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# DEVELOPMENT OF AN AUTOMATED SYSTEM TO EVALUATE THE ACUSTOELASTIC COEFICIENTS OF METALIC MATERIALS

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**Abstract.** The main methods used to evaluate mechanical stresses are destructive, like the well known hole-drilling and saw-cut methods. All of them are based on the measurement of the deformation caused by the stress relaxation after machining using strain gauges or optical sensors. Non-destructive methods are generally limited by the sophistication of the instrumentation and by the ability to measure only near surface, as observed in neutron diffraction and X-ray methods. Ultrasonic techniques have been used since the sixties, but the data acquisition rate and the storage capacity of the measurement systems were not high enough to allow fully application outside laboratories. The development of new instruments generates a new gamma of applications, like those on structural elements. Mechanical stresses, both applied and residual are related to the wave speeds by an acoustoelastic coefficient, witch is specific for each kind of wave. This work presents the development of a system to evaluate that coefficient for metallic materials, mainly sheets. A mechanical fixture, ultrasonic transducers, pulse-receiver, data acquisition board and specially developed software called L-stress v.1.0 compose the system. The system can be also used to evaluate stresses in real parts; provided the acoustoelastic coefficients are known and minor modifications are made. The paper presents the excellent correlation between the measured and expected results for samples extracted from metallic sheets.

***Key words.*** *Acustoelasticity, stress measurement, mechanical stresses, non-destructive methods.*

## 1. Introduction

The mechanical design makes intensive use of computational tools, especially to model numerically the real conditions of loading. Although the design process includes methods and parameters others than those involved in load calculations and in the estimative of the capacity of an element in supporting them, it is clear that this part of the process is of fundamental importance.

The development of computational tools with the ability to use real data to feedback the calculations has been one of the greatest goals for programming engineers nowadays. Those tools could simulate the effects of several loading and compare them with experimental measurements taken place in real tests, witch would allow the program itself to correct the method of calculations to reach the real values. In other words, this engineering dream would be target with computers that thought.

Self-correcting codes, witch are actually programs to search targets and that learn with partial results, are been developed using several branches of logic and neuronal networks. Whatever is the method used to make the computer to think, the result of each iteration would have to be compared with the target or targets. For engineering applications, the results gotten from well-controlled boundary conditions could be applied to estimate the variables to every real condition. That is basically the same process used by humans to develop empirical theories. These theories came from the observation of real situations and they describe what is supposed to be a well-ordered behavior.

However, this new reality of the design of mechanical parts does not exclude the experimental verification. As matter of fact, although the need of measurements become less frequent as long as the simulation codes become more reliable, the measurements need to be more accurate and precise in the determination of the design variables. If the self-correcting codes based their decisions on not accurate measurements, the effects could be catastrophic. Meanwhile, more accurate measurements lead to more complete theories.

Once the importance of the experimental methods to the development of better design is established, it is necessary to find more suitable ways to get the concerning variables through measurements. The concerning variables for Mechanical Engineering Design are stresses, deformation, temperature, velocity, wear and several others. Particularly to structural calculations, mechanical stress is the most relevant parameter to be evaluated. It has to be compared to material strength to allow one to evaluate if the design fit the requirements.

The term stress is used to express the relation between two measurable characteristics, force and geometry; both related to mechanical elements failures. Usually, with the right geometry the part will not fail, no matter as great is the applied force. So, stress was defined as the ratio of the applied load to some geometric characteristic of the part, witch is able to express the dimensions of the region that resists to that applied load. The simplest example of the application of that definition is the calculation of the stress as the ratio between force and area for a bar loaded axially. This ratio is called normal stress and it has a limiting value called strength.

The problem becomes more complicated when analyzing complexes geometries and multiple loads. In that case, the stresses can vary along the part, been more intense in some regions of it. Moreover, mechanical elements can have internal stresses even in the absence of external load, because of its fabrication process or previous loading. These stresses are called residual stresses.

Residual stresses are one of the main causes of failures in mechanical parts. They are caused by elastic energy stored inside the element. Usually, they rise from high magnitude loading, not expected in regular operation. Tensile stresses are the most dangerous, because they could lead to catastrophic failures.

The most used methods to measure residual stresses are applied for quality control along fabrication processes. Most of them are destructive, and the samples cannot be used after they have been tested. The calculus of the original stresses is made using the deformations (saw-cut and hole-drilling methods) or displacements (opening of a crack). Those methods cannot be used to evaluate components in operation and they do not allow the estimation of the residual stresses before processing. It can lead to a misjudgment of the risk of using the components.

