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TEMPERATURE EFFECT ON THE PROPAGATION OF CRITICALLY REFRACTED LONGITUDINAL WAVES (L_{CR}) FOR STRESS MEASUREMENT

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Abstract*: Pipelines are widely used for transporting natural gas, oil and derivatives by several companies in Brazil and around the world. Due to their economic importance, it is interesting to develop methods capable of providing information about their integrity, allowing to decide whether a sector of the pipelines should or should not be replaced. The evaluation of stresses in the walls of oil pipelines is very important to provide valuable information to determine the integrity of the structure and enable a better and safely use of the product. This work uses the technique of ultrasound as a tool for stress analysis due to its non-destructive aspect, relatively low cost and portability of instrumentation equipment. The process of measuring mechanical stresses with ultrasound uses acoustoelastic theory, which relates the speed of wave propagation with the stresses in the object under analysis. The technique is based on the application of a sonic beam in the material and in the analysis of the reflected and detected beam to get data about the mechanical stresses in the material. This study evaluated the influence of temperature on the propagation velocity of ultrasonic waves in the API 5L X70 steel used to manufacture petroleum pipelines and in the acrylic shoes used as a base for the transducers. For measurements we used a transmitter and a receiver transducers, an ultrasonic pulser/receiver device and an application developed in the LabViewTM environment in a portable system. The results confirmed previous works in this subject and showed that there is a significant influence of temperature on the speed propagation of ultrasonic waves and that this influence can be quantified.*

Keywords: *Ultrasound, L_{CR} Waves, Stress Measurement, Acoustoelasticity*

1. INTRODUCTION

The use of pipelines by the oil industry for of natural gas, oil and derivatives transportation has increased substantially in recent decades. To support the growth of the pipeline network, it is necessary the development and implementation of various engineering projects that often require large amounts of resources. Pipelines of large dimensions and with a high degree of complexity require appropriate maintenance schemes with optimized techniques of inspection. The failure, in many cases, can lead to environmental disasters, with immeasurable economic and social consequences (Andrino, 2007).

The experimental evaluation of the stresses in the walls of pipelines is an effective way of predicting if the product is working in adequate operating conditions (Kudryavtsev et al, 2004). There are several methods for measuring stress, such as X-ray diffraction, neutron diffraction and propagation of ultrasonic waves. In X-ray and neutron diffraction, the required equipment is frequently too large and unsuitable for use in the field. A valuable alternative, in this case, is to use ultrasound and the concepts of acoustoelasticity.

There is a relationship between the velocity of ultrasonic waves and stresses in the region of the material crossed by such waves. Many researchers conducted experiments in order to improve this technique and to obtain new insights about its use (Andrino, 2003; Andrino, 2007; Caetano, 2003; Santos, 2005 e Santos, 2007). It was observed that the velocity of ultrasonic waves depends not only on the material studied, but also on the temperature at which the test is performed, the pressure exerted by the support of the transducers on the piece, and the microstructure and texture of the material (Santos, 2007).

The objective of this study is to determine the influence of temperature on the speed of longitudinal waves in steel API 5L X70, very commonly used in the manufacture of petroleum pipelines. The quantification of this and other factors of influence is essential to evaluate the stresses using the measurement method of the longitudinal waves. This work follows the study performed by Fraga, Andrino e Santos (2008) using the same kind of material.

2. ULTRASONIC WAVES

Ultrasound wave is a type of wave that requires a material medium to propagate and has frequencies above 20 kHz. For general application in testing of materials, the method uses, preferably, frequency band between 0.5 MHz and 15 MHz, as Fig. (1).

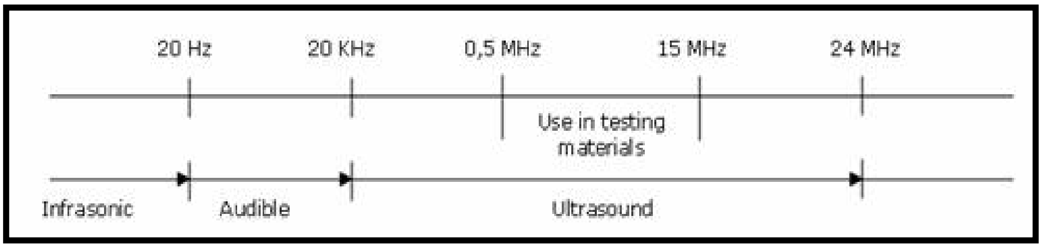
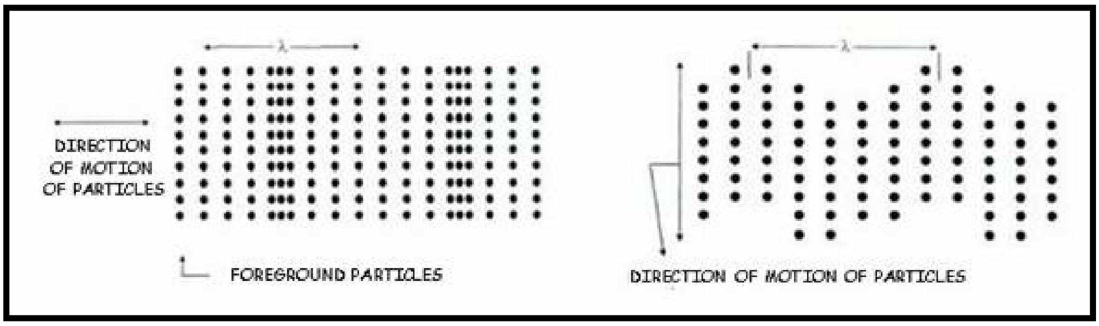


Figure 1. Spectra of sound frequencies (Minicucci, 2003).

