# ACOUSTIC WAVES GENERATED BY A PULSED LASER IN PARTLY TRANSPARENT MEDIA

**H. Meri [a], B. Audoin, and C. Rossignol**
Laboratoire de Mécanique Physique UMR CNRS 5469, Université Bordeaux 1, FRANCE
[a] h.meri@lmp.u-bordeaux1.fr

## Abstract

Acoustic waves generated and detected by laser in partly transparent media are studied. A model is proposed to calculate the acoustic displacements generated by photothermal process in anisotropic microstructures. Heat and acoustic wave equations are solved using spatial-temporal Fourier transformations. The thermoelastic generation is assumed to be governed by the optical absorption phenomena.

Numerical simulations are compared to experimental results obtained on partly transparent samples. A Nd:Yag laser with 20 ns pulse duration has been used for the generation. The detection is performed with a CW laser interferometer.

Waveforms are calculated and measured at epicentral and at off-epicentral configurations. Signals resulting from longitudinal and shear bulk waves generated in the material, as well as head waves resulting from mode conversion at the interfaces, are examined.

## Introduction

Comparatively to the ultrasonic techniques using piezoelectric transducers, the laser thermoelastic generation offers the advantages of non-surface damage, noncontact nature, controllability of the source features, etc.

Assuming optical laser pulses of low power and materials in which optical penetration is not negligible, the source is due to the thermal expansion [1]. This buried phenomenon results from optical penetration and thermal diffusion. Much of the previous work has been centred on the properties of the longitudinal precursor produced by the effect of subsurface sources in the thermoelastic regime. For highly thermally conducting and highly optically opaque materials (metals), the subsurface source arises mainly from thermal diffusion [2-6]. Furthermore, for nonmetallic materials the optical penetration is responsible for the substantial precursor waveforms [6]. The features of the precursor (amplitude and temporal width) have been explored [4,5,7,8].

For the partly transparent materials, the source burying by optical penetration is the dominant process for the acoustic generation. Glass materials have a thermal diffusion length of only few nm for a laser pulse time of few ns. Moreover, these materials have the optical penetration depth of hundreds or even thousands of μm. Then source burying by diffusion becomes negligible compared to source burying by optical penetration. The optical absorption depending on the laser wavelength can be considered as an instantaneous process.

Several authors [7-9] have modelled the effects of optical penetration on the acoustic generation in transparent materials. They developed the analytical one-dimensional (1-D) model because of the complexity of the ultrasonic signals in 2-D or 3-D configurations. The 1-D model provides the longitudinal mode, but neglects the transverse mode emerging from reflections and conversions visible for off-epicentral detection.

In this paper, we study the effects of the optical penetration on the epicentral and on the off-epicentral displacement waveforms. A two-dimension (2-D) model, providing transverse modes, for a line source is put forward. This model takes into account the subsurface sources arising from optical penetration, as well as the width and the temporal shape of the source. A 2-D Fourier transform is used to calculate the acoustic displacement fields. Then the theoretical waveforms are numerically produced by inversion of the transformed solution.

A theoretical analysis of the waveforms on transparent isotropic materials is proposed to interpret the displacement signals. Experiments in glass with different optical absorption are used to validate the proposed model.

## Physical model

We consider an infinite orthotropic plate of finite thickness *h*. The normal to the plate surfaces is one of its principal axes, $\underline{X}_1$. The line source, located at $x_1=0$, is parallel to another principal axis, say $\underline{X}_2$ (Figure 1). In this configuration, the problem is invariant along the $\underline{X}_3$ direction.