There are cases when it is necessary to inspect all components in service, and not only a sample of them. That requirement is established when one component can lead to a catastrophic failure. Railroad wheels failures are typical, because one single broken wheel can cause the derailment of the whole train. There are also cases when it is necessary to evaluate every component in one structure, if the history of loading is not known. So, the need of a non-destructive method to measure stresses is evident.

The most used non-destructive methods to measure residual stresses are based on X-rays and ultrasound (Lu, James and Morfdim, 1996). Neutron diffraction is also used, but it requires a nuclear reactor, what makes its application not suitable for most of the mechanical systems. X-rays has been used with good results to measure surface stresses. The method has a very good signal to noise ratio, but it requires a specialized instrumentation and a well-trained operator. It also requires some knowledge to relate the results to the stresses.

Ultrasonic method is an easy to use, low cost method; witch can be automated and do not require experienced operators. The method consists in the generation of ultrasonic waves in the material, both longitudinal or shear waves, and the measurement of the travel time of those waves in the region of interest. The wave depends on the stress state, as much as of other parameters like texture, grain size, inclusions, …

This work presents the development of an automated system to evaluate the relation between mechanical stresses and the ultrasonic wave speeds in metallic materials. The factor witch express that relation is called acoustoelastic coefficient. Once the coefficient is found or known, the system can be used to evaluate stresses in similar elements, under different loadings. A mechanical fixture, ultrasonic transducers, pulse-receiver, data acquisition board and specially developed software called L-stress v.1.0 compose the system.

## 2. Acoustoelastic Theory

Hughes and Kelly (1953) developed the expressions relating the principal deformations ($\alpha_i$) with the ultrasonic wave speeds ($V_{ii}$), using the Lame's constants ($\lambda,\mu$) and the third order elastic constants ($l,m.n$), as shown in equations 1, 2 and 3. The first index in the velocity is the direction of propagation and the second is the vibration direction. The density is $\rho_o$ and the sum of the principal deformations ($\alpha_1 + \alpha_2 + \alpha_3$) is noted $\theta$.

$$\rho_0 V_{11}^2 = \lambda + 2\mu + (2l + \lambda)\theta + (4m + 4\lambda + 10\mu)\alpha_1 \tag{1}$$

$$\rho_0 V_{12}^2 = \mu + (\lambda + m)\theta + 4\mu\alpha_1 + 2\mu\alpha_2 - \frac{1}{2}n\alpha_3 \tag{2}$$

$$\rho_0 V_{13}^2 = \mu + (\lambda + m)\theta + 4\mu\alpha_1 + 2\mu\alpha_3 - \frac{1}{2}n\alpha_2 \tag{3}$$

For uniaxial stress state, $\alpha_1 = \varepsilon$ and $\alpha_2 = \alpha_3 = \nu.\varepsilon$. The expression witch relates the variation of wave speeds with the changes in deformation can be written after derivation of equations 1, 2 or 3. Equation 4 shows the expression relating longitudinal wave speed variation with the changes in deformation and the elastic constants. The value $L_{11}$ represents the acoustoelastic constant, witch can be both calculated using the elastic constants or measured indirectly by wave speed and deformation changes.

$$\frac{dV_{11}/V_{11}^0}{d\varepsilon} = 2 + \frac{\mu + 2m + \nu\mu(1 + 2l/\lambda)}{\lambda + 2\mu} = L_{11} \tag{4}$$

The stress variation $d\sigma$ can be placed instead of $d\varepsilon$, by using the Young's modulus (E). The distance between longitudinal ultrasonic transducers must be kept the same in all measurements, so the velocity can be replaced by the travel time. Equation 5 shows the resulting equation, where $t_o$ is the reference time-of-flight for an unstressed state.

$$d\sigma = \frac{E(dV_{11}/V_{11})}{L_{11}} = \frac{E}{L_{11} \times t_0} dt \tag{5}$$

The variation of stress can be calculated using Equation 5, provided the values for $t_o$ and $L_{11}$ are known. Bray and Stanley (1997) presented the acoustoelastic coefficient for rail and some commercial steels. Caetano (2003) showed the values for API 5L x70 steel, used in gas pipelines.