The ultrasonic waves used to measure stresses are mainly classified as longitudinal or transverse, although Rayleigh waves are also used. The longitudinal waves are those whose vibrations occur in the same direction of propagation and for transverse waves, also known as shear waves, the vibrations are perpendicular to the direction of propagation, as shown in Fig. (2).



(a) Longitudinal Waves **(b) Transverse Waves**

Figure 2. Planes for the propagation of longitudinal and transverse waves (Rodrigues and Mineiro, 2000).

2.1. Critically Refracted Longitudinal Waves (L_{CR})

The critically refracted longitudinal wave is a type of wave very suited for strain measurement by ultrasound. It spreads just below the surface, minimizing the effects of surface irregularities, such as corrosion. Its speed is more sensitive to changes in stress (Santos and Bray, 2000b). In addition, it has a low damping compared to longitudinal waves such as *Creeping waves* according to Junghans and Bray (1991). To obtain this type of wave propagating in steel, we used a transducer that generates longitudinal waves on an acrylic base, so that the angle of incidence of the longitudinal wave is about 28 degrees to the normal direction to the surface of the object tested. Figure 3 illustrates this situation.

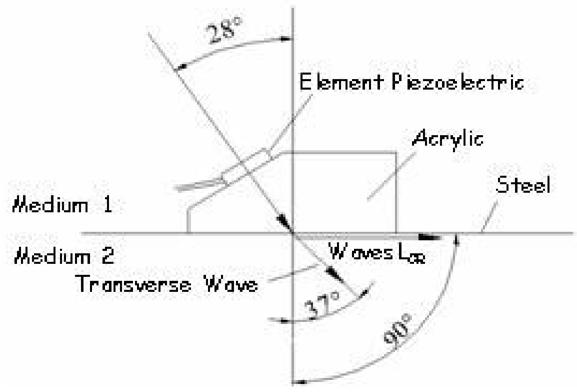
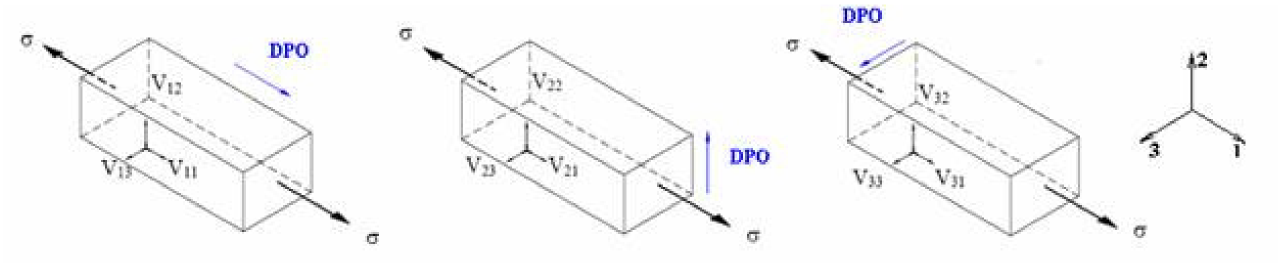


Figure 3. Generation of a critically refracted longitudinal wave (Andrino, 2003).

2.1.1. Application of the L_{CR} Waves to Measure Stress

According to Bray and Stanley (1997), ultrasonic techniques for measuring stress in materials are based on the behavior of the speed of the sound wave and are related to the state of stress acting on a particular mechanical component. Considering, for example, a specimen of a given material in form of bar under action of tensile stresses in the longitudinal direction, it is possible to generate waves that propagate in three perpendicular dimensions related to the specimen, as can be seen in Fig. (4).



(a) Direction 1 **(b) Direction 2** **(c) Direction 3**

Figure 4. Coordinate system of a stress field (Bray and Stanley, 1997).

For the speeds V_{ii}, the first index refers to the direction of wave propagation (DPO); the second index refers to the direction of motion of particles. In Fig. 4a, the V_{11} waves propagate in the direction 1. V_{11} is the speed of the particles in the same direction of wave propagation (longitudinal waves). Velocities V_{12} and V_{13} represents the wave velocity in directions perpendicular to the particle motion (transverse waves). In Fig. 4b and 4c waves propagate in orthogonal directions in relation to the stresses. V_{22} is the velocity of longitudinal wave that propagates in the direction 2. V_{33} is the velocity of longitudinal wave that propagates in the direction 3. σ is the applied stress. All other speeds refer to the transverse waves.

