 1024$ pixels (Fig. 6), and about 0.6 seconds for a map size of $1024 \times 512$ pixels. The second evaluation stage in the spatio-temporal variant takes about 100 seconds to calculate a set of 64 complex optical phase-change maps $\Delta \hat{\Phi} (x, t_n)$ from a set of 64 $\Delta \Phi (x, t_n)$ maps of size $1024 \times 512$ pixels (Fig. 7).
All these calculation times were obtained with a personal computer equipped with an AMD Athlon 64 3000+ processor at 1.81 GHz and 1 GB of RAM. An INTEL Pentium 4 processor at 3 GHz and with 1 GB of RAM was also tried, resulting slightly better performance for all the cases but the spatio-temporal variant in which a much better performance (25% reduction of processing time) was observed.

4 RESULTS

In Figs. 5 to 10 we show a representative set of results to illustrate the performances of VUPTVH for NDT of metallic plates, including a video file in Fig. 7.

Fig. 5 shows the interaction of several guided waves with cylinder-shaped defects not open to the observed part surface. Two different flat bottom bores (whose geometry is defined in Fig. 2) of the same diameter $D = 2.2$ mm and depths from the observed surface $e = 0.5$ mm and $e = 1.4$ mm, respectively, were machined in a plate 5 mm thick. The interactions of the waves with these flaws are shown in Fig. 5(i) and (ii). The wave in Fig. 5, row (a) is a quasi-Rayleigh mode of central frequency $1.00$ MHz and wavelength 2.91 mm. The propagating energy is concentrated in a region close to the observed surface of depth comparable to the wavelength. Therefore, this wave is sensitive to near-surface defects but its capability to interact with flaws strongly decays with depth. This fact is clearly seen in Fig. 5, row (a): the wave is strongly scattered in 5(a, i) but the deep bore of 5(a, ii) barely affects the wavetrain. On the other hand, in many Lamb modes the energy propagates throughout the whole depth of the plate, and hence these modes can be used to detect superficial as well as deep imperfections. Rows 5(b) and 5(c) show the effect of the aforementioned flat bottom bores in two different incident Lamb modes, an A1 mode of central frequency 1.18 MHz and wavelength 3.05 mm in row 5(b) and a S2 mode of central frequency 2.00 MHz and wavelength 2.45 mm in row 5(c). In the four cases, the flaws are detectable.

A diagram showing the second evaluation stage described in subsection 3.3.2(a) is
shown in Fig. 6. It corresponds to the field of Fig.5 (a, i). The original instantaneous optical phase-change map is Fourier transformed, filtered and inverse Fourier transformed, rendering a complex map whose amplitude, Fig. 6(c) and phase, Fig. 6(d) are proportional to the acoustic amplitude and phase of the SAW. By combining the information from the amplitude and phase maps, the filtered instantaneous optical phase-change map is obtained, Fig. 6(e). Some interesting wave phenomena can be seen like the scattering of the guided acoustic wave by the material flaw (circular wavefronts emanating from a point at the flaw location), a quasi-standing wave pattern due to the interference of the incident and scattered waves (Fig. 6(c), left half) clearly observable as oblique bright and dark fringes, and an intermode spatial beating [Fernández et al. 2007] due to the presence of two Lamb modes in the incident wave (Fig. 6(c), right half), observable as vertical bright and dark fringes.

A synthetic video movie showing the temporal evolution of the four previously described optical maps is available in the on-line version of the Journal (Fig. 7). The capability of recording the whole-field evolution of the wavetrain allows one to evaluate certain features of the wave propagation and interaction with flaws that are currently not possible to assess by means of other detecting techniques. For example, the geometry of the wavefronts (size, curvature, wavelength) can be precisely determined in each snapshot map. Also, both the phase and group velocities can be measured by analysing, respectively, the movement of the carrier inside the burst envelope and the movement of the envelope itself. In our case, the theoretically predicted non-dispersive nature of the quasi-Rayleigh wave is verified since no difference is detected in such velocities. Moreover, the global effect of the flaw in the propagation of the wave is observed with great detail: as the incident wave reaches the defect, a cylindrical scattered wave emanating from such defect superimposes the original plane wavetrain, giving rise to a standing wave pattern clearly observable in the modulus of the complex map (Fig. 7(b)) as static bright and dark fringes.

