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The stresses and strains imposed on mechanical components can result in mechanical failures. Such stresses can be applied, pre-existed, or both. The pre-existed stresses, also known as residual stresses, result from internal residual strain caused by elastic energy within the mechanical element. In metals, they are generated during the thermomechanical processing of the material [1-2] or loading in service. In composites, the concept is not the same and residual stresses are not expected to perform a role as significant as for the metals in the failure process. Notwithstanding, for both type of materials, the applied stresses in service plays an important role in the expected life. This study aimed to evaluate stress in aircraft structural components based on the acoustoelectric effect. The study concentrated efforts in the structural materials, emphasizing Aluminum and composites. The method used L_{cr} waves (p-waves) as the main tool. The final objective was to evaluate the suitability of such method to be used on-board in the future, after further development.

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FINAL REPORT

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INTRODUCTION

The stresses and strains imposed on mechanical components can result in mechanical failures. Such stresses can be applied, pre-existed, or both. The pre-existed stresses, also known as residual stresses, result from internal residual strain caused by elastic energy within the mechanical element. In metals, they are generated during the thermomechanical processing of the material [1-2] or loading in service. In composites, the concept is not the same and residual stresses are not expected to perform a role as significant as for the metals in the failure process. Notwithstanding, for both type of materials, the applied stresses in service plays an important role in the expected life.

On-boar health monitoring of aircrafts requires reliable inspection systems, protected against environmental changes and damages caused by loading. Knowing the stress in critical spots give the flight commander the information required to take decisions about what action would be performed. Also, knowing the plastic damage in selected spots allows the maintenance personnel to predict when the component should be serviced or replaced.

Because most of the methods of measuring stresses are destructive, they cannot be used with aircrafts. Strain gages can be used, but they are not adequate for most critical locations. Besides, they are fixed transducers, which cannot be used in another place after the first measurement, so a large amount of them is required to inspect structures like in aircrafts. Thin-solid films have the same limitations. Nondestructive methods, like X-ray and neutron diffraction usually do not meet the safe requirements.

Among those non-destructive techniques for measuring stresses, one notable for its low cost and portability (for field applications) utilizes ultrasonic waves. It also allows easy and fast measurements, has good resolution, and is safe. Measuring stresses with ultrasound is possible from what is known as the acoustoelastic effect. The acoustoelastic effect relates the strain of a body subjected to a static state of stress with the propagation speed of elastic waves in it [3].

To measure stress, we can apply acoustoelasticity employing three main techniques: Rayleigh waves, acoustic birefringence, and critically refracted longitudinal waves, or L_{cr} waves. The Rayleigh wave technique relies on the main characteristic of this waves—the propagation in the surface of the medium—and is thus suitable for surface stress measurements. Researchers have applied Rayleigh waves with adequate results [4-7] to investigate both external and residual stress measurements. The acoustic birefringence technique relates the stress to the difference in speed of two ultrasonic shear waves propagating in the same direction, but polarized in orthogonal directions [8-11]. L_{cr} waves are longitudinal subsurface waves (body waves) and are less sensitive to surface imperfections than Rayleigh waves. Since they are longitudinal, L_{cr} waves are more sensitive to stress variations [7, 12-14].

According to acoustoelastic theory, a change in wave velocity is related to stress by acoustoelastic coefficients, which depend on the second- and third-order elastic constants of the material. We can use these constants to calculate the acoustoelastic coefficients or obtain them experimentally by applying a known stress and then measuring the variation in the wave speed [15-19].

Because the elastic properties of a material directly influence the acoustoelastic effect and the former may differ according to direction, materials with dissimilar properties in different directions answer differently to the wave propagation. In metals, the non-uniformity results, in part, from the manufacturing process. An example of a process that generates these differences is rolling. Rolling is used in the manufacturing of aircraft Aluminum, where alloys for coatings and structural reinforcements are laminated. This process produces a symmetry known as orthorhombic, allowing us to classify the material as orthotropic [18]. In composites, the actual distribution of the fibers is the factor that influences the non-uniformity of the material. For many of the structural parts nowadays used, the fibers are oriented in just one direction, leading to a complete different set of speed results depending on the wave type and its propagating direction.

Most researchers working with applied stress measurements using ultrasound ignore the anisotropy generated by rolling in metals [19-20]. Instead, they relate stress and wave velocity using an isotropic model. This is done mainly because such a model is simple and because, even for second-order elastic constants, the anisotropy generated by rolling is generally weak [15]. The problem with this method is that third-order elastic constants can also influence the results. However, when using longitudinal waves propagating in the direction of the unidirectional applied stress, it is expected that the anisotropy has small effect on the results, since the elastic properties in the main directions are known. A study is required to analyze the texture effect. For composites, these assumptions require even deeper studies.