## 3. System Components

Figure 1 shows the mechanical fixture used to apply stress to a sample extracted from a metallic sheet. Two hydraulic cylinders actuate in lateral bars, witch are compressed against two steel blocks. The sample is the linkage between the blocks; when the compressive force in the lateral bars tries to separate them, tensile stresses are generated inside the sample. The force applied to the sample can be calculated from the hydraulic pressure and the area of the cylinders; the tensile stress can be calculated provided that the sample cross-sectional area is known. The system is basically a tensile stress machine.

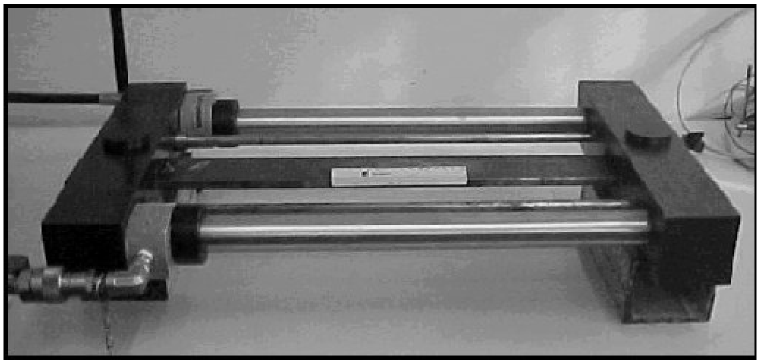


Figure 1. Tensile Stress Machine

A regular $L_{CR}$ probe is composed of the piezoelectric element or transducer mounted in a Plexiglas base (PMMA), allowing the wave to hit the surface under test in the prescribed angle, about 28° (critical angle). Two sensors make up the transducer, one emitter and one receiver. The link of the transducers in made of aluminum. The pulse-exited transducers are 2.25-MHz, 12-mm square. The distance (d) between them is 112-mm, measured between the spot where the wave gets in the sample and the spot where the wave leave it. Figure 2 shows the $L_{CR}$ probe.

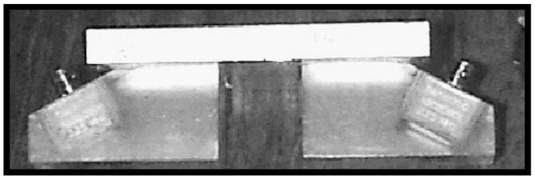


Figure 2. Probe arrangement for ultrasonic $L_{CR}$ waves

Preliminary tests showed high influence from the contact pressure between probe and samples. It is probably caused by the finite stiffness of the arrangement. There is also a minor influence of the positioning, because of surface interaction effects. Figure 3 shows a fixture used to access those problems; it uses a load cell and a hydraulic actuator to control the pressure between surfaces. It also places the probe in the same place always.

A pulse-receiver, model Panametrics 5072 PR, was used to excite the waves. The electrical pulse reaches the emitting transducer and generates the longitudinal wave; witch reaches the sample and goes to the other transducer. The wave generates a new electrical signal and the pulse receiver amplifies it before sending to the data acquisition system.

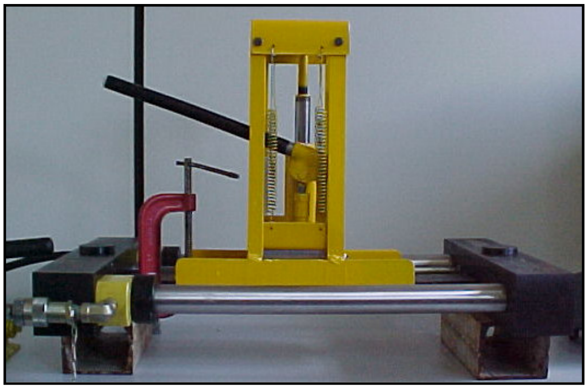


Figure 3. Fixture to control the interface pressure and the position of the probe (in yellow)

Figure 4 shows the whole system. An oscilloscope AD board, NI 5911, a computer and a special program, detailed in item 5, compose the data acquisition system. The electrical signal sent by the pulse receiver is acquired by the system and compared with the applied stresses to calculate the acoustoelastic coefficient.