Figures 8 to 10 show different snapshot maps and profiles extracted from the movie of
Fig. 7 (d). The central horizontal section marked in Fig. 8 is displayed in Fig. 9, where a quasi-stationary pattern at the flawed area is perceived after the wavetrain has passed that point. To demonstrate the nature of such vibration, its spatio-temporal evolution is shown (profiles in Fig. 10, column (iii), corresponding to zone B of the central horizontal section marked in Fig. 8). In addition, the spatio-temporal evolution of the wavetrain in zone A (Fig. 10, column (ii)) is presented for comparison purposes. In opposition to the propagating nature of the wavetrain, the vibration around the defect is non-propagating and corresponds to a vibrational eigenmode formed in the zone between the flat bottom of the bore and the plate surface.

5 CONCLUSIONS

A novel capability of the TV holography technique, combined with ultrasound, for non-destructive testing of shell-like structures, that we call Video Ultrasonics by Pulsed TV Holography (VUPTVH), has been presented. The direct output of the system, for both narrowband and broadband fields, is a digital map of the instantaneous optical phase-change, which is proportional (apart from noise) to the out-of-plane component of the instantaneous acoustic displacement of the observed part surface. For narrowband fields only, a subsequent evaluation stage allows to obtain the optical phase-change amplitude, the total optical phase-change phase, and the filtered instantaneous optical phase-change, which are proportional (apart from noise) to the out-of-plane components of the acoustic amplitude, the total acoustic phase, and the instantaneous acoustic displacement, respectively.

In addition, if a set of experiments are made under repeatability conditions with an increasing delay between the ultrasound generation and the optical probing, then synthetic movies of the aforementioned acoustic fields, including transient events, can be generated.

Some experimental results illustrating the application of the technique to flaw de-
tection in aluminium plates using surface waves have been presented. Different acoustic
phenomena like travelling waves, quasi-standing wave patterns, an intermode spatial beat-
ing, scattering of the incident wave by the material flaws, and a quasi-stationary pattern
due to a vibrational eigenmode have been identified.

Some of the advantages of VUPTVH compared to alternative optical techniques for
probing ultrasound are the following:

- Whole-field method. No need of scanning the probing beam over the part surface.
- Short acquisition time of each snapshot map of the acoustic field. True transient
  analysis capability.
- Field of view easily selectable over a wide range by changing the imaging optics
  (zooming capability).
- High temporal resolution (of the order of the pulse duration, about 10 nanoseconds).
- High immunity to environmental perturbations.
- High flexibility in the temporization of the events: laser firing and ultrasound gener-
ation. This allows recording the holograms before the ultrasonic waves reflected or
scattered by the specimen boundaries affect the area under inspection, thus avoiding
the use of acoustic absorbers and improving the fidelity of the measurements.
- Total measurement time, including repetitive data acquisition and processing, very
  competitive (typically one or two orders of magnitude shorter) in comparison with
other ultrasound pointwise probing technologies that, to generate 2D data, employ
mechanical or optical scanning.

A critical performance figure of the technique is the minimum measurable out-of-plane
acoustic displacement. In our current prototype, it is of the order of one nanometre.
Although this is only a discrete figure compared to time-average or stroboscopic TVH
and to laser velocimetry, when combined with whole-field and transient analysis capability with snapshot acquisition, it gives rise to a system with unique performances.

Envisaged future work lines are the development of digital holography techniques, including hybrid optical-numerical treatment of the optical wavefronts, and narrowband generation of the ultrasound by laser.

ACKNOWLEDGEMENTS

This work was co-funded by the Spanish Ministerio de Educación y Ciencia and by the European Comission (ERDF) in the context of the Plan Nacional de I+D+i (project number DPI2005-09203-C03-01) and by the Dirección Xeral de Investigación, Desenvolvemento e Innovación da Xunta de Galicia in the context of the Plan Galego de IDIT (project number PGIDIT06PXIC303193PN). Supplementary co-funding from the Universidade de Vigo (project number I608122F64102) is also acknowledged. The authors would like to thank Prof. Mariano Pérez-Amor for his advice and encouragement throughout the development of VUPTVH. The authors acknowledge the contribution of calibration samples from Tecnatom, S.A. and Applus Norcontrol, S.L.U. Machining of ultrasound generating hardware, especial optomechanic elements and test plates was made by the technician Mr. Pablo Barreiro.

References


Academic.


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FIGURE CAPTIONS

Fig. 1. Working principle of non-destructive testing by optical probing of ultrasound.

