Sound speed resolved by photoacoustic technique

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In this work a new method for measuring the speed of sound in materials is reported. This method uses the photoacoustic effect, which is the generation of sound waves by pulsed optical radiation incident on a material sample. The sound waves generated on the surface of the sample travel through the material and are detected with two piezoelectric sensors separated by a known distance. An appropriate processing of the photoacoustic signal permits the separation of the information of the generated longitudinal waves, of their reflections, as well as of other types of waves generated (shear, surface, etc). The advantages and disadvantages, of this method are discussed in comparison with standard methods.

Keywords: Photoacoustic effect; sound speed; piezoelectric sensor.

En el presente trabajo se reporta una técnica novedosa para medir la velocidad del sonido en materiales. Este método de medición utiliza el efecto fotoacústico, que consiste en irradiar una muestra de material con pulsos cortos de radiación láser, registrando la onda acústica generada con dos sensores piezoeléctricos separados por una distancia conocida. Un procesamiento adecuado de la señal fotoacústica permite separar la información de las ondas longitudinales generadas, de sus reflexiones, así como de los frentes de onda de otro tipo de ondas generadas (cortantes, de superficie, etc.). Se discuten sus ventajas y desventajas frente a los métodos usuales.

Descriptores: Efecto fotoacústico; velocidad de sonido; sensor piezoeléctrico.

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1. Introduction

The cardinal importance of the elastic constant to physics, material science and engineering has led to the development of many measurement methods in recent years. These methods may be broadly divided into static, resonance, wave propagation and scattering approaches. Scattering based techniques using high frequency isothermal ultrasound are reasonably accurate. Pulse wave propagation methods time the flight of bursts of sound, while resonance methods measure the frequency of normal modes of vibration; both methods produce high precision exceeding one part in 10^4 [1,2].

The commonly applied ultrasonic pulse echo method uses a short pulse of ultrasound generated by a transducer, often in direct contact with the specimen. The pulse propagates through the material of interest, reflects from the opposite end, and returns to generate a signal in the same transducer, namely, the echo. A measurement of the round trip travel time and travel distance yields the sound speed, from which an elastic constant is determined.

Moreover, Micro-Electro-Mechanical Systems (MEMS) development is necessary to measure some elastic characteristics of materials such as: Young's moduli and Poisson's ratio. Several techniques have been used to determine Young's moduli [3,4]. We work with a photoacoustic technique that permits excitation without contact. Therefore, we wanted to explore the possibility of measuring the speed of sound with this same technique. Preliminary results obtained from measurements of the speed of sound using photoacoustic techniques on several samples of metals are presented.

2. Basic theory

The ultrasonic pulse-echo method uses a short pulse of ultrasound generated by a transducer, often in direct contact with the specimen. The pulse propagates through the specimen of interest, reflects from the opposite end, and returns to generate a signal in the same transducer, namely, the echo. A measurement of the round-trip travel time and travel distance yields the sound speed. In this method, it is necessary to understand the bond between the transducer and the specimen and correct unavoidable shifts in the phase of the echo associated with this bond [5]. Recently, the development of fast analog-digital acquisition cards has made it possible to use methods based on digital signal processing in contrast to classical pulse overlapping or phase comparison methods [6,7].

The basic problem is to determine the time delay between two signals, each of which consists of only a few oscillations. In many instances it is possible to define some features (the principal oscillation, for example) that can be used as a basis for the measurement of the time delay. Because of pulse attenuation and dispersion, ultrasonic velocity measurement is difficult and uncertain when using classical methods. Instead, it is possible to use methods based on digital signal processing such as the Cross-correlation Function and the Hilbert Transform [6]. The vast majority of these systems use piezoelectric sources and detectors. These are well characterized but are restricted in both spatial and temporal bandwidth. In addition, they require either highly repeatable or permanent attachment to the structure being tested for reliable results. Laser generated acoustic waves, in contrast have an extremely high bandwidth, both spatially and temporally, and the technique is effectively non-contact, two features which facilitate straightforward and repeatable testing of material structures.

