Application of Critically Refracted Ultrasonic Longitudinal Waves (L_{CR}) for the Inspection of Aluminum Alloys

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Abstract. *The safety requirements in the aviation industry are very strict and one of its major concerns. This, of course, can be explained by the enormous risks involved. In most cases, accidents regarding airplanes are very dangerous and prevention, rather than maintenance, is the right approach. Routine inspections always take much time and are not accurate. Most of time, these are evaluations of the stress in a structure, in order to prevent the nucleation of cracks. That way, if a part is considered damaged it can be replaced before failure. There are many methods of measuring stress, and some of them are non-destructive methods that can be applied to aeronautical components in service. However, ultrasound techniques combine portability, simplicity and low costs.* L_{CR} *waves (critically refracted longitudinal waves) belong to a class of ultrasonic waves that propagate near the surface of the material. They are the most sensitive to strains. The objective of this work is to validate the acoustoelastic theory with the 7050 aluminum alloy used in the manufacturing of aeronautical structural components. Ultrasonic transducers attached in a probe with acrylic shoes were used to generate* L_{CR} *waves along an aluminum bar. Then, measures of the time-of-flight of the waves were made. The signals were processed using an industrial computer with a 250 MHz DSP board. In a solid under stress, the acoustoelastic theory predicts a linear relation between stress and the velocity of waves. A hydraulic pump was used as the source of traction, and two different techniques to obtain the time-of-flight of the waves were compared (cross correlation between the waves and direct calculation of the time-of-flight of each wave). The results confirmed the theoretical predictions and showed a linear relation between the load applied and time-of-flight of the* L_{CR} *wave (Solid Mechanics and Dynamics).*

Keywords*: Ultrasound, Stress measurement, Aircraft materials, Acoustoelasticity.*

1. INTRODUCTION

Failure process in aeronautical structures usually leads to tremendous disasters, so that studies related to the prevention of such problems are of great importance. An aircraft, civil or military, during its time of service is subjected to several kinds of loads, according to Fig.1, that affects its structural integrity and, when monitored, facilitates the repairing or replacement of affected components, significantly prolonging the useful life of the aircraft (Niu, 1988).

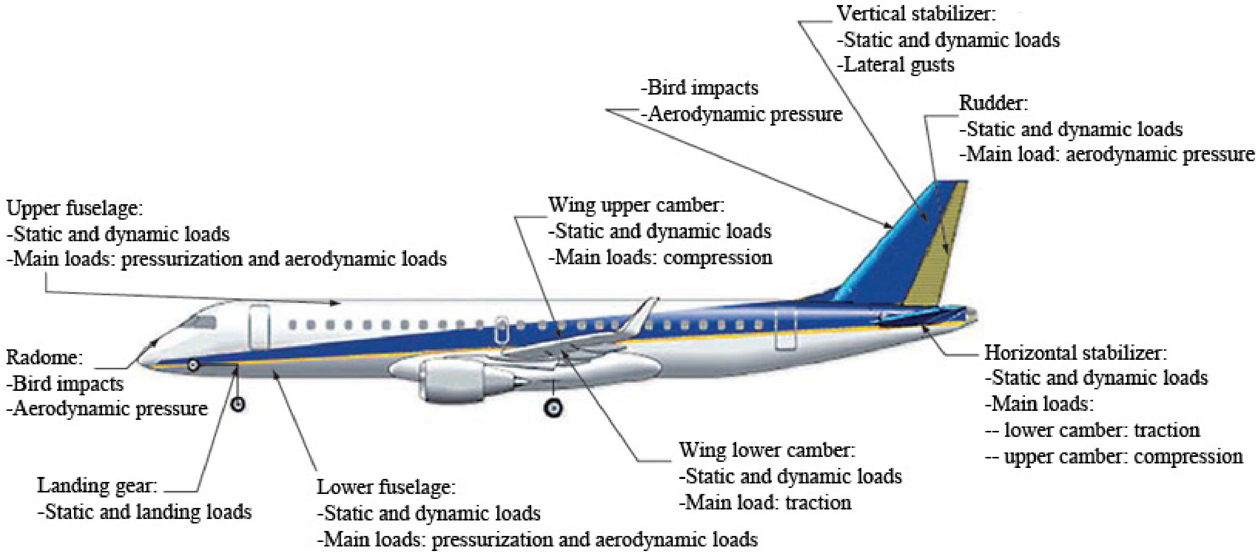


Figure 1. Main loads actuating over the airplane during its flight (Rezende, 2007).