Fig. 2. Notation for the incident surface acoustic wave, $u_1(x,t)$, in a plate. A flaw consisting of a flat bottom bore is also depicted.

Fig. 3. Layout of the VUPTVH system.

Fig. 4. Notation for the acoustic incident and scattered fields.

Fig. 5. Instantaneous optical phase-change maps of an aluminium plate 5 mm thick. The incident acoustic wave is a narrowband, practically pure single-mode wavetrain 90 cycles in length propagating from right to left. The size of the field of view is 110 mm × 110 mm. In column (i) there is a flaw in the form of a flat bottom bore of diameter $D = 2.2$ mm at a depth $e = 0.5$ mm from the observed specimen surface, located approximately at 1/3 of the image height from the top and horizontally centered. In column (ii), the flaw is a flat bottom bore with $D = 2.2$ mm and $e = 1.4$ mm, located approximately at 1/4 of the image height from the bottom and horizontally centered. Row (a): incident quasi-Rayleigh mode of central frequency 1.00 MHz. Row (b): incident A1 mode of central frequency 1.18 MHz. Row (c): incident S2 mode of central frequency 2.00 MHz.

Fig. 6. Sketch of the second evaluation stage, spatial version, applied to the field of Fig. 5(a,i). (a) Instantaneous optical phase-change map, $\Delta \Phi$. (b) Detail of the Fourier transform of (a). (c) Optical phase-change amplitude, $\Delta \Phi_m$. (d) Total optical phase-change phase, $\varphi_m - \omega t$. (e) Filtered instantaneous optical phase-change, $\Delta \Phi^F$. The box in (b) indicates the filtering window.

Fig. 7. Synthetic video movie of the transient scattering of a narrowband 1.00 MHz quasi-Rayleigh wavetrain 7 cycles in length, propagating from right to left, by the flat bottom bore of Fig. 5 (a, i). The movie was obtained by global processing of the set of maps (method (b) of subsection 3.3.3). The following optical phase-change fields are represented: (a) the instantaneous optical phase-change map, $\Delta \Phi$; (b) the optical phase-change amplitude, $\Delta \Phi_m$; (c) the total optical phase-change phase, $\varphi_m - \omega t$, and (d) the
filtered instantaneous optical phase-change, $\Delta \Phi^F$. The interval between the ultrasound generation and the optical probing was increased by 250 ns from each frame to the next. The size of the field of view is 110 mm $\times$ 55 mm.

Fig. 8. Snapshot map of the movie of Fig. 7(d), corresponding to the filtered instantaneous optical phase-change field $\Delta \Phi^F$, of a narrowband 1.00 MHz quasi-Rayleigh wavetrain 7 cycles in length propagating from right to left, scattered by the flat bottom bore of Fig. 5 (a, i). The centre of the scattered wave coincides with the bore. The strong amplitude seen at the scattering centre is mainly due to a vibrational eigenmode with a diametral nodal line originated in the residual wall between the bottom of the bore and the plate surface, as demonstrated in Fig. 10. The size of the field of view is 110 mm $\times$ 55 mm. The zones marked as A and B are analysed in Fig. 10.

Fig. 9. Profile, corresponding to the horizontal central section marked in Fig. 8, of the out-of-plane component of the instantaneous acoustic displacement, $u_3$, calculated as the filtered instantaneous optical phase-change field, $\Delta \Phi^F$, re-scaled to nanometres.

Fig. 10. (i) Snapshot maps of the filtered instantaneous optical phase-change field, $\Delta \Phi^F$, taken from the movie of Fig. 7(d), corresponding to five different instants of the vibration cycle separated by a quarter of a period $T$. (ii) Profiles of the out-of-plane component of the instantaneous acoustic displacement, $u_3$—calculated as the filtered instantaneous optical phase-change field, $\Delta \Phi^F$, re-scaled to nanometres—of the zone A of the same horizontal central section marked in Fig. 8. A clear behaviour of travelling wave is observed. (iii) Same as (ii) but for the zone B. A clear behaviour of vibrational eigenmode with a stationary node at the center is observed. It is the same eigenmode shown in Fig. 8.
Figure 1: Working principle of non-destructive testing by optical probing of ultrasound.

Figure 2: Notation for the incident surface acoustic wave, $u_i(x, t)$, in a plate. A flaw consisting of a flat bottom bore is also depicted.
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