2.1. The photoacoustic method

The term "photoacoustic" (PA) usually refers to the generation of acoustic waves by modulated optical radiation or any type of modulated radiation. PA generation can be classified according to two excitation modes: continuous-wave (cw) modulation mode, in which the excitation beam is modulated near 50% duty cycle; and the pulsed mode, in which the excitation beam is of very low duty cycle but high peak power. In the pulsed technique, the signal is acquired and analyzed in the time domain, making it possible to use of simple gating techniques for noise suppression [8].

Depending on the incident power, two predominant source mechanisms are available for laser-generation of acoustic waves. One is the thermoelastic regime, where the incident power density is below $\approx 10^7\ W\big/\mathrm{cm}^2$. In this case, the laser radiation is absorbed within a small volume element, which undergoes a rapid rise in temperature and consequent expansion. If the incident power exceeds $\approx 10^7\ W\big/\mathrm{cm}^2$, the source moves into the ablation regime where surface particles undergo vaporization, causing the formation of plasma.

In the pulsed PA technique, the excitation pulse is typically short and the acoustic propagation distance during the excitation pulse is typically much smaller than the dimensions of the sample; hence, in most cases, the PA pulse shape is independent of boundary reflections, and the sample can often be treated as infinite in extent.

The amplitude p of a photoacoustic signal generated by a laser pulse inside solid samples is proportional to the laser energy in the thermoelastic regime [9] and can be described by

$$p \propto \frac{\beta V}{C_p} E_o \mu_a, \tag{1}$$

where *Cp* is the heat capacity, β is the thermal expansion coefficient, V is the speed of sound, E_0 is the laser pulse energy, and μ_a is the absorption coefficient of the sample.

On the other hand, it has been demonstrated that the PA pulse length τ_a is related to the laser pulse duration τ_L and the "acoustic transit time" τ_t, defined as the acoustic propagation time across the PA source of length l in the direction of observation:

$$\tau_a \approx \left(\tau_L^2 + \tau_t^2\right)^{1/2} \tag{2}$$

There is interest in the use of PA short-pulse generation for material testing applications. Such narrow acoustic pulses with highly reproducible shapes are ideally suited for measuring thin film properties such as thickness, sound velocity, attenuation, etc.

In the experiment reported here, we determine the speed of sound from the time interval between signals of two sensors, separated by a distance d, by the analysis of the following cross correlation function:

$$R_{f_1 f_2}(t) = \lim_{T\to\infty} \frac{1}{T} \int_0^T f_1(\tau) f_2(\tau + t) d\tau \tag{3}$$

$$f_1(t) = s_1(t) + n_1(t)$$

$$f_2(t) = s_2(t) + n_2(t),$$

where s_1(t) y s_2(t) are detected signals and n_1(t) and n_2(t) are noises. The correlation analysis yields a measure of the similarity between the original waveform, and the waveform after the time is shifted; and it is easily understood that the correlation function reaches a maximum when the time shift t agrees with the propagation time, since signals from the sensor are identical but shifted by the propagation time T_p. From Eq. (3), we have:

$$R_{f_1 f_2}(\tau) = R_{s_1 s_2}(\tau) + R_{n_1 s_2}(\tau) + R_{s_1 n_2}(\tau) + R_{n_1 n_2}(\tau) \tag{4}$$

To determine T_p without bias, starting from the correlation function, it is necessary to point out that there be no correlation between the noise terms must exits nor between the noise and the signals. That is, $R_{n_1 s_2}(\tau) = R_{s_1 n_2}(\tau) = R_{n_1 n_2}(\tau) = 0$. A careful experimental arrangement and an appropriate sensor selection guarantee that the previous statement can be completely satisfied.

The correlation function is concentrated around the maximum value ($\tau = T_p$) and diminishes when increasing ($|\tau| > T_p$). The two minima on each side of the maximum, at times τ_1 andτ_2, define the bandwidth (B) of the signals. That is:

$$(\tau_2 - \tau_1) \propto \frac{1}{B} \quad \text{or} \quad \Delta\tau \propto \frac{1}{B}. \tag{5}$$

It is clear that the determination of the speed of sound using this method depends heavily on the estimation of T_p. In digital signal processing, this estimation depends on the time of the sampling rate used in the acquisition. To improve the resolution, there are two alternatives: the former, the use of a polynomial to determine the maximum point of the correlation function, and the second is the application of the Hilbert transform to the correlation function to determine the maximum value when the Hilbert transform becomes a zero crossing point. The advantage of using the Hilbert transform is that this function has zero crossing, independently of the $\Delta\tau$ variations and, consequently the bandwidth [10].