The main causes of accidents in aircrafts are due to an inefficient flight planning, human factors and an inadequate maintenance. These causes are related to the lack of precise information regarding the damage generated by loads applied to the airplane during flight (Reddy, 2004).

Through the on-board monitoring of the aircrafts integrity the commander of the flight obtains stress information of critical points, not only making possible a more efficient flight planning, allows the maintenance to predict when the component must be replaced or repaired. However, such technology requires reliable control systems, protected against environmental changes and damages caused by the shipment.

Most stress measuring techniques are destructive and cannot be used in aircrafts. Through the extensometers we obtain the stresses in the material without damaging it, nevertheless such method is not adequate for the majority of critical points, since they are fixed, not reusable and a large amount of sensors is necessary to inspect aeronautical structures. Such limitations are also observed during the usage of solid films. Nondestructive methods like x-rays or neutrons diffraction normally do not meet safety requirements.

Ultrasound technique (UT) is the one that best suits, presenting low costs, simplicity of application, portability, good resolution and security. Setup time is also a plus, since this technique is fast to calibrate and use, despite others nondestructive methods. UTs are based on the acoustoelastic theory that relates the variation of body wave velocity with the deformation within the piece. Many kinds of acoustic waves are employed to measure stress and strain.

The main techniques of ultrasound stress analysis are: acoustic birefringence, which uses shear waves propagating to in an orthogonal direction to the stress field, and the L_{CR} technique, which relates the velocity of a longitudinal wave with stress and strain (Bray and Junghan, 1995). Nowadays, both methods are applied in the field and there are commercial systems on the market using them for specific applications.

For the inspection of aeronautical structures, the best suited technique is the based on L_{CR}, since it uses longitudinal waves propagating about one wavelength from the surface, fulfilling with the requirements associated to structural features (thin plates), which require a technique for the evaluation of stresses near the surface, where they are usually larger.

As in the case of fairing in the aircrafts the stress levels are generally higher when near to the boundaries between the component and the air around the aircraft, this technique proves advantageous for future practical applications.

In terms of materials used in aeronautics, aluminum alloys are widely used due to its low density compared to ferrous metals. Among these alloys, the 7000 series corresponds to alloys with high resistance to compressive stresses, being commonly used for upper wing coverings, frames, landing gear and ribs. While such links presents a great resistance to compressive stresses, it also has major problems regarding their resistance to corrosion, and requires the use of various heat treatments. The alloy used in this work is AA7050 with heat treatment T7451 that ensures greater resistance to corrosion and better fracture toughness (Niu, 1988).

This work aims to validate the acoustoelastic theory, employing L_{cr} waves to measure stresses, for 7050 aluminum alloy used in the manufacturing of aeronautical structural components.

2. ULTRASONIC WAVES

Ultrasonic waves are mechanical waves, which require a material medium to propagate, with frequencies above 20 kHz. The useful frequency for material testing is from 0,5 MHz to 15 MHz.

The way the particles of excited medium perform the oscillation movement determines the type of wave: longitudinal and transverse. Longitudinal waves are those whose vibrations occur in the same direction of propagation. Transverse waves, also known as shear waves, are characterized by vibrations perpendicular to the direction of propagation, as shown in Fig. 2.

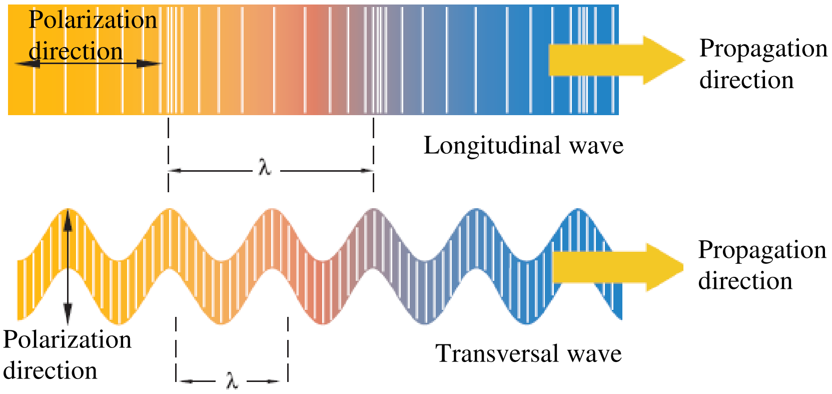


Figure 2. Propagations planes of the longitudinal and transversal waves (Olympus, 2011).