The speed of ultrasonic waves that propagate in the same direction as the applied stress is related to the state of triaxial deformation according to Eq. (1), (2) and (3) (Bray and Stanley, 1997).

$$\rho_0 V_{11}^{\ 2} = \lambda + 2\mu + (2l + \lambda)(\varepsilon_1 + \varepsilon_2 + \varepsilon_3) + (4m + 4\lambda + 10\mu)\varepsilon_1 \tag{1}$$

$$\rho_0 V_{12}^{\ 2} = \mu + (\lambda + m)(\varepsilon_1 + \varepsilon_2 + \varepsilon_3) + 4\mu\varepsilon_1 + 2\mu\varepsilon_2 - \frac{1}{2} n\varepsilon_3 \tag{2}$$

$$\rho_0 V_{13}^{\ 2} = \mu + (\lambda + m)(\varepsilon_1 + \varepsilon_2 + \varepsilon_3) + 4\mu\varepsilon_1 + 2\mu\varepsilon_3 - \frac{1}{2} n\varepsilon_2 \tag{3}$$

Where ρ_0 is the initial density; l, m and n are third order elastic constants (Murnagham's constants); the terms ε_1, ε_2 e ε_3 are components of deformation of the directions 1, 2 and 3; λ and μ are second order elastic constants (Lame's constants). These latter constants are related to the elastic properties known as Young's modulus (E) and shear modulus (G), according to Eq. (4) and (5).

$$G = \mu \tag{4}$$

$$E = \mu\left(\frac{3\lambda + 2\mu}{\lambda + \mu}\right) \tag{5}$$

The Eq. (1), (2) and (3) can be simplified, considering that the deformation is acting only in the direction 1 (uniaxial state) and υ is the Poisson's ratio. Therefore, the following considerations can be made with respect to deformation:

$$\varepsilon_1 = \varepsilon \tag{6}$$

$$\varepsilon_2 = \varepsilon_3 = -\upsilon\varepsilon \tag{7}$$

The Eq. (1), (2) e (3) can be simplified to:

$$\rho_0 V_{11}^{\;2} = \lambda + 2\mu + \left[4(\lambda + 2\mu) + 2(\mu + 2m) + \upsilon\mu \left(1 + \frac{2l}{\lambda} \right) \right] \varepsilon \tag{8}$$

$$\rho_0 V_{12}^{\;2} = \rho_0 V_{13}^{\;2} = \mu + \left[4\mu + \upsilon \left(\frac{n}{2} \right) + m(1 - 2\upsilon) \right] \varepsilon \tag{9}$$

Deriving Eq. (8) in relation to deformation and regrouping terms, we obtain:

$$\frac{dV_{11} / V_{11}^{\;0}}{d\varepsilon} = 2 + \frac{\mu + 2m + \upsilon\mu(1 + 2l/\lambda)}{\lambda + 2\mu} = L_{11}\,, \tag{10}$$

where $V_{11}^{\;0}$ is the speed of longitudinal wave when the material is free of stress. L_{11} is the acoustoelastic constant for critically refracted longitudinal waves in the direction of loading. With Hooke's Law, it can be obtained a convenient expression for the variation of stresses with the change in travel time of the wave:

$$d\sigma = Ed\varepsilon \Rightarrow d\sigma = \frac{E(dV_{11}/V_{11})}{L_{11}} = \frac{E}{L_{11}t_0}dt\,, \tag{11}$$

where t_0 is the travel time of the wave when the material is free of stresses and dt is the variation of the travel time between two states of stress.

3. STUDY OF FACTORS INFLUENCING THE MEASUREMENT PROCESS

The variation of stresses in the material is not the only factor causing variations in speed of propagation of an ultrasonic wave, as seen in Eq. (11). It also depends on factors such as: temperature, force exerted by the support of the transducers on the piece, surface texture of the material, microstructure and residual stresses.

Studies show that the travel time of longitudinal waves propagating in a material presents a linear relationship with temperature (Santos, 2007), which is the focus of this study. Quantifying the influence of this factor allows the correct stress measurement, correcting the travel time using the knowledge of the temperature at which the material is.

According to Bray and Stanley (1997), the actual stress can be measured when Eq. (12) is used, which takes into account the effect of several factors.

$$\Delta\sigma = \frac{E(t - t_0 - \Delta t_{RS} - \Delta t_T - \Delta t_{TX})}{L_{11}t_{ref}} = \frac{E\Delta t_F}{L_{11}t_{ref}} \tag{12}$$