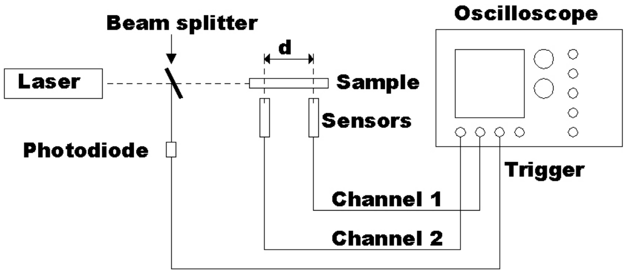

FIGURE 1. Experimental setup employed for the photoacoustic measurement. L= Lens, BS= beam splitter, PZT = piezoelectric sensor, S = sample, d = sensor separation.

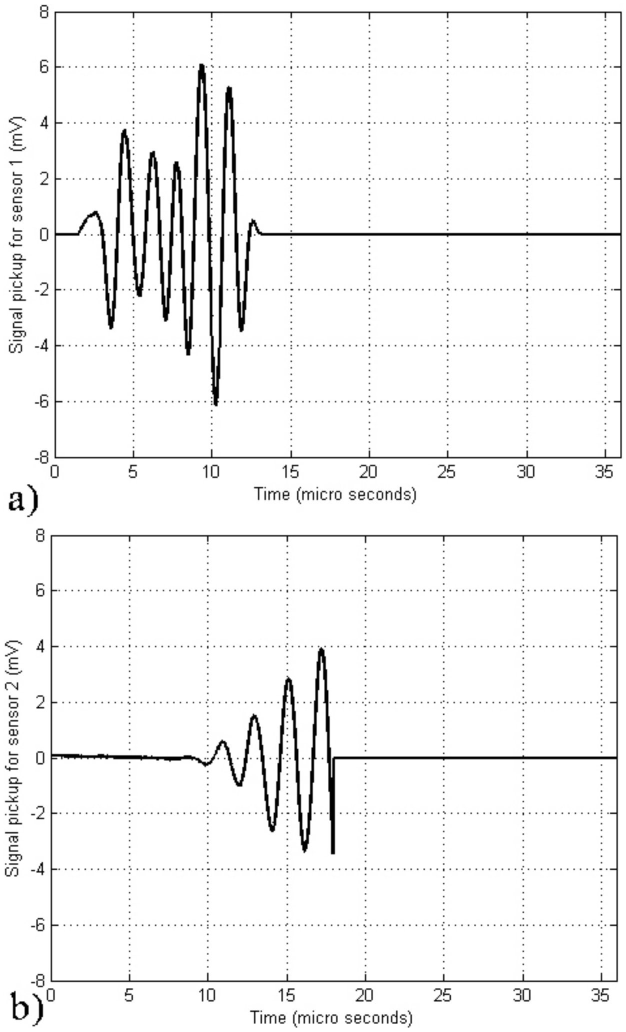

FIGURE 2. a) Example of signal from sensor 1; b) Example of signal from sensor 2.

3. Experimental setup

Figure 1 shows the experimental setup for the determination of the speed of sound by the photoacoustic technique. An Nd :YAG laser (Continuum Electro-Optics Inc. Mod. MINILITE II, λ=532 nm), Oscilloscope (Tektronix Inc. mod.TDS5054B), and two ceramic sensors PZT, with the same design as reported in Ref. 11, were used. Signals from the sensors were acquired using a 6×10^6 Hz sampling rate. A hundred records for each channel were averaged simultaneously. The averages were stored in wfm format files, and the whole digital signal processing was carried out under the MATLAB platform.

The sample was shaped into 3.1 mm thick pieces with dimensions 25.1 mm $\times$ 6.7 mm; a lens to focus the beam in the sample to increase the energy density on the sample was used. The laser light was focused on the surface of a sample covering a diameter of about 2 mm. No damage was observed on the sample surface because the experiments were performed in the thermoelastic regime.