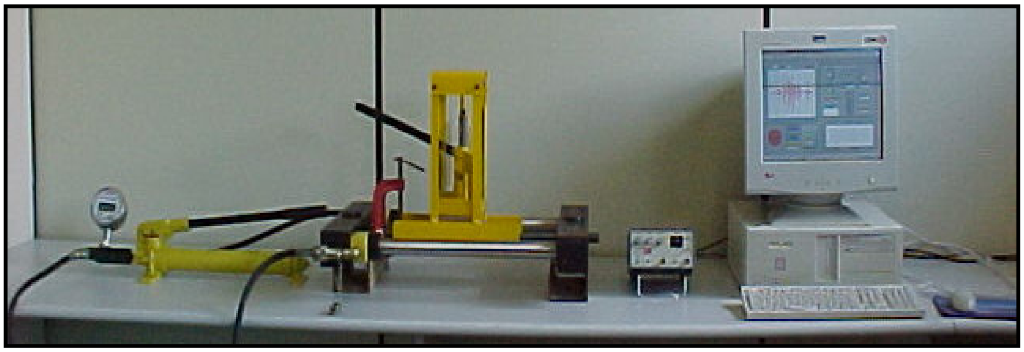


Figure 4. System to evaluate acoustoelastic coefficients for metallic sheets

### 4. Procedure to evaluate acoustoelastic coefficients

The procedure consisted of increasing the load and measuring the variation in the time-of-flight for the $L_{CR}$ wave between the sender and the receiver. The couplant used was a commercial gel and the environment had temperature control.

The maximum load depends on the material. The load should be high enough to the system senses the stresses and not so high to cause yielding of the bars near the hole. Once the load is defined, the number of steps can be chosen.

For clamping the probe to the bar, pressure was applied directly through the probe and bar interface. Hydraulic pressure was applied to the probe and test bar to reduce the effect of the probe fixture deformation on the travel-times. The pressure on the probe was controlled using a load cell and the force was always 1000 N.

The measurements of travel times were repeated five times on each load level, for each bar. After one reading is acquired, the probe was taken from the bar, the couplant was replaced and the probe was installed again in the same place for a new reading in the same load level. Each reading was the average of at least ten waves. The measurements were taken in both sides of the bars and averaged. Eventual bending would act on both sides in opposite way, so the average would be the best estimate for the constant.

Stresses were calculated using equation 5 with $L_{11}$ = 1,0 and were plotted against the applied stresses. The angular coefficient of the best-fit straight line is the acoustoelastic constant. The values for both sides were averaged, giving the acoustoelastic constant for each bar.

### 5. Data Acquisition Program

The data acquisition program was first developed to measure stresses in mechanical parts using $L_{CR}$ waves and it was adapted to control the whole process of calculate the acoustoelastic coefficient. The program is called L-stress v. 1.0 and it was written in LabView v. 6.1, a graphical programming language developed by National Instruments. LabView uses the concept of Virtual Instrument (VIs) that is each program is a VI. L-stress is based on the package of VIs (libraries and drivers) that came with the data acquisition board or on those that are free to download on Internet. It was registered in the patent office of Brazilian government.

The data acquisition board (NI 5911) uses internal and external trigger and it is able to get data at 100 MS/s using its single channel. L-stress can be used with other boards, provided the LabView drivers are available. Most of oscilloscope boards have those drivers.

L-stress is made with five screens, posted in folders. The first folder is where the program and the authors are presented. The second is used to define the basic data for the process; so one can chose the number of load steps, how many measurements by step and the maximum hydraulic pressure to be applied. This last parameter will be used in future, to control also the hydraulic application of the force using another digital board. There are controls to set the materials properties, as Young's Modulus and Poisson coefficient. The number of waves that will be averaged in each measurement is also set using this folder. It is necessary because previous works shows that the noise could be removed averaging at least five waves. Preventing a future possibility of having a pulse-receiver plugged directly in the computer PCI interface, the program allow one to set the pulse-receiver gain and the energy of the pulse.

The basic functions of a digital oscilloscope are presented in the third folder, showed in Figure 5. This screen was based on the original VIs that came with the board, after modifications to reach our goals; some new features were included. The data acquired can be seen in the graphic placed in the upper left side of the screen. Data acquisition rate, number of data points, trigger controls and board settings are in the right upper corner. There is also what we called the progress indicators; witch is placed on the lower left side. They show the level of pressure in each acquisition and the number of the wave that is been acquired. After each wave acquisition, it is necessary to press the button "Nova Aquisicao", witch can be used only after the current acquisition finish. The waves acquired in each step are averaged and a new button called "nova pressao" appear on the screen; one should set the new pressure level manually using the pump and click on that button for new readings. When the final pressure level is achieved, the button will not appear again.