$$t = t_0 + \Delta t_{RS} + \Delta t_T + \Delta t_F + \Delta t_{TX} \tag{13}$$

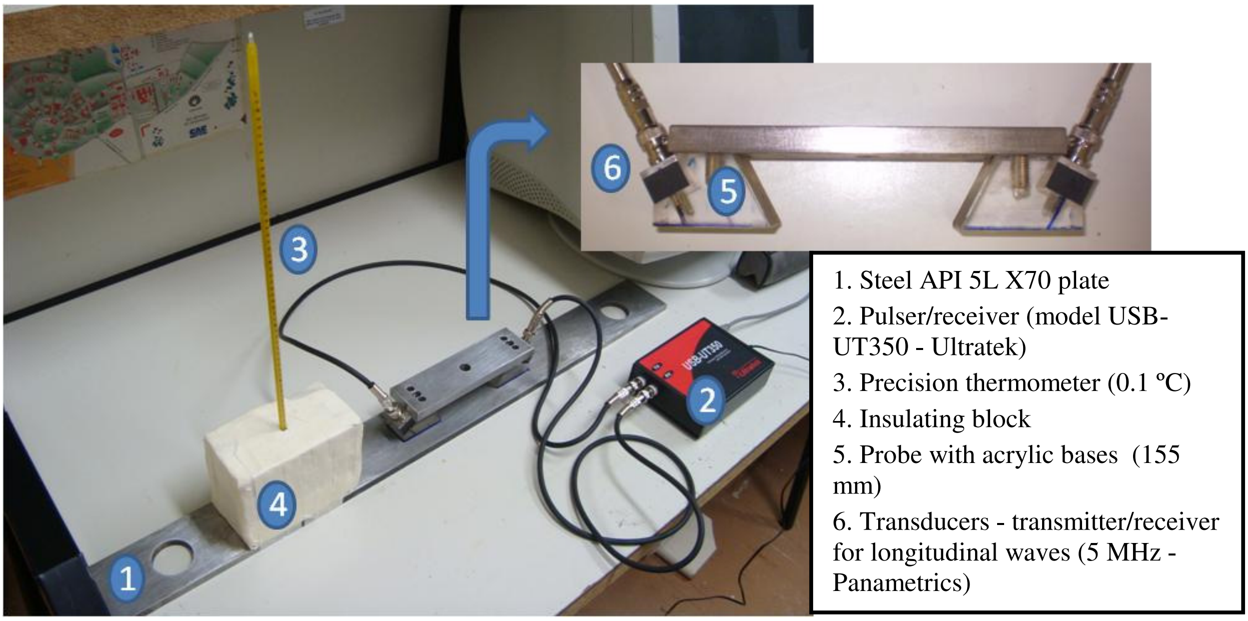
The term t_{ref} is the travel time of the wave at a reference temperature, with the material free of stresses. The term Δt_{RS} is the change in travel time of the wave due to residual stresses, the term Δt_{T} consider the fact that the temperature at which the test is performed is different from the reference temperature, the term ΔT_{TX} considers the effects of texture material, as in the case where there is corrosion, or when it has anisotropic properties. Finally, Δt_{F} is primarily the effect that we want to calculate, caused by the variation of an external force to the material.

4. EXPERIMENTAL PLANNING

To evaluate the influence of the temperature in the travel time of $\mathrm{L_{CR}}$ waves two experiments were conducted. In experiment 1, the influence of temperature on the speed of $\mathrm{L_{CR}}$ waves was determined in a steel API 5L X70 plate. Experiment 2 aimed to verify the influence of temperature on the propagation velocity of longitudinal waves in acrylic, which is the material used in the manufacture of the transducers base. This second experiment was used in the discussion about how much is the influence of the acrylic shoes on the speed variation.

4.1. Experiment 1

Figure (5) shows the equipment used for assembly of the experiment 1. The travel time inside the bar (1) was measured using a probe composed of a pair of transducers Panametrics model A406 S (5) attached to angular acrylic shoes (6). For better contact between the acrylic base and the plate, we used a regular ultrasonic couplant gel. The distance travelled by the wave inside the steel bar was 155 mm. Such distance is used to calculate the time of reference in Eq. (11) or (12).

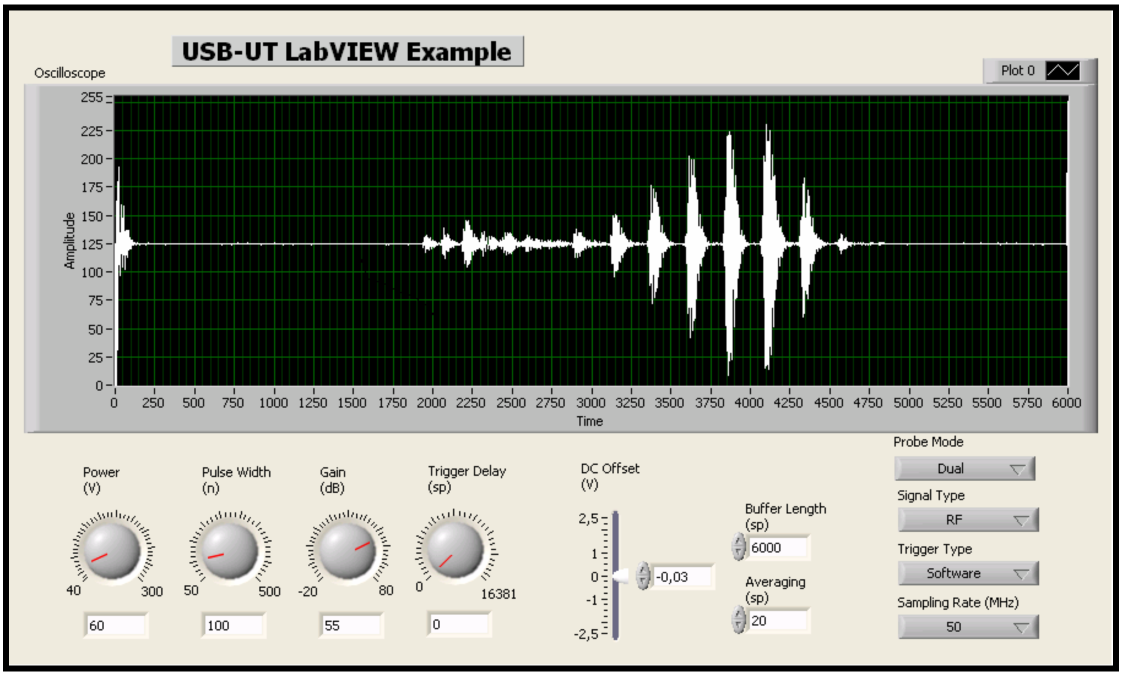


1. Steel API 5L X70 plate
2. Pulser/receiver (model USB-UT350 - Ultratek)
3. Precision thermometer (0.1 ºC)
4. Insulating block
5. Probe with acrylic bases (155 mm)
6. Transducers - transmitter/receiver for longitudinal waves (5 MHz - Panametrics)

Figure 5. Experimental arrangement for measuring the travel time and temperature of the plate.