2.1. Longitudinal waves critically refracted (L_{CR})

Critically refracted longitudinal wave is a type of wave very well 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, 2000). In addition, it has a low damping compared to other kinds of longitudinal waves such as Creeping waves according to Junghans and Bray (1991). To obtain this type of wave propagating in aluminum, it is necessary to use a transducer that generates longitudinal waves through an acrylic base, so that the angle of incidence of the longitudinal wave is 25,7 degrees to the normal direction to the surface of the object tested, as shown in Fig. 3.

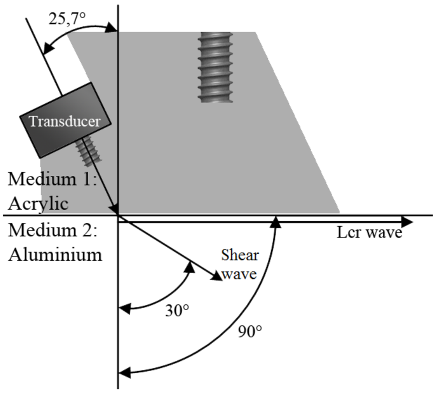
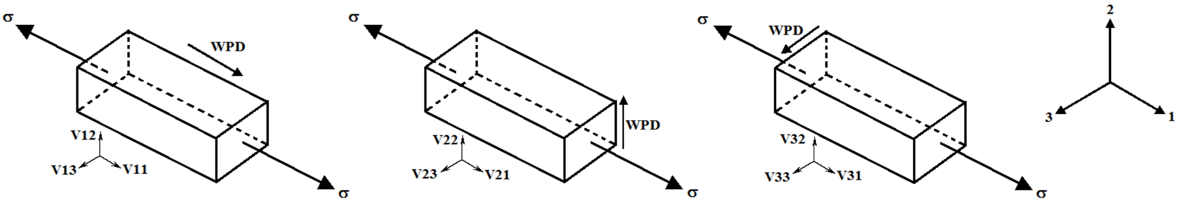


Figure 3. Incidence of L_{CR} in Aluminum.

2.2. Application of the critically refracted longitudinal waves (L_{CR}) to measure stress

The ultrasonic method for stress measurement is based on the acoustoelastic theory, which relates the presence of stresses in a solid with the change of wave propagation speed when it travels through the material under investigation.

Considering a solid medium pulled in one direction, the waves can spread in three orthogonal directions, Fig. 4, where the first index of the speed refers to the direction of wave propagation (DWP) and the second index to the direction of particles motion. Thus, V_{11} (Fig 4.a) represents the particle velocity in the same direction of wave propagation (longitudinal waves) and velocities V_{12} and V_{13} correspond to the speed of wave in directions perpendicular to the particle motion (transverse waves).



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

Figure 4. System of Coordinates of a Stress Field (Bray and Stanley, 1997).

The velocities of ultrasonic waves with the same propagation direction of the applied stress are related to the state of triaxial deformation according to Eq. (1), (2) and (3) (Bray and Stanley, 1997).

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

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

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

The term ρ_0 is the initial density of the material; l, m and n are the elastic constants of third order of Murnaghan; the terms ε_1, ε_2 and ε_3 are strain components in the directions 1, 2 and 3; λ and μ are Lamé elastic constants of second order.

These last constants relate with elastic properties known as Young's modulus (*E*), Poisson's ratio (υ) and transversal's modulus (*G*), according to Eq. (4), (5) e (6).