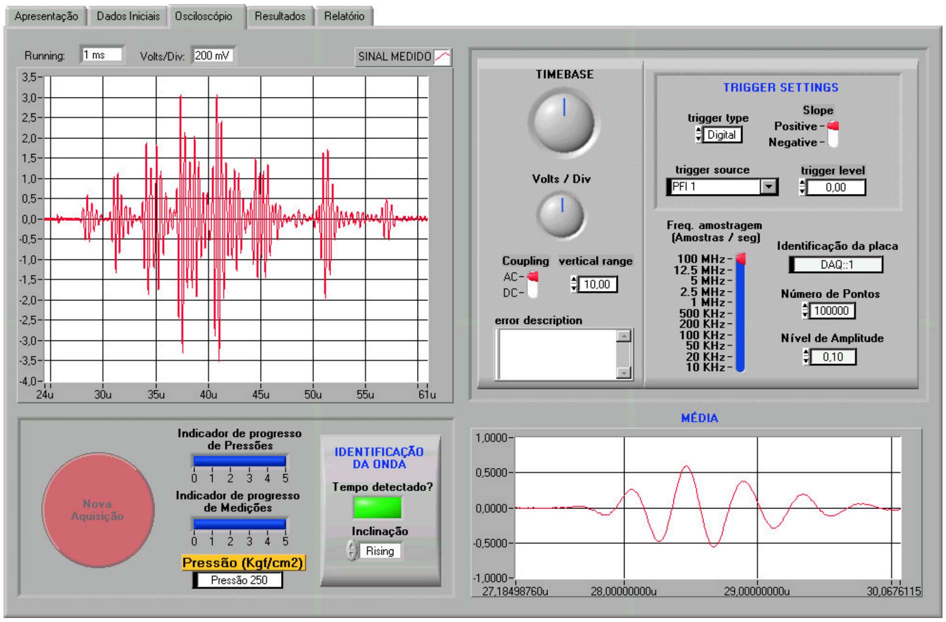
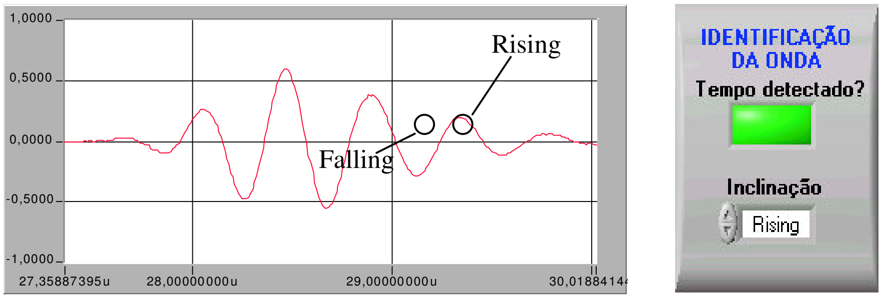

Running: 1 ms
Volts/Div: 200 mV
trigger type: Digital
trigger source: PFI 1
trigger level: 0,00
vertical range: 10,00
Identificação da placa: DAQ::1
Número de Pontos: 100000
Nível de Amplitude: 0,10
Inclinação: Rising
Pressão (Kgf/cm2): Pressão 250

Figure 5. Third screen of L-stress, showing the functions of a digital oscilloscope and a group of additional controls

The averaged wave is plotted in a graphic placed in the lower right side of the screen. One zoomed plot is shown in Figure 6. To get the right wave, the first one in the trains of waves showed in the Figure 5, the user should inform the program about the amplitude level. It means that the program has to know how higher is the reference point, placed on the first maximum of the wave. The program uses that value to locate the time when the signal cross the zero amplitude to all averaged waves and record the same data point to calculate the travel time in every step. If the amplitude setting is too low, the program could take noise as the wave signal. If the amplitude is too high, the program could miss the first wave and take other with large amplitude. The first wave to arrive is the $L_{CR}$ wave.

The time of flight can be taken in the first zero crossing or in the second. The user can set one or another using the appropriate control to choose between "Falling" and "Rising", as shown in Figure 6. The control is shown on the right side of the same figure. The same control shows the indicator in green when the program is able to find the reference; red is shown when the reference cannot be found and the user should check the amplitude setting.

The results are presented in the following screen; witch is unblocked after the last step of measurement. That screen shows the applied pressures, the number of data, the times acquired and the applied stresses, calculated from the hydraulic pressure. The folder has three pages (figure 7). The first shows a plot of the calculate stresses against applied pressure and it is used when the acoustoelastic coefficient is know and is been checked. It also show the stress calculated using the hydraulic pressure and the user can compare both results.