The temperature was measured using a thermometer in contact with the bar and with the bulb isolated by a box of Styrofoam. The temperature along the experiment variates from 22.6 °C to 36.0 ºC. The tests were performed at intervals of about 0.5 ºC. Ten samples of waveforms were captured and analyzed for each selected temperature.

The pulse was exited by a pulser/receiver Ultratek model USB-UT350, connected to a data acquisition board NI 5911. This equipment is able to acquire data at 100 MHz. A computer program developed in LabVIEW^{TM} was used to visualize the waveforms captured by the receiver transducer, to adjust the parameters of the ultrasonic pulse emitted and also to perform the acquisition of the signal. The interface can be seen in Fig. (6).



USB-UT LabVIEW Example

Power (V): 60
Pulse Width (n): 100
Gain (dB): 55
Trigger Delay (sp): 0
DC Offset (V): -0,03
Buffer Length (sp): 6000
Averaging (sp): 20
Probe Mode: Dual
Signal Type: RF
Trigger Type: Software
Sampling Rate (MHz): 50

Figure 6. Application developed in LabVIEW^{TM}.

All the signals captured by the oscilloscope had the appearance shown in Fig. (7). The criterion used to determine the travel time of L_{CR} wave is the second crossing with the zero after the first peak of the graph whose value is approximately 6 mV as can be seen in Fig. (8). The first peak was chosen because the L_{CR} wave is the fastest among the waves detected, as cited before. The travel time for every temperature was recorded and the relation was plotted as show in item 5 (Results).

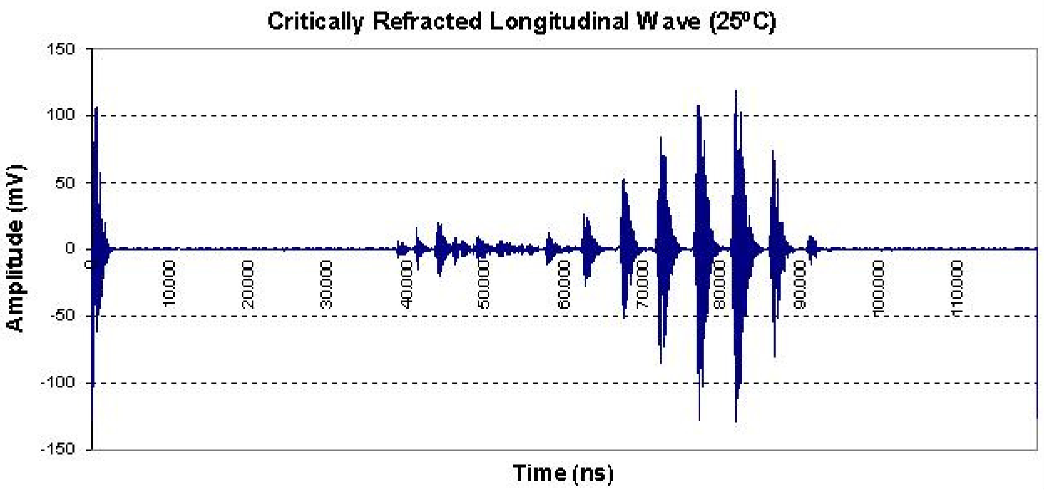


Figure 7. Signal recorded by the oscilloscope program.

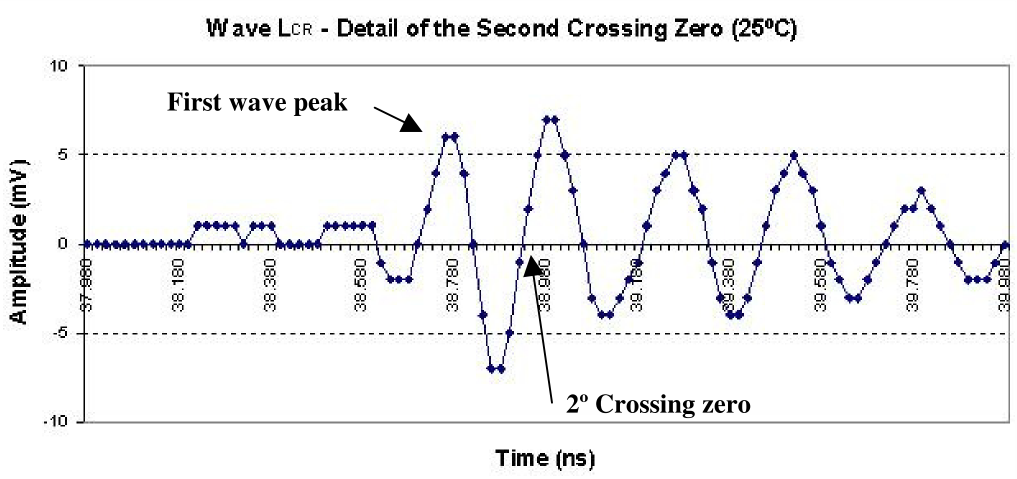


Figure 8. Signal recorded and the intersection with the zero after the first peak of the L_{CR} wave.