As stated before, the L_{cr} method seems to be the correct selection to measure stresses in many instances. It can be used for metallic parts, as shown by Pereira Jr. [21] in his MSc thesis, like Aluminum or other lighter metallic components. Because the composites are usually applied in thin plates or slender beams, the L_{cr} is also an adequate alternative, since the longitudinal wave travels about one wavelength from the surface.

This report describes the findings of the Acoustoelastic Laboratory of University of Campinas, in the tentative of answer two main questions: Can L_{cr} method give the information required when used to inspect stresses in aircraft structural metallic components? Can we inspect composites structural parts using a similar L_{cr} based measurement technique? Those questions motivated the development of a scientific research sponsored by the Air Force Office for Scientific Research with a grant of $ 69,420.00 for a three year period, started in April 2010. The report shows the objectives and methodology, the development of the study, the answers found, and the proposal for new studies.

Objectives

The study aimed to evaluate stress in aircraft structural components based on the acoustoelastic effect. The study concentrated efforts in the structural materials, emphasizing Aluminum and composites. The method used L_{cr} waves (p-waves) as the main tool. The final objective was to evaluate the suitability of such method to be used on-board in the future, after further development.

METHODOLOGY

The methodology presented in the proposal is described as follows. It has seven steps and, as already mentioned in the previous report. As can be seen, the targets for each step were fully accomplished.

a. Reviewing of the state of art. In this first step we intended to know the systems used in the present, their characteristics and limitations. We would also search for researches in the area to learn how we can contribute to the safety of the aircrafts, through their papers and reports or direct contact.
b. Selection of the materials to be studied. The Aluminum was the main focus of study. The Aluminum was our main focus of study. We would ask AFOSR to select a composite to be evaluated too, but, instead, we consulted Brazilian companies in the aeronautic area to find which material would be more adequate for our study. Regarding the format of the parts to be studied, our main focus would be on plane surfaces, like sheets to make aircraft hulls.
c. Development of the inspection system. This step required the selection of the commercial products to perform the experimental evaluation, and the development of those that cannot be bought; the assembly of the system; initial tests, and calibration for each material under evaluation.
d. Development of the routines for data treatment. Because of the dispersive nature of the measurement in non-uniform materials, especially in composites, we would work to implement the best routines to get the useful results. It would require fundamental research about wave propagation and signal processing. There was no guarantee that we could inspect composites with such technique, so the study would also evaluate different strategies, aiming to get adequate results. To change the type and characteristics of the sensors was one of the possibilities.
e. Tests for influence factors. The main factors at that time identified for measurements with L_{cr} waves were temperature, surface uniformity, texture (metals), and system characteristics, like transducer natural frequency, size, probe size, and so on. We would look for new factors and evaluate the influence of them with the already known.
f. Application of the system to evaluate the stress and strain in the structural components. After controlling the influence factors, we would evaluate the behavior of L_{cr} wave in the selected materials and study the viability of applying the method in the inspection.
g. Final report and technical communications. The papers to communicate our results would be submitted at this point of the research. The information to be included would depend on the AFOSR authorization. The final report would also be issued at this time, including suggestions to future research works and developments.

The initial schedule proposed would cover 24 months total.

DEVELOPMENT

The development of the study followed the methodology presented above. As mentioned before, the initial schedule would cover 24 months total. Because of some delay in the processing of the funds sent by the US government inside Brazilian Finance System, the period for this research ranges from April 2010 to April 2013.

To describe how the research was performed and the results, each step of the methodology is discussed in this section, including the references for the sources, when applicable. They are:

a. Reviewing of the state of art.

This step included the search for advances about acoustoelasticity, including equipment, papers about innovations, composites, and methods for stress measurement. The results of this research allow the developing of three MSc. Theses, two Undergraduate Scientific Researches and two undergraduate final works. The complete review can be consulted in the Theses. Unfortunately, the theses are in Portuguese, but most of the references are in English and can be consulted if necessary. The documents are in the following links:

- Author: Tainá Gomes Rodovalho – Sponsor: AFOSR
  http://www.bibliotecadigital.unicamp.br/document/?code=000871644

- Author: Rodrigo Junqueira Leão – Sponsor: AFOSR
  http://www.bibliotecadigital.unicamp.br/document/?code=000871675

- Author: Paulo Pereira Júnior – Sponsor: CAPES - Brazil
  http://www.bibliotecadigital.unicamp.br/document/?code=000812437

We also included the theoretical development in those theses and in other documents cited in this report. The main development in this area was to understand and list in a clear format how we can measure stresses using the wave speed. The Thesis of Eng. Pereira Jr [21], the third cited above, describes deeply the theory about it.

b. Selection of the materials.