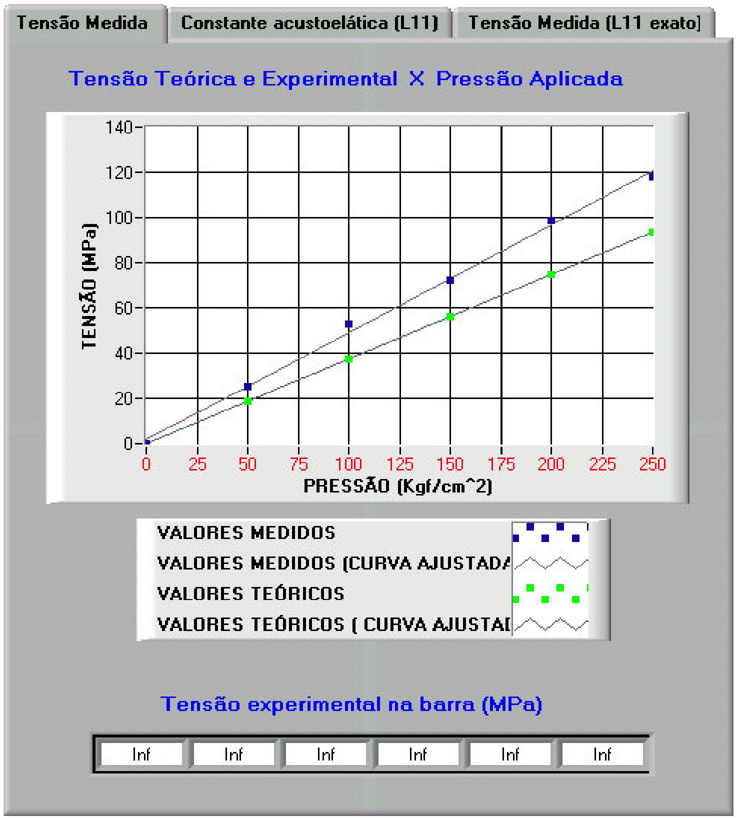


IDENTIFICAÇÃO DA ONDA

Tempo detectado?

Inclinação: Rising

Figure 6. Averaged wave (left) and the controls to detect the right data point for travel time measurements (right).



Tensão experimental na barra (MPa)

Inf Inf Inf Inf Inf Inf

Figure 7. Results Folder with the first of its three pages showing the plot of calculated and measured stresses against the applied hydraulic pressure.

The second page shows a plot of calculated stresses against experimental ones. This graphic is used to estimate the acoustoelastic coefficient. Minimum square method is used to calculate the best fit and the correct values. The third page is similar to the first one, but the measured stresses are calculated using the correct acoustoelastic coefficient, found in the second page.

When the user aims to measure stresses using L-stress software, he has to inform the $L_{11}$ value in the second folder. If the value is not informed or is zero, the program will understand that it is been used to determinate the acoustoelastic coefficient. In that case, the array of values showed in the lower side of Figure 7, page 1, will not be fulfilled and the word "Inf" will be shown in every cell. That's because the coefficient will be calculated only in the second page and the values will be shown in the third one.

The last folder is the report. It is a summary of the tests. The user has to identify himself or the person who is responsible by the experiment and register the date. The data about the pulse-receiver settings and a table with the final results will also be shown. The user has the option of printing or recording in digital media. After that decision, the user can restart the tests or close the program.

It is important to note that the program controls the whole process alone. Once the initial variables are defined, there is no need of an operator. Actually, because the mechanical system is not fully automated, the operator needs to increase the pressure between load steps. New developments will include a new digital board and a hydro pneumatic system to change the load between steps and the systems will be complete.

## 6. Results

Two sets of experiments were accomplished to test the efficiency of the system. The first one aimed to find the acoustoelastic coefficient for special steel, used in gas pipelines, and the other to evaluate aeronautic aluminum.

### 6.1. Acoustoelastic Coefficient for API 5L x70

These initial tests are part of a project to evaluate stresses in welds of pipelines using ultrasound. The first step is to find the acoustoelastic coefficient. Only the initial evaluation of the system is shown here and so the results are not final. They are meant to check if the system responds and if the measurements sound.