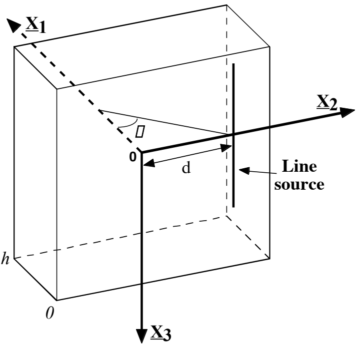

Figure 1: Geometry of the problem

To describe the thermoelastic laser generation of ultrasound, one needs to solve the heat equation and the acoustic wave equation. In absence of thermal diffusion the equation of heat conduction is:

$$\rho C_p \frac{\partial \mathrm{T}}{\partial t} = \beta(1-R)I_0 g(x_2) f(t) e^{-\beta x_1} \ , \qquad (1)$$

where $\mathrm{T}(x_1,x_2,t)$ is the temperature rise field, $\rho$ is the density, $R$ stands for the reflection coefficient and $C_p$ denotes the specific heat; $I_0$ is the incident energy per line unit emitted by the laser; $\beta$ is the optical penetration coefficient (the inverse of the optical penetration length). The spatial distribution of the laser line-source is given by $g(x_2)$ , whereas $f(t)$ gives its temporal distribution.

Using Auld's notations [10] and considering the thermal expansion due to the temperature rise field, the acoustic wave equation is written as:

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla\cdot\left(\left[C\right]:\nabla_x \mathbf{u}\right) - \left[\lambda\right]\nabla \mathrm{T} \ , \qquad (2)$$

where vector $\mathbf{u}(x_1,x_2,t)$ is the mechanical displacement field and $\left[\lambda\right]$ is the thermoelastic coupling tensor, defined as a product of the elastic tensor $\left[C\right]$and the thermal expansion tensor $\left[\alpha\right]$. The governing equations are supplemented by initial and boundary conditions. The sample is initially at rest, and the stresses are zero on the free surfaces ($x_1=0$ and $x_1=h$).

Governing equations, (1) and (2), with the aforementioned boundary conditions are solved using double-Fourier transform techniques in time $t$ and space $x_2$ [11]. Applying these transforms yields to the set of linear partial derivative equations with respect to the depth $x_1$ only. The solution is composed of a sum of exponential functions of $x_1$. Double inversion of Fourier transforms results in formal expressions for the displacement as a function of position and time in the form of infinite integrals:

$$\mathbf{u}\left(x_1,x_2,t\right) = \frac{1}{(2\pi)^2}\int_{-\infty}^{+\infty}\left[\int_{-\infty}^{+\infty}\mathbf{U}(x_1,\mathbf{k},\omega)e^{-j(k_2 x_2)}dk_2\right]e^{j(\omega t)}d\omega \ , \qquad (3)$$

where $\mathbf{k}$ denotes the wave vector.

A numerical integration method allows us to calculate the normal component of the displacement.

## Experimental procedure

A Nd:Yag laser is used for ultrasonic generation. The pulse duration is 20 ns and infrared light emission is obtained at 1064 nm with a low energy to ensure the themoelastic regime. The collimated optical beam is focused by a cylindrical lens. The normal displacement is measured on the side opposite to the excitation by means of an optical heterodyne probe. Experiments have been performed on isotropic materials that have different optical absorptions. Three partly transparent glasses, Schott NG-1, NG-5 colured glass, and an ordinary glass samples were used. NG1, NG2 and ordinary glass have an optical penetration depth of about 19%, 38% and 345% of their thickness, respectively. Various parameters of these materials are given in Table 1.

Table 1: Materials parameters.

| | Samples | | |
|---|---|---|---|
| **Symbol (units)** | **Schott NG1** | **Schott NG5** | **Ordinary glass** |
| $h$ (mm) | 1,3 | 2,94 | 5,8 |
| $\beta$ (mm$^{-1}$) | **4** | **0,9** | **0,05** |
| $\rho$ (g.cm$^{-3}$) | 2,43 | | 2,52 |
| $C_{11}$ (GPa) | 65 | 72 | 84 |
| $C_{44}$ (GPa) | 23 | 25 | 28 |
| $R$ | 0,06 | | 0,08 |
| $C_p$ (J.Kg$^{-1}$.K$^{-1}$) | 700 | | 700 |
| $\alpha$ (K$^{-1}$) | 6,5x10$^{-6}$ | | 10x10$^{-6}$ |

The efficiency of detection for the ordinary glass sample is improved by coating the rear surface by a mirror film. This perturbation of the boundary conditions of the glass sample may slightly affect the amplitude of the reflected waves.