After consulting the people who work directly with manufacturing of aeronautic parts, we decided to choose Aluminum alloy 7050, used as structural parts. We also decided to use carbon fiber composites with epoxy matrix (HexTow® AS4 / Hexply® 8552) in the form of sheets. The fibers are arranged one directionally, as in most structural parts.

The research had two main branches: analytical/numerical simulations and experimental evaluation, both of for Aluminum and composite. The first looked to understand the effect of stresses in wave propagation trough simulations. Experimental work aims to measure the effect of applied stresses on the selected structural materials taking in account all effects. Provided our numerical models fit the experiments adequately, we expected to refine it progressively until we can simulate the behavior of the structural materials in service conditions, in a future research.

Before conducting experimental work, experimental plans were developed. We needed to know if the wave speed was sensitive to the stresses, so we had to build samples of both materials that could be measured in two situations: with and without stresses. Besides, we had to develop samples to get other parameters associated with the measurement processes, like the elastic constants and the effect of the rolling direction (Aluminum) and fiber direction (composite).

We also have to develop the models to the simulations. Because of the lack of experience and knowledge about this subject, we decide to employ the models presented in the literature and improve them according to our needs, if necessary.

Samples for experiments

In this section, to facilitate the understanding of the report, we present the main samples employed in the tests performed.

The Aluminum samples were mostly in the format of bars, as shown in Figure 1. They were extracted from a rolled sheet bought in the market, but the study of the elastic constants involves several different formats of samples, as shown in Figure 2. Of course, care was taken to do not introduce stresses in the bars during cutting processes. In this case, we did not perform a thermal process for stress relief, as we use to do with steel. This could lead to slight different initial stresses in each bar, but not to different response to applied stresses.

The bars were used to find the acoustoelastic coefficient L^1_{11}, which is employed in the calculation of the stresses from Equation (1) using longitudinal waves. In that equation, υ_1 is the wave of a longitudinal speed propagating in the main principal direction; ε is the deformation; σ_1 is the stress in the principal direction; E is the Young's modulus. The same bars where used to verify the effect of the influence variables, like temperature, as will be presented later in this report.

$$\frac{dv_1^{(1)}/v_1^{(1)}}{d\varepsilon} = \frac{E\left(dv_1^{(1)}/v_1^{(1)}\right)}{d\sigma_1} = L_{11}^1 \Leftrightarrow d\sigma_1 = \frac{E\left(dv_1^{(1)}/v_1^{(1)}\right)}{L_{11}^1} \qquad (1)$$

The development of equation (1) can be seen in one of the papers published by our research group about the determination of the effect of the anisotropy in the wave speed [22]. It's worth to mention that the acoustoelastic coefficient for isotropic metallic materials can be calculated from the elastic constants or from the elastic properties, as show in Equation (2). In that equation, l, m and n (not showed) are third-order elastic constants; λ e μ are the Lamé's constants.

$$L^{1}_{11} = \frac{dv_1^{(1)}/v_1^{(1)}}{d\varepsilon} = 2 + \frac{\mu + 2m + \upsilon\mu\left(1 + {}^{2l}\!/\!_{\lambda}\right)}{\lambda + 2\mu} \qquad (2)$$