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

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

$$\upsilon=\frac{\lambda}{2(\lambda+\mu)} \tag{6}$$

If it is considered the deformation only on direction 1 (uniaxial state), the Eq. (1), (2) and (3) can be simplified, being the Poisson ratio by which we obtain the relation between orthogonal deformations:

$$\varepsilon_1=\varepsilon \tag{7}$$

$$\varepsilon_2=\varepsilon_3=-\upsilon\varepsilon \tag{8}$$

Thus, the Eq. (1), (2) and (3) can be rewritten by:

$$\rho_0 V_{11}{}^2=\lambda+2\mu+\left[4(\lambda+2\mu)+2(\mu+2m)+2\upsilon\mu\left(1+\frac{2l}{\lambda}\right)\right]\varepsilon \tag{9}$$

$$\rho_0 V_{12}{}^2=\rho_0 V_{13}{}^2=\mu+\left[4\mu+\upsilon\left(\frac{n}{2}\right)+m(1-2\upsilon)\right]\varepsilon \tag{10}$$

Deriving Eq. (9) in relation to deformation, regrouping terms and assuming that the relative changes in wave speed are small, we obtain:

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

Where the longitudinal wave velocity for the material is in its natural state (stress-free) and L_{11} is the acoustoelastic constant for critically refracted longitudinal waves in the direction of loading.

Using the constitutive equation (Hooke's Law), which relates stress with strain; we obtain an expression that best describes the relationship between strength change and the change in the wave travel time:

$$d\sigma=Ed\varepsilon\Rightarrow d\sigma=\frac{E(dV_{11}/V_{11})}{L_{11}}=\frac{E}{L_{11}t_0}dt \tag{12}$$

As t_0 is the travel time of the wave when the material is free of stress and *dt* is the variation in wave travel time between two states of stress.

3. EXPERIMENTAL DETAILS

An experiment was performed in order to validate the acoustoelastic theory explained before with a bar manufactured with the aluminum alloy 7050 (with heat treatment T7451). In the Eq. (12), the Young's modulus *E* and the acoustoelastic constant L_{11} are already known parameters from the literature. Therefore, using t_0 and *dt* obtained from the measurements, it is possible to estimate the stress applied in the specimen.

3.1 Specimen used for the tests

It consists of a bar with a rectangular section of 12.7 x 70 mm measuring 760 mm of full length. A hole in each extremity of the bar was conceived to connect the specimen to the traction device. The bar was obtained by lamination process in the longitudinal direction, which may cause some anisotropy in the material. In this work, however, this influence was considered irrelevant and the material was assumed to be isotropic. If such assumptions is contested by the results, it will be analyzed in future work.

3.2 Experimental Setup

To apply stress to the aluminum bar, two hydraulic cylinders were used to convert the pressure from a hydraulic manual pump into a traction force, which could be transmitted to the bar under test by the device illustrated in the Fig. 5. A strain gage of 120Ω gives the information about the real stress applied in the center of the bar, the same place where the ultrasound setup is measuring. To monitor the aluminum temperature, a type K thermocouple was fixed to the bar.

3.3 Transducers assembling and usage

In the tests performed, two ultrasonic transducers were used, one emitting signal and another receiving it. Each one has a nominal frequency of 5 MHz and was mounted upon acrylic shoes as shown in previous schematic. The two transducer-shoe groups were linked by a rigid bar to maintain unchanged the distance travelled by the acoustic wave. A water-based coupling gel was used to fulfill the air gap between transducers and the acrylic base, as well the surface between the acrylic and the aluminum bar under test. This assembly is referred by the term "probe". During the experiments, a weight was used to generate a steady contact force between the probe and the aluminum bar.

3.4 Data acquisition equipment

An ultrasonic pulse-receiver (model USB-UT350 Ultratek) was connected to the emitting transducer and the signal collected by the receiver was acquired with a digitizer board of 250 MHz, model NI PXI 5114 from National Instruments. The strain gage and thermocouple were connected in I/O block connector model SCC-68 and the signals received were conditioned in a NI PXI 6221 board. The digitizer and the signal conditioner board are connected in an embedded controller model NI PXI 8108 with an Intel Core 2 Duo T9400 processor with PC functionalities. The embedded controller runs a specially developed LabView routine to acquire the data and save it for posterior treatment. A scheme of the data acquisition system with the traction device is shown in Fig. 5.

3.5 Methodology

To assure reproducibility, three tests were made with the pump pressure varying from 0 to 20 MPa in steps of 4 MPa. In each step, five measurements were made in order to guarantee repeatability. Before increasing the pressure of the system, the probe was moved away from the bar and the system was rearranged.