4.2. Experiment 2

The method used to check the travel time of the wave in acrylic was the pulse-echo. The method uses a transducer that has the function of both transmitter and receiver.

To find the relation between the speed of the longitudinal wave (or time) in acrylic as a function of the temperature, we used a precision thermometer and built a thermal insulator to involve one of the shoes used in the previous test. The bulb of the thermometer was placed in contact with the acrylic base and was also isolated. One side of the shoe was not isolated to allow contact with the transducer. This arrangement is shown in Fig. (9).

(a) Experimental setup **(b) Detail of the transducer placed on acrylic shoe**

Figure 9. Experimental arrangement for measuring the travel time and temperature at the acrylic shoe.

The ultrasound transducer and the pulser/receiver are the same used in experiment 1. The acrylic shoe 40mm-wide was heated to 40 °C. Insofar as it cooled; data about the travel time were collected using the pulse-echo method.

5. RESULTS

The results were obtained by graphical analysis using the software LabVIEW^{TM} and a datasheet. The parameters for calculating the speed of L_{CR} wave propagation for the two experiments are shown in Tab. (1). Figure (10) presents a 2D drawing with the distances covered by the wave in experiment 1.

Table 1. Parameters used in the experiment.

Parameters	Values
Propagation speed of sound in acrylic (m/s)	2660 (25 ºC)
Distance traveled in acrylic (mm)	32
Distance traveled in steel (mm)	155

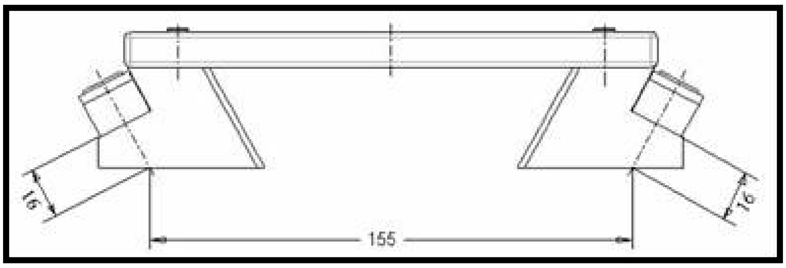


Figure 10. Distance traveled by the wave L_{CR} in the steel plate and acrylic.

5.1. Experiment 1

Figure (11) and Fig. (12) show that the experimental data of the travel time of longitudinal wave and speed of wave propagation have a linear relationship with temperature, according to the literature.

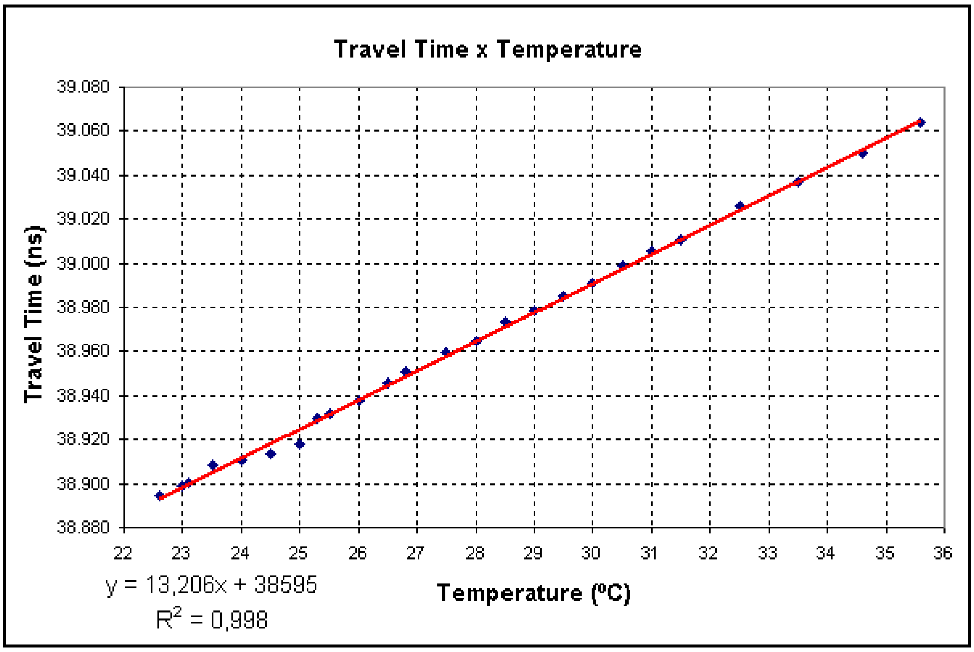


Figure 11. Travel time of L_{CR} wave as a function of temperature measured at the plate.