The maximum applied pressure was 300 bar and it was applied in six steps. It means that the force applied to the bar varied from 0 to 86000 N and the stress from 0 to about 113 MPa. Table 1 shows the results for travel times in nanoseconds. The first line, denoted as P (bar), presents the applied hydraulic pressure. The following lines present the travel times for each one of five measurements in each load step. The average and the standard deviation are also shown.

The sensitivity of the method was evaluated before the measurements using equation 5. Because the coefficient was not known, we used the value for regular carbon steel 1020. Bray and Stanley (1997) reports the value $L_{11}$= 2,38 for that steel. Using this value, the Young´s Modulus and the time $t_o$ for the same steel, the sensitivity is 4,6 MPa/ns. It means that a standard deviation of ten nanoseconds implies that we have 65% of chance to have the stress between ± 46 MPa of the estimated value. The value is about 15% of the yielding limit for 1020. This is not a very precise result, but it is what we have.

Table 1. Travel times for each load steps for API 5L x70.

| **P (bar)** | **0** | **60** | **120** | **180** | **240** | **300** |
|---|---|---|---|---|---|---|
| 1 (ns) | 27850,5 | 27855,3 | 27860,6 | 27859,4 | 27861,8 | 27859,0 |
| 2 (ns) | 27853,9 | 27855,9 | 27859,8 | 27860,8 | 27861,0 | 27867,9 |
| 3 (ns) | 27846,6 | 27854,1 | 27856,7 | 27857,4 | 27861,9 | 27868,5 |
| 4 (ns) | 27850,9 | 27855,2 | 27858,6 | 27857,1 | 27860,6 | 27865,7 |
| 5 (ns) | 27850,1 | 27853,1 | 27858,2 | 27858,6 | 27864,3 | 27864,4 |
| ***Average (ns)*** | ***27850,4*** | ***27854,8*** | ***27858,8*** | ***27858,7*** | ***27861,9*** | ***27865,1*** |
| STD | 2,59 | 1,08 | 1,48 | 1,52 | 1,43 | 3,78 |

The results show a maximum standard deviation of about 4 nanoseconds. Using the previously calculated sensitivity, we have 65% of chance to have the stress between ± 18,0 MPa of the estimated value. That is a better result; specially considering that the steel we are testing has Yielding limit about 380 MPa and that 1020 steel limit is about 280 MPa. It means that the standard deviation is about 5% of the Yielding limit. It is important to note that this analysis is about the variation in just one load step and do not take account the dispersion caused by the non linearity.

The value of the acoustoelastic coefficient can be found using the program. For this single measurement in just one bar, the value found was 1,46. Tests reported by Caetano (2003) and Andrino (2003) showed that the correct value for that material is 1,52 and that the standard deviation related to the linearity is about 7,3%, what makes our result very reliable. Using $L_{11}$ = 1,46, the sensitivity changes again and the standard deviation increase to about 8%.

Figure 8 shows the comparison between the measured and the applied stresses. There is a little bit of instability near zero stress but there is a clear correlation between them. The correlation coefficient ($R^2$) is about 0,93.

### 6.2. Acoustoelastic Coefficient for Aeronautic Aluminum

The same procedure was used to evaluate 7050 Aluminum. The bars were thicker than steel bars and the applied stresses were calculated for their cross-sectional areas. The maximum hydraulic pressure was 200 bar and we used just four steps.

Table 2 shows the results. The standard deviation is also about 4 nanoseconds. The acoustoelastic coefficient found using this bar is 1,94. This value is not coherent with the values reported by Santos et al. (2003), witch found values of 2,66 and 2,95, depending on the rolling direction.

Figure 9 shows the comparison between the measured and the applied stresses. There is also instability near zero stress but there is a clear correlation between them. The correlation coefficient ($R^2$) is also about 0,93.