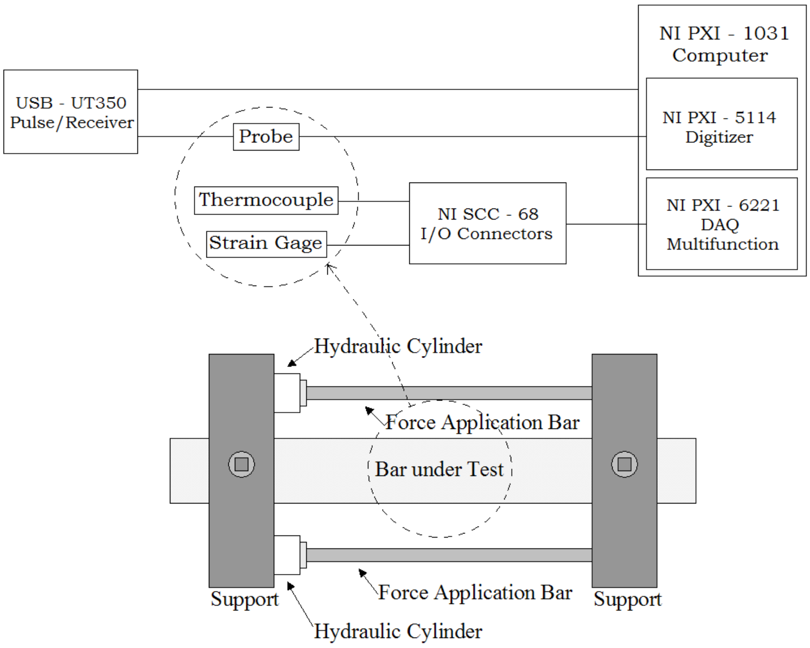


Figure 5. Traction device (down) with scheme of the data acquisition system (up)

4. RESULTS

The waveforms collected from the experiment were treated in four different ways. In the first one, the time of flight of the L_{CR} wave was measured considering the time between the initial trigger and the second crossing of zero amplitude, after the first significant peak of the L_{CR} pulse (Fig. 7).

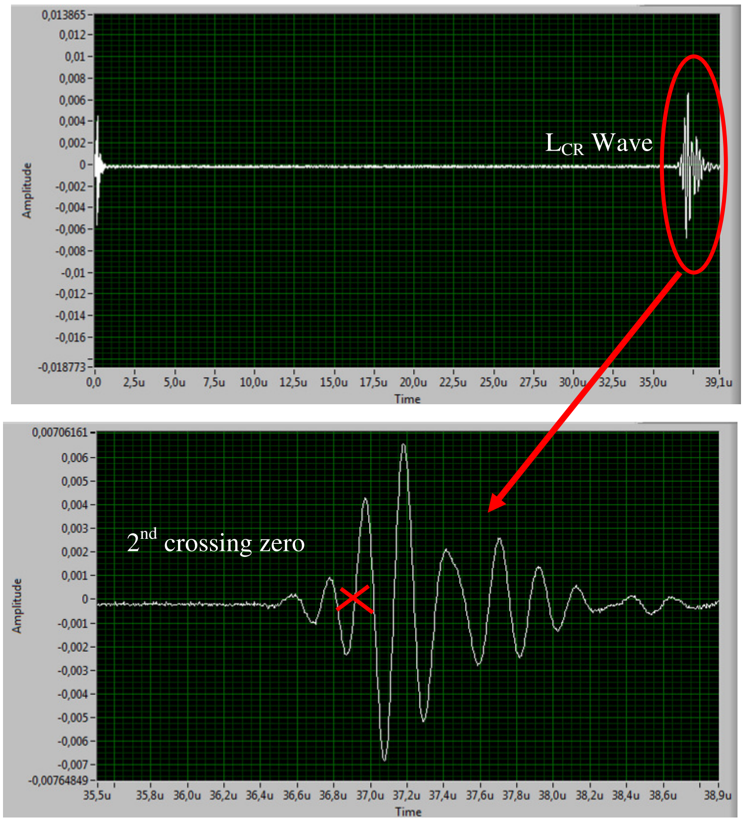


Figure 7. Second crossing zero of L_{CR} wave.