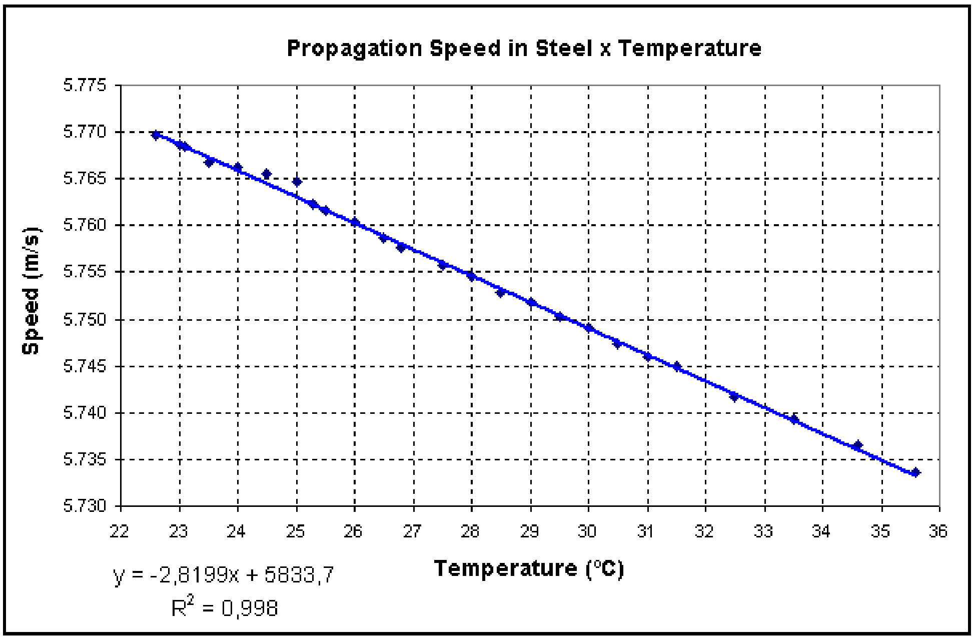


Figure 12. Propagation speed of sound in steel API 5L X70 in function of temperature.

5.2. Experiment 2

Figure (13) and Fig. (14) show that the propagation speed as a function of the temperature can be represented by a linear equation. The distance (pulse-echo distance) in acrylic is 80 mm.

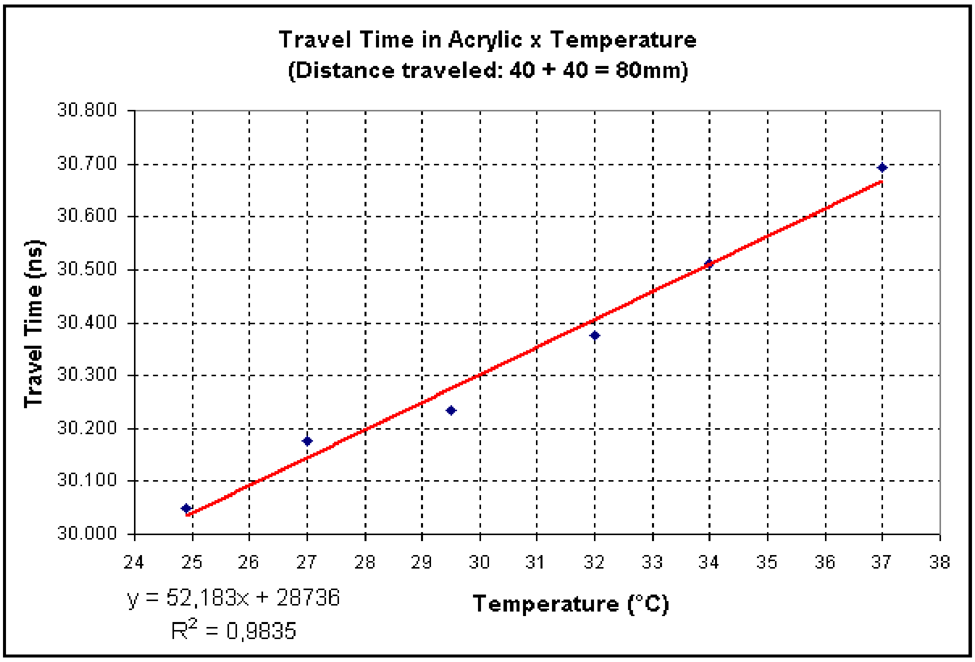


Figure 13. Travel time in function of temperature in an acrylic base of 40 mm wide.