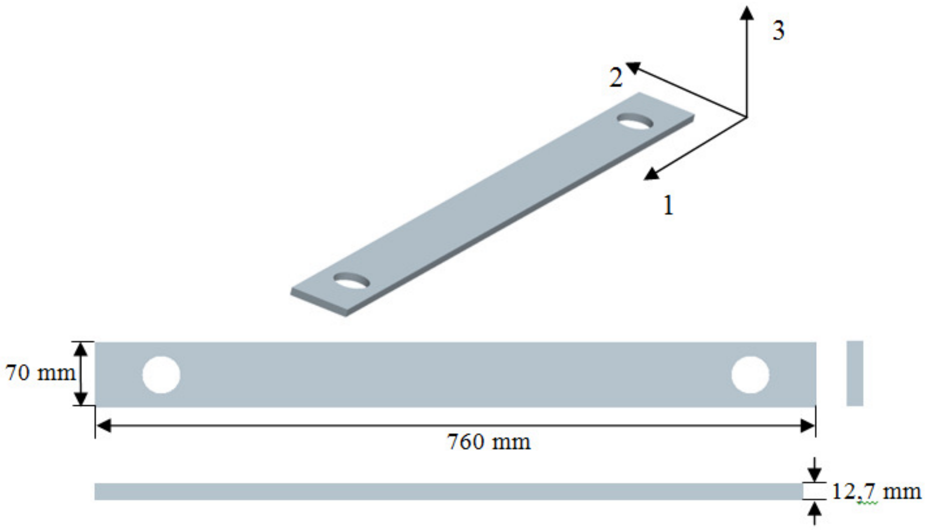


Figure 1 – Format of the Aluminum bars used in the AFOSR research [21]

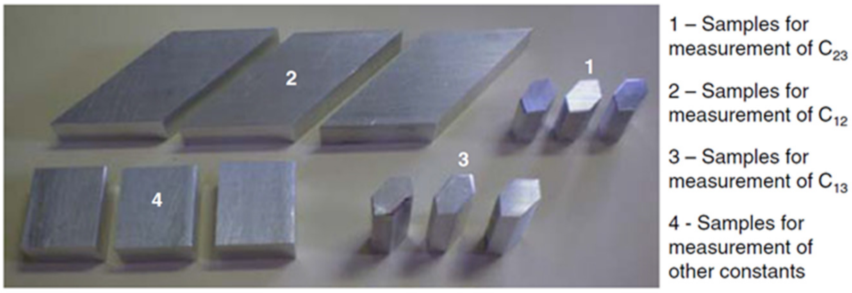


Figure 2 – Format of the Aluminum samples used to find the elastic constants [22]

The method we use for measuring stresses – the L_{cr} wave method, requires the wave hits the surface in the first critical angle. This angle is calculated using the Snell's Law and depend on the wave speed in the propagation direction. For isotropic metals that speed is known and can be found in published compendiums. For orthotropic metals the speeds can be measured. We did that with the Aluminum. However, for composites the wave speed strongly depends on the fiber direction. In braided composites, the effect is probably minimized by the fiber distribution, but for unidirectional structural composites we need to evaluate the wave speed in other directions away from the fiber's. This information would also be valuable to understand the response to stress in each direction.

So, the composite samples to evaluate the effect of the fiber direction was built in the format of a 24 side polygonal specimen. Figure 3 shows the sample.

For measuring stresses, the samples were similar to the bars for Aluminum tests. Figure 4 shows the bars (5) and the measurement probe. For the tensile test equipment to leave the fibers of the sample undamaged, it was necessary to bond aluminum plates (1) on it to minimize the effects of load grips. The contact of the fixing fixture could generate higher stress concentration points, favoring rupture in the region, and could also break the superficial fibers of the sample. The aluminum plates were fixed on the sample surface using Araldite® Professional, epoxy glue.

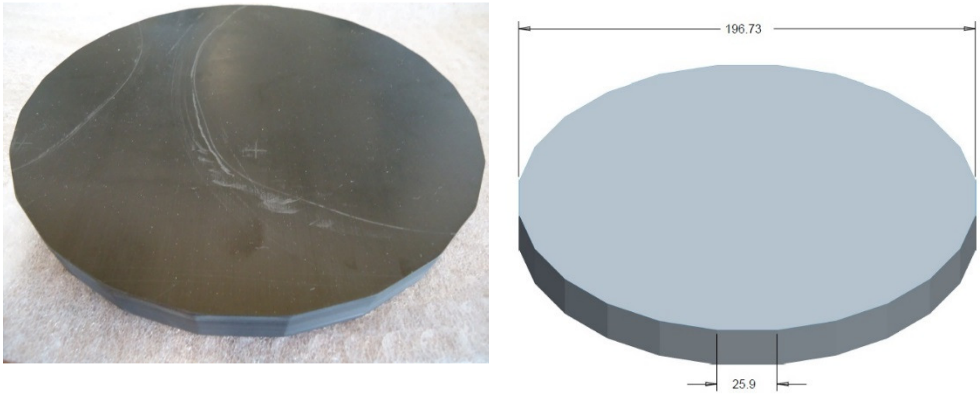


Figure 3 –Polygonal samples used to find the elastic constants [23]