Using the time of the second crossing zero as the time of flight, the stresses measured with the strain gage compared with the stresses calculated by Eq. (12), considering the material parameters for aluminum as E = 71,7 GPa and L_{11} = 2,7 for the three experiments, are shown in Fig. 8.

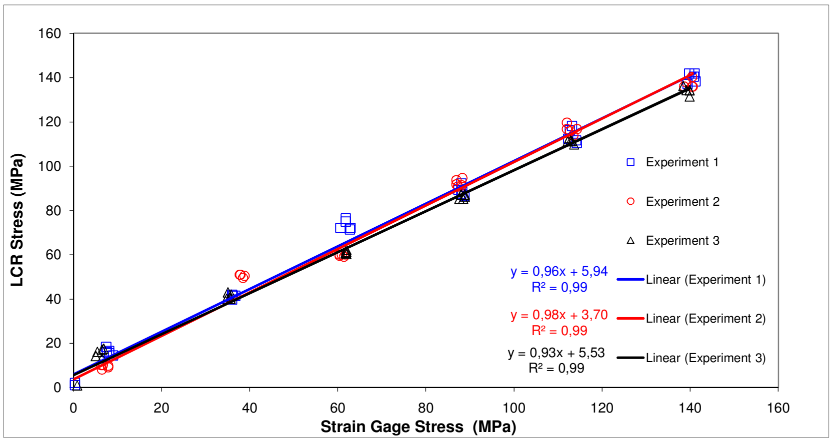


Figure 8. Comparison between the stress measured by L_{CR} method and the stress measured by strain gage.

In Fig. 8, all three experiments are presented with their respective trend lines, equation and R-squared.

The influence of temperature at speed of L_{CR} waves is well known from previous studies and they show a linear relation between time of flight of L_{CR} wave and temperature (Santos, 2007 and Santos, 2010). Studies in progress indicate an increase rate of 15,9 ns/°C in time of flight with temperature for the aluminum used in this work. The temperature during the experiments varied from 25 °C to 27,5 °C which corresponds to a variation of 39,75 ns (28,62 MPa, according to Eq. 12). The values of time of flight measured were corrected with the rate of 15,9 ns/°C and the temperature of each measurement to consider only the influence of stress in the speed of L_{CR} waves. The relation between the stress measured by the strain gage and stress calculated with the time of flight corrected by the temperature is shown in Fig. 9.

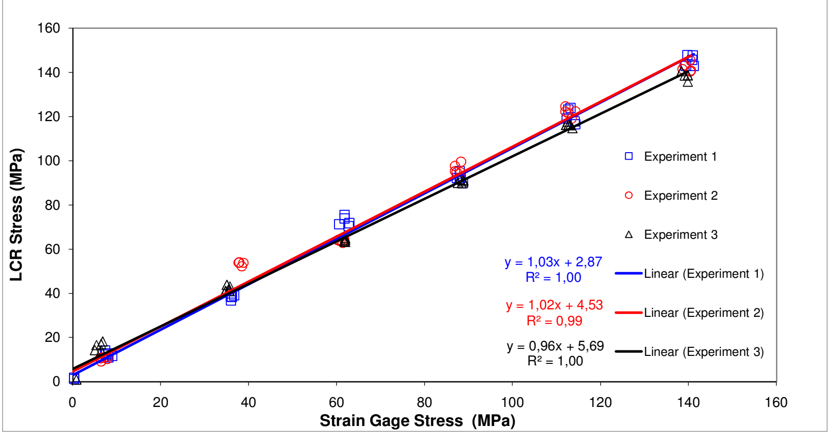


Figure 9. Comparison between stress measured by L_{CR} method with correction of temperature with stress measured by strain gage.

Another way to find the difference between time of flight in two different states of stress is using the cross correlation function (Andrino, 2007). From the differences between the measurements of time in all levels of stress applied to the bar with the time measured in the unstressed state using the cross correlation function, the calculated stress by L_{CR} wave compared with the measured with strain gage can be seen in Fig. 10.