## Analysis of the waveforms in transparent materials

The path of ultrasound between the source and the receiver is explained in Figure 2.

The calculation of the wave arrival times is based on ray theory and the law of refraction (Snell's law) for multiple reflection or conversion (the angles of refraction are denoted by $\theta_i$ and $\theta_j$ for the longitudinal and transverse waves, respectively), and on Huyghens's construction for head wave generation.

Figure 2-a assumes the line source without optical absorption on the material. It is clear that propagation of waves components include direct longitudinal and transverse waves (denoted L and T) and the subsequent multiple reflections of waves, going back and forth between the two surfaces of the plate (iLjT, where i,j=0,1,2,.. and i+j is an odd number) [12].

The instantaneous buried source has to be taken into account if we recall that the plate is partly transparent (Figure 2-b). Rayleigh surface waves, lateral wave (Lras) propagating at longitudinal wave velocity along the surface, and the multiple reflection and conversion arrival waves (iLjT, where i,j=0,1,2,.. and i+j is an even number) can be measured.

Receiver probe location $d$ is an important factor for the interpretation of received ultra-sonic signals. For some $d$, the so-called "head wave" HW, existing beyond the critical angle $\theta_c$ on the transverse mode (Figure 2-c) is visible.

Figure 3 shows an example of the calculated arrival times for all waves assumed to propagate in the glass sample.

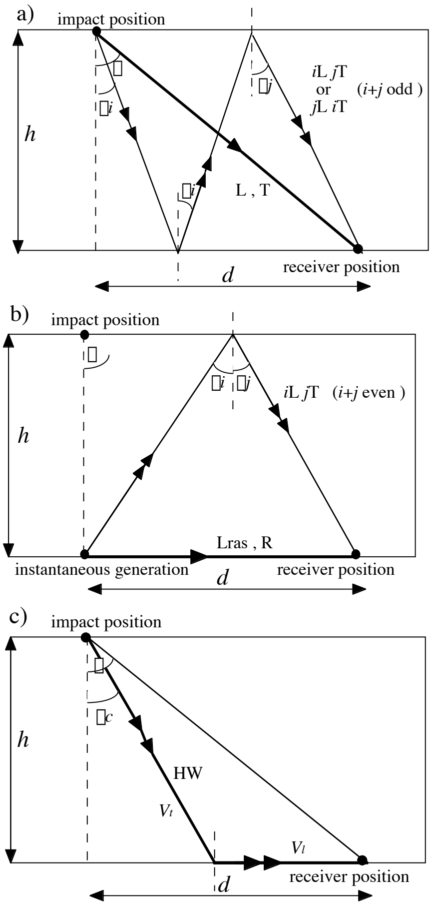

Figure 2: Outline of some of possible wave components resulting from interaction of ultrasound with surfaces in a transparent isotropic medium.

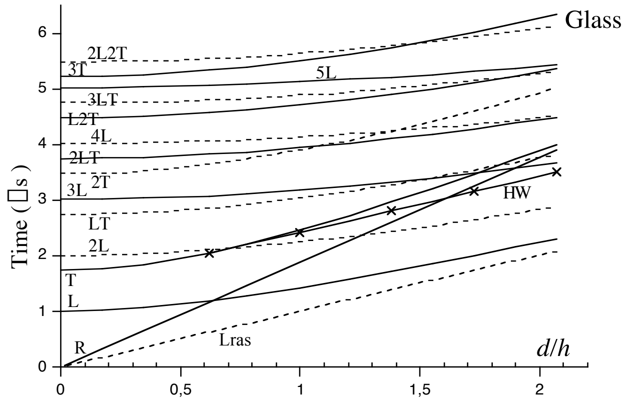

Figure 3: Bulk and head wave in glass: theoretical wavefronts generated on the first surface (solid line) and issued from simultaneous generation on the rear surface (dashed line).

## Results

In this section we present a comparison between the experimental waveforms and the calculations. The dimensionless time $t / t_l$ is used as a variable, where $t_l$ is the arrival time of the longitudinal wave for the epicentral position. Calculated displacement in Figures 4 and 5 is scaled vertically to take into account the source magnitude.