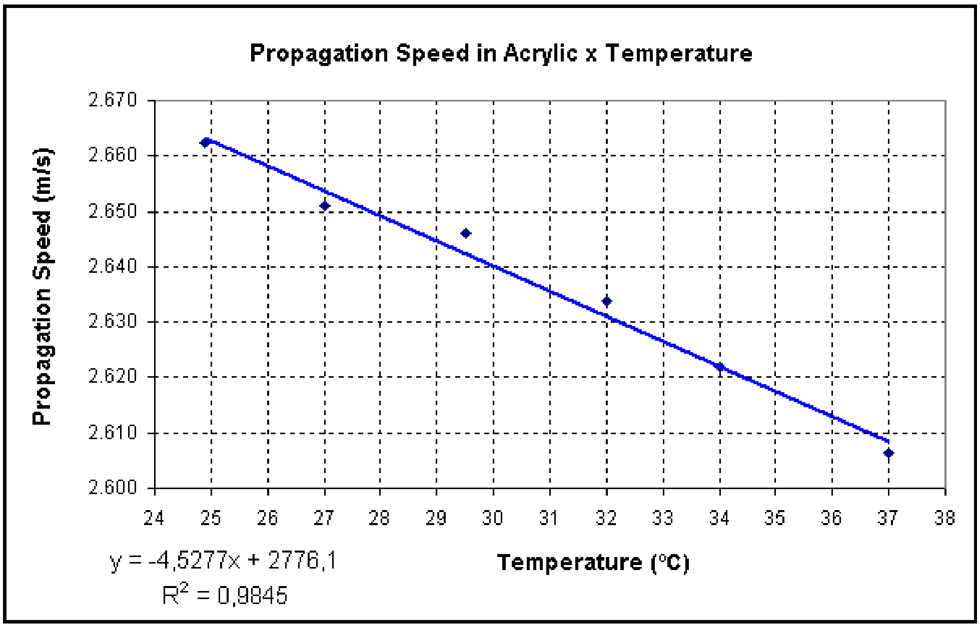


Figure 14. Propagation speed of sound in acrylic as a function of temperature.

From the curve of the propagation speed as a function of temperature, it is possible to calculate the time needed to travel 32 mm, corresponding to the distance of the wave in the acrylic base (Fig. 15). This time and the variation expected allows assumptions about the influence of the components along the travel path of the ultrasonic wave on the time variation detected in Experiment 1.

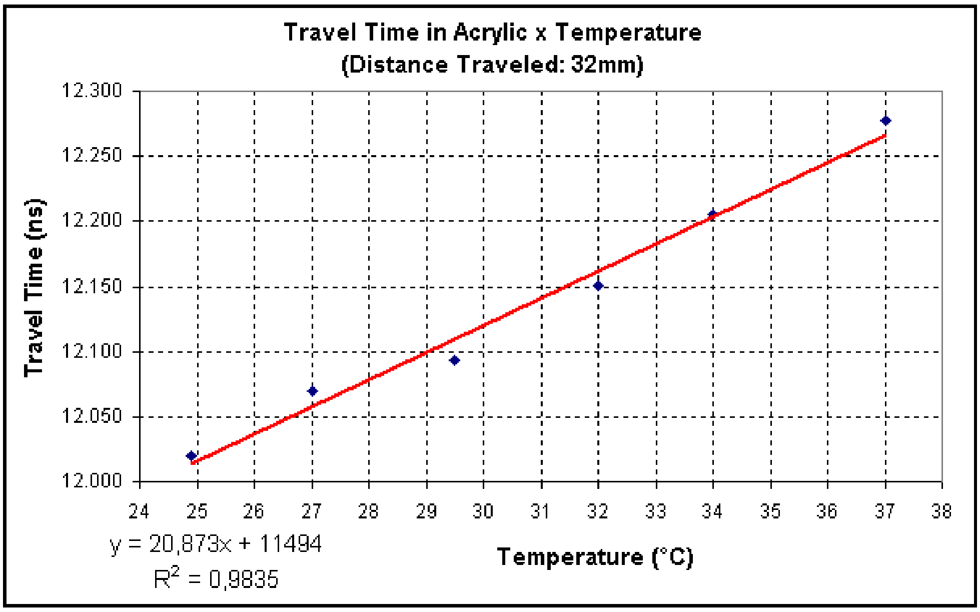


Figure 15. Time to travel 32 mm in acrylic (16 mm in each base of the transducers).

Experiment 1 showed a rate of 13.2 ns/°C and experiment 2 of 20.9 ns/°C. Comparing experiment 1 with experiment 2, it appears that the speed of sound propagation in acrylic undergoes a stronger influence of temperature. However, the experimental analysis shows that the temperature of the acrylic shoes does not follow the temperature of the steel plate during the experiments. It can be seen through the difference of the angular coefficient of the graphs for the two experiments that experiment 2 presented the steepest variation of the angular coefficient.

Moreover, although the speed of sound propagation in acrylic suffered a stronger influence of temperature, this effect is not significant in the experimental arrangement employed. A possible explanation for this is that the thermal conductivity of acrylic is very low (0.17-0.22 W/m.K) compared to carbon steel (around 60 W/m.K). Thus, acrylic bases do not suffer temperature changes very quickly, especially when the temperature difference between them and the steel plate is not significant, as in the experiments presented here.

6. CONCLUSION

We measured the variation of the time-of-flight of L_{CR} waves traveling inside API 5L X70 steel, when the temperature changes. The experimental setup was composed by a conventional ultrasonic system and temperature meter. Data of travel times were acquired at several temperatures and the results were plotted to find the form of the best fit equation.

The results confirm what was predicted by the literature, that is, the effect of temperature on the travel time of ultrasonic waves assumes a linear behavior (Santos, 2007). The higher the temperature, the greater the travel time (or the lower the speed of propagation).

The variation of the speed of L_{CR} waves with the temperature is found to be 13.2 ns/^{o}C, when using the probe presented. Previous work of Fraga, Andrino e Santos (2008); Santos (2007) and Andrino (2007) found coefficients between 13 and 16 ns/^{o}C, but using slightly different setups. Apparently, the variation found in acrylic do not have influence in the results, once the time until it heats to the next temperature level is higher because of its low conductivity.

These data, in the future, will allow a proper measurement of stress on the walls of steel API 5L X70 pipelines, by reading the travel time of ultrasound waves propagating on the material and correcting the time depending on the temperature of the component under evaluation.

7. AKNOWLEDGMENTS

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