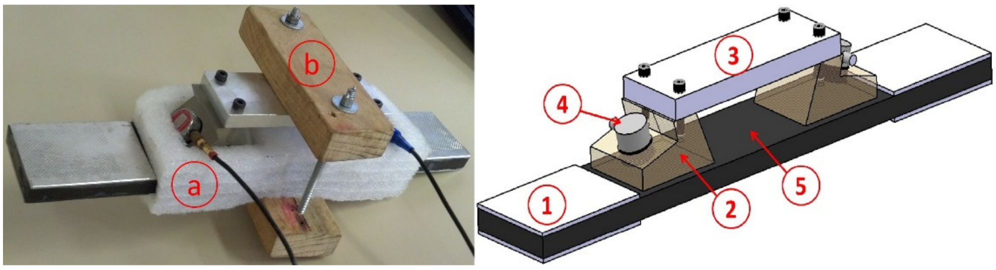


Figure 4 – Samples of unidirectional composites in format of bars for tensile stress tests

Because we used the L_{cr} wave technique, it was necessary to employ angled wedges (2). Those angles were the critical angles calculated using Snell's Law, as mentioned, and the polygonal specimen. The wedges (rexolite$^{@}$ shoes) were fixed to a connection bar (3) that blocked them from moving away. In the right side of the figure we show a positioner made of foam (a), used to keep the probe in the same longitudinal position, and the wood clamp, to keep the probe in contact during the measurements. Both parts were necessary because we used a vertical tensile stress machine and the probe could fall from the composite bar.

The composite samples used in our tests were manufactured by GME Aerospace, a Brazilian company that produces parts for the aeronautic industry. As mentioned, they were made with material composed of carbon fibers (HexTow® AS4), unidirectional, pre-impregnated (prepreg) with epoxy matrix (HexPly® 8552 from Hexcel®). Table 1 shows the materials' properties.

The process of manufacturing the composites follows very strict rules for aerospace materials. The process includes numerically controlled cutting and autoclave in vacuum as showed in Figure 5. Details about the process are in Ms. Rodovalho Master Thesis [23].

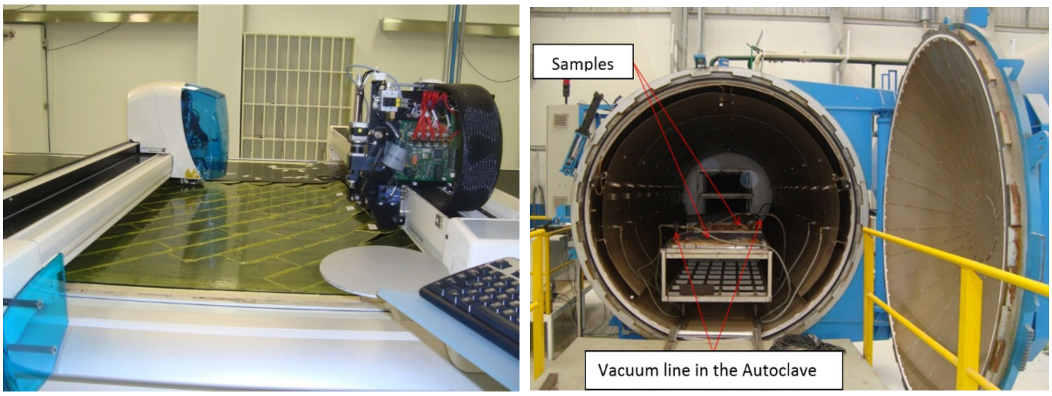


Figure 5 – Manufacturing of composite parts. Left: cutting machine. Right: Autoclave

Table 1. Physical and mechanical properties of prepreg Hexply® AS4/8552

Lamina density (g/m³)	1.59
Nominal fiber volume (%)	58.52
Lamina thickness (mm)	0.187
Longitudinal elastic modulus (GPa)	142
Transversal elastic modulus (GPa)	9.5
Shear modulus (GPa)	5.0
Longitudinal tensile strength (MPa)	2336
Transversal tensile strength (MPa)	81
Shear strength (MPa)	114

c. Development of the inspection system.

The system is basically the same for both, metal and composite applications. It was derived from the one already used for railroad wheels and oil pipes. The differences were on the transducers: Aluminum required 5 MHz transducers [16] and, for composites we used 1 MHz. Before deciding which frequency we should use, several lower and higher frequencies were tested for both materials.

Figure 6 shows one of the arrangements used, in this case, for composites. Similar probes were used for Aluminum, but the angles of incidence in the shoes were different. Details about the system for composites can be seeing in the paper "Stress analysis in carbon/epoxy composites using Lcr waves", recommended for publication by the reviewers of Journal of Composite Materials and attached to this report in the recommended version. Figure 7 shows one of the many arrangements used with the complete system along the measurements. In that case, it was used to measure the wave speed in the polygonal specimens.