Synchronization between acoustic signal acquisition and each pulse of the Laser is required. Therefore, a fast photodetector for monitoring each laser pulse completed the system (Thorlabs Inc. model 201/579-7227, $<$1 ns rise time). The photodetector output triggered an oscilloscope and was the initial reference in time for the detection of the photoacoustic signals.

4. Analysis

After signal acquisition, averages of 100 signals for each channel were obtained. Figure 2 shows the typical waveforms of two sensors, $s_1(t)$ and $s_2(t)$. The pulse arrived at the second transducer after a time T_p= d/V, where V is the sound speed and d is the separation between transducers, the time T_p is obtained through the maximum of the cross correlation function of $s_1(t)$ and $s_2(t)$. An example of an autocorrelation function is shown in Fig. 3. Note that the correlation peak occurs at T_p = 2.668 microseconds, which corresponds to the 5134.9 m/sec sound velocity for Aluminum.

However, many ripples appear around the peak. Applying the Hilbert Transform, these ripples, which are not involved in the time measurement, can be removed. This situation can be observed in Fig. 4. Observe that the maximum of the

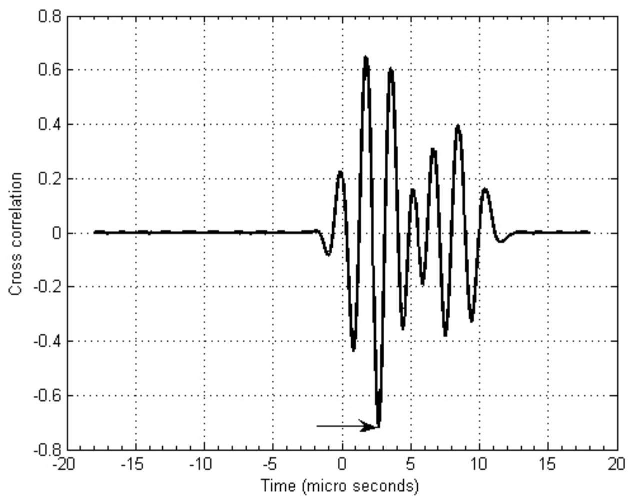

FIGURE 3. Cross correlation function for Aluminium, with d = 0.0137 the separation between sensors, the maximum value is indicated by the arrow.

TABLE I. Values of travel time, sound speed and error for 3 metals.

Material	T_p [μs]	Speed [m/s]	% error
Aluminium	2.668	51344.9325	0.0029
Cooper	3.71	3692.7223	0.0036
Steel	2.73	5018.3150	0.007