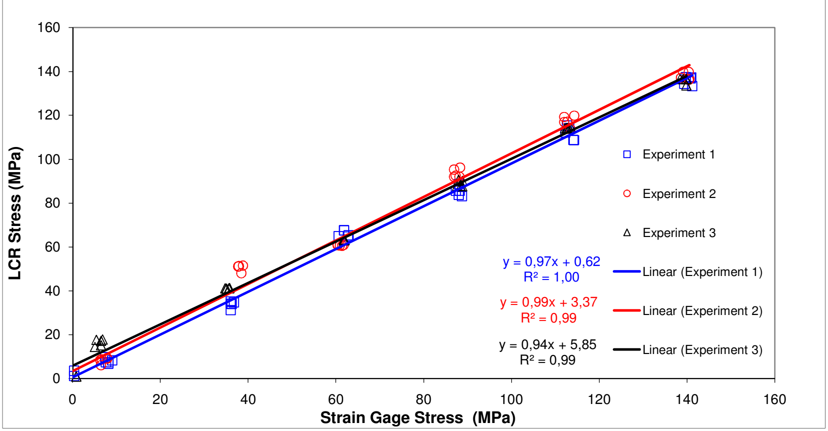


Figure 10. Comparison between stress measured by L_{CR} method using the cross correlation with stress measured by strain gage.

The final method to process the signals was resampling the waveforms before using the cross correlation function. The sampling frequency was increased to 2,5 GHz by resampling the original data and using linear interpolation. The stress calculated using the time of flight obtained by the cross correlation of the resampled waveforms is presented in Fig. 11.

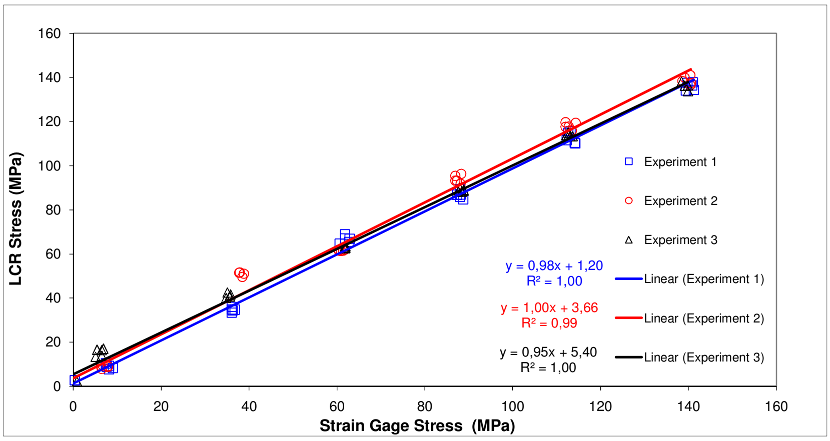


Figure 11. Comparison between stress measured by L_{CR} method using the cross correlation of the resampled data with stress measured by strain gage.

The results obtained using the second crossing zero method show good agreement between the stress measured using the L_{CR} waves and the strain gages, even without resampling the data and correcting the temperature. The equations of the trend lines present angular coefficients close to the unit, the biggest offset obtained was 5,9 MPa and all R-squared were not less than 0,99.

5. CONCLUSION

The aim of this work was to confirm the acoustoelastic theory for 7050 aluminum by measuring the variation of time of flight of L_{CR} waves, calculating the stress with Eq. (12) and comparing with results obtained from a strain gage fixed on the bar. We used signal processing techniques as cross correlation and resampling to obtain better precision data and the time of flight measured had to be corrected by a temperature factor for the material studied.

We applied different levels of stress with the traction device and the waveforms, data from L_{CR} wave time of flight, strain gage and thermocouple were collected.

The results obtained from the experiment confirmed the linear behavior between L_{CR} wave time of flight and stress and more than that, the stress measured by L_{CR} method were very close to the stress measured by the strain gage as can be seen in Fig. 8 to Fig. 11.

For this particular application, the use of cross correlation and resampling did not represent a great improvement of the results because the measure of time of flight with the second crossing zero had already showed satisfactory results. However, the correction of the time by the influence of temperature is necessary when the experiments occurred in different temperatures since the influence is significant.

The use of cross correlation can be more appropriate since it is not necessary to find the second crossing of zero in the waveform to establish the time of flight, what can be more complicated in a signal with high levels of noise. In addition, the resampled waveforms with a higher sample rate can be useful when using equipments with low sampling frequency.

The experiment showed that L_{CR} ultrasonic waves can be used to measure stress applied to this particular aluminum alloy when its unstressed state is known.

6. ACKNOWLEDGEMENTS

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