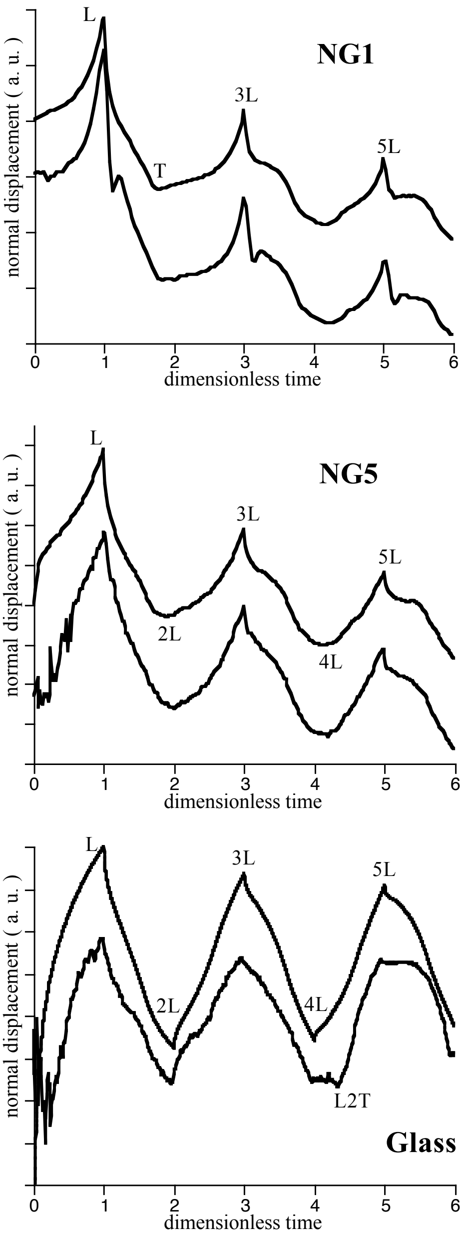

Figure 4: Calculated (above) and experimental (below) normal displacement at the epicentre on the opposite side of the excitation for three samples.

*Epicentral waveforms*

Figure 4 shows the experimental and calculated waveforms for normal displacements on the epicentral axis. A good agreement in every essential feature is observed.

The shape of the first echo (precursor) changes with the ratio between the optical penetration length and the thickness. Echoes caused by instantaneous generation of longitudinal wave modes on the rear side (the peaks denoted by "iL" where i is an even number) appear with the increase of the optical penetration; in addition, the echoes related to the arrival of shear wave modes "jT" tend to vanish.