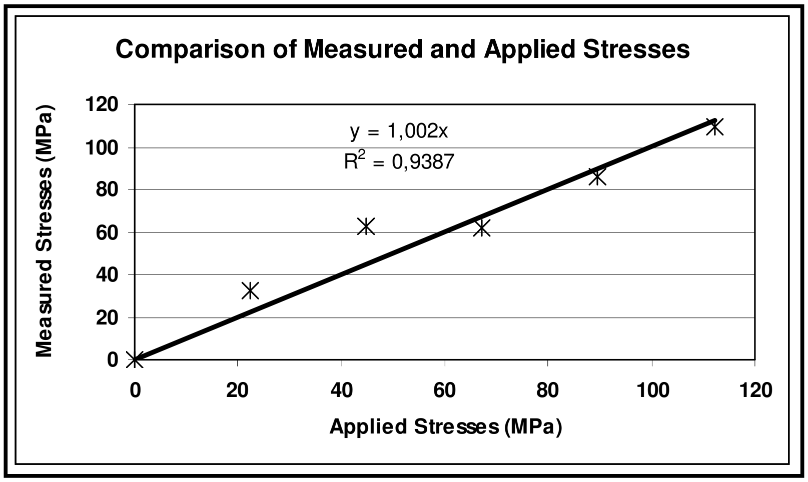


Figure 8. Comparison of Measured and Applied Stresses using the acoustoelastic coefficient $L_{11}$ = 1,46 for API 5L x70

Table 2. Travel times for each load steps for Aluminum 7050.

| **P (bar)** | **0** | **50** | **100** | **150** | **200** |
|---|---|---|---|---|---|
| 1 (ns) | 27758,3 | 27766,5 | 27776,0 | 27788,6 | 27804,4 |
| 2 (ns) | 27764,9 | 27765,1 | 27773,9 | 27786,5 | 27803,4 |
| 3 (ns) | 27763,4 | 27761,6 | 27775,9 | 27788,4 | 27803,6 |
| 4 (ns) | 27758,5 | 27762,7 | 27776,6 | 27786,0 | 27801,7 |
| 5 (ns) | 27756,5 | 27763,1 | 27774,4 | 27789,1 | 27803,4 |
| ***Average (ns)*** | ***27760,3*** | ***27763,8*** | ***27775,4*** | ***27787,7*** | ***27803,3*** |
| STD | 3,6 | 1,9 | 1,1 | 1,4 | 0,9 |

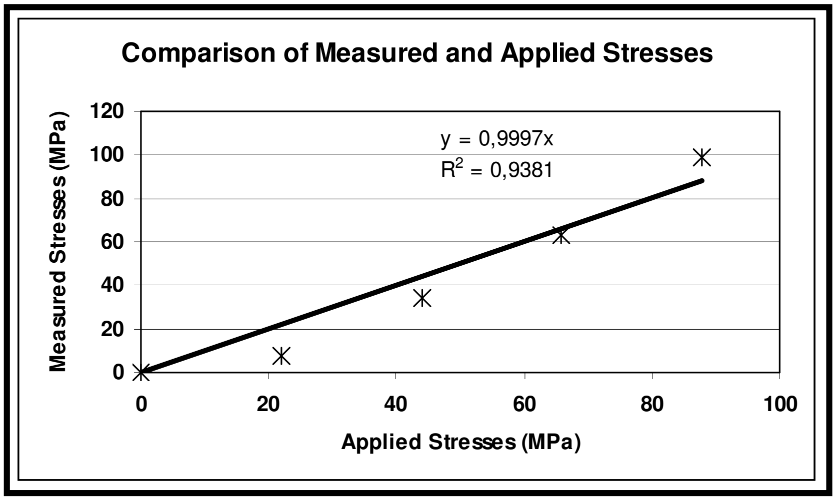


Figure 9. Comparison of Measured and Applied Stresses using the acoustoelastic coefficient $L_{11}$ = 1,94 for Aluminum

## 7. **Conclusions**

This work presented an automated system to evaluate acoustoelastic constants of metallic materials and to measure stresses composed by a tensile stress fixture, an ultrasonic probe for longitudinal waves, a pulse receiver, a computer based data acquisition system and a program specially developed, called L-stress v.1.0.

The results of measurements taken from two different metals, API 5L x70 steel and 7050 aluminum, showed that there is a clear correlation between the measured and the applied stresses and that it is possible to find the acoustoelastic coefficient using the system. However, those results showed high dispersion, especially at lower values of stresses. Some factors could influence the dispersion, like non-homogeneity of the bars, anisotropy and residual stresses.

Although the systems still needs further developments and optimization, the results shows that there is a response of the ultrasonic system when stress changes and that it is possible to estimate the stress value for metallic materials using the proposed system.

Some new features will be installed in the system in near future. The most important are the mechanical actuators and the digital controller, to make the system fully automated. A new pulse-receiver plugged directly in the computer is another improvement; it will make the settings easier and the user can set the energy and amplification through the program. L-stress will be able to generate a data sheet with all previously tested materials and check if new tests are coherent with old ones. Also, the uncertainty will be recorded and calculated by the program, using classical methods.

## 8. Acknowledgements

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