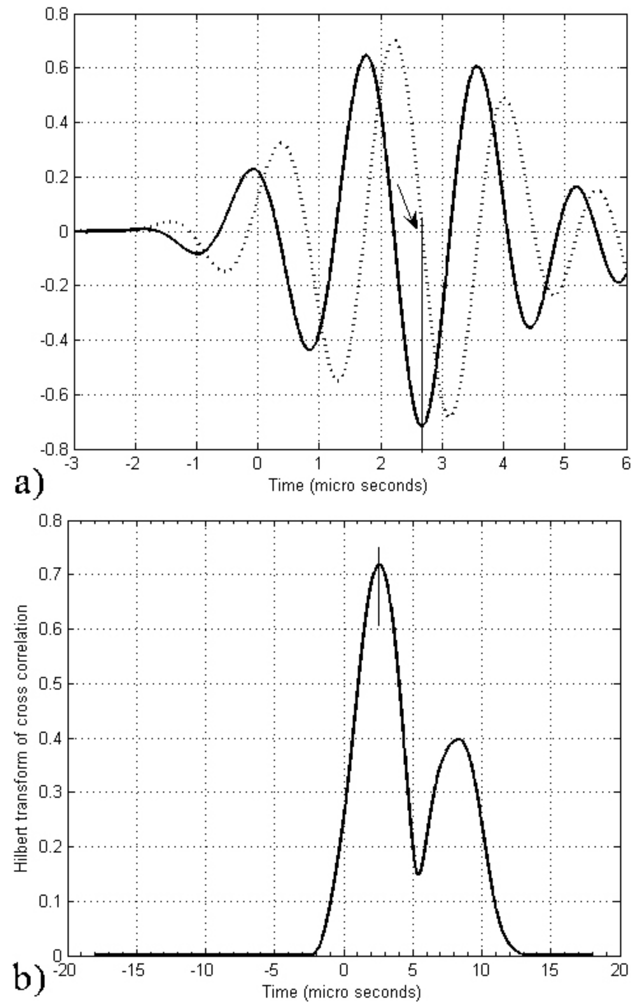

FIGURE 4. a) Comparison between cross correlation (solid line) and the Hilbert transform (dotted line).The maximum value of cross correlation function is indicated by the arrow; at this point the Hilbert transform has zero crossing; b) The magnitude of the Hilbert transform (envelope) of cross-correlation function and its maximum value.

correlation function corresponds to the zero crossing point of the Hilbert transform, Fig 4a. In addition, the magnitude of the Hilbert transform (envelope), simplifies the localization of the maximum value more than the cross correlation function (see Fig. 4b). Also, Fig. 2 shows that even though attenuation exists, the cross-correlation function between the initial wave $s_1(t)$ and the attenuated issue $s_2(t)$ has a maximum value at the correct propagation time. This result is similar to that reported by Adamosky *et al.* [12].

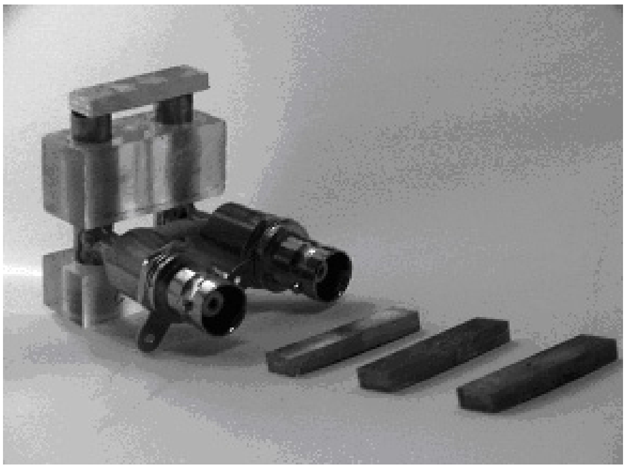

FIGURE 5. Sensor assembly and material samples. The sample is placed in the top part of the sensor assembly and signal area read through the connection on the right-hand side.

From Fig. 4b, we see that the same time difference can be obtained from the peak of the envelope, the magnitude of the Hilbert transform. Then we ask which is the better method for the propagation time measurement: the magnitude of the Hilbert transform or the cross correlation function? We find that if

1) there is no dispersion but there is a constant phase shift,
2) there is no dispersion but there is a frequency-dependent attenuation ratio, and
3) There is dispersion, then it is preferable to use the envelope or magnitude of the Hilbert transform.

A similar conclusion was obtained by Sugasawa [13] for the case of the analytic signal concept.

5. Results and discussion

The materials were prepared in bar shapes, as in Fig. 5, to couple to the two sensors. The assembly of the sensors ensures that the distance between the sensors is always the same, d = 0.0137 m.

Table I summarizes the results for three materials. This table includes relative errors; the values for the reference sound speed are taken from Ref. 14.

In our measurement setup, it is possible to pick up both longitudinal waves and shear waves and their reflections. This means that the photoacoustic signal will have several pulses that bias the correlation function, and that the error measurement will increase. It is necessary to change the placement of the sensors in the sample to overcome this limitation. In addition, to explore the interaction with other types of waves (surface waves, Lamb, Love, etc) piezoelectric detectors that are fast and ringing–free are required. These changes and improvements are the objective of our work in course.

6. Conclusions

In this paper we have presented the photoacoustic method, as a versatile tool to determine the speed of sound in different materials, using, to generate the photoacoustic signal, a pulsed low-energy laser. The technique proposed does not demand that transducers have short rise times.

Moreover, we employed the Hilbert transform to measure the time difference between pulses. The results obtained with this method improve the results obtained with the common cross-correlation function. This leads us to the conclusion that, using our method, we can estimate the correct time difference between pulses, and as a result, we can measure the speed of sound correctly under various conditions. The major limitation of the method is the inability to extract different types of waves, longitudinal, shear and surface acoustic generated by the laser pulse; current work is aimed at overcoming this problem.

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