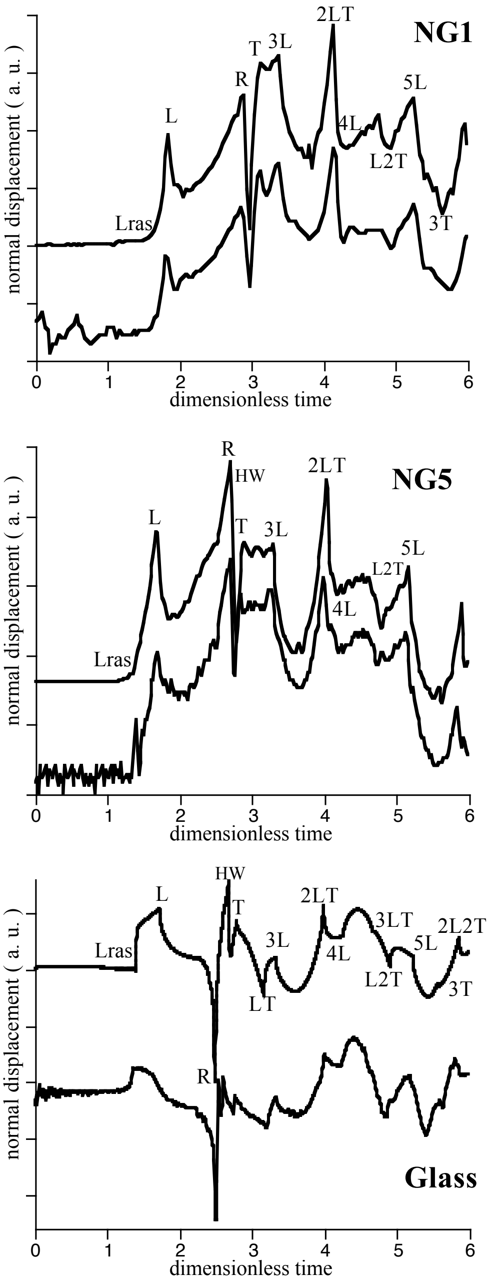

Figure 5: Calculated (above) and experimental (below) normal displacement at off-epicentre on the opposite side of the excitation (rear side) for three samples.

*Off-epicentral waveforms*

A very good agreement between measurements and calculations is found for the off-epicentral configurations as well (Figure 5).

The arrival of lateral waves (Lras) is visible for all three samples. The temporal profile of the arrival of the longitudinal wave (L) is a clear image of the precursor for the epicentral detection (especially the first part of the curve).

Transverse modes and their reflection are detectable, particularly those originating from conversion.

For the glass sample, the echo amplitudes show slight differences between the model and the experiment, due to the perturbation of the boundary conditions by coating the detection side.

## Conclusion

A 2-D model of the thermoelastic generation of ultrasound in an orthotropic plate taking into account the optical penetration has been proposed. An analysis of the waveforms generated by the instantaneous generations is developed to interpret the signal shapes. Good agreement is observed between the experimental data and the numerical calculation. It has been found that in the off-epicentral configurations, for the transparent materials, a lateral wave is observed. In addition, transverse acoustic modes are detectable.

## References

[1] L.M. Lyamshev and B.I. Chelnokov, "Sound generation in a solid by penetrating radiation", Sov. Phys. Acoust. **29**, 220-225 (1983).

[2] C.B. Scurby, R.J. Dewhurst, D. A. Hutchins, and S.B. Palmer, “Quantitative studies of thermally generated elastic waves in laser-irradiated metals”, J. Appl. Phys., vol. 51, pp. 6210-6216,1980.

[3] L.R.F. Rose, “Point-source representation for laser-generated ultrasound”, J. Acoust. Soc. Am.,vol. 75, 723-732,1984.

[4] P. A. Doyle, “On epicentral waveforms for laser-generated ultrasound”, J. Phys. D:Appl.Phys., vol. 19, 1613-1623, 1986.

[5] M. Dubois, F. Enguehard and L. Bertrand, “Analytical one-dimensional model to study the ultrasonic precursor generated by a laser”, Phys. Rev. E, vol. 50, pp. 1548-1551, 1994.

[6] R.J. Conant and K. L. Telschow, “Longitudinal wave precursor signal from an optically penetrating thermoelastic laser source”, In Review of Progress in Quantitative Nondestructive Evaluation, edited by D.O. Thompson and D.E. Chimenti, Plenum, New York, pp. 497-504, 1989.

[7] K. L. Telschow and R.J. Conant, “Optical and thermal parameter effects on laser-generated ultrasound”, J. Acoust. Soc. Am., vol. 88, pp.1494-1502, 1990.

[8] F. Enguehard and L. Bertrand, “Effects of optical penetration and laser pulse duration on laser generated longitudinal acoustic waves”, J. Appl. Phys., vol. 82, pp. 1532-1538, 1997.

[9] F. Enguehard and L. Bertrand, “temporal deconvolution of laser-generated longitudinal acoustic waves for optical characterization and precise longitudinal acoustic velocity evaluation”, J. Acoust. Soc. Am., vol. 103, pp. 771-784, 1998.

[10] B.A.Auld, “Fields and waves in solids”, Krierger, Malabar, Florida, 1990.

[11] S.Guilbaud and B.Audoin, "Measurement of the stiffness coefficients of a viscoelastic composite material with laser-generated and detected ultrasound", J. Acoust. Soc. Am., vol. 105, pp. 2226-2235, 1999.

[12] B. Castagnède, M. Deschamps, E. Mottay and A. Mourad, “Laser impact generation of ultrasound in composite materials”, Acta Acustica, vol. 2, pp. 83-93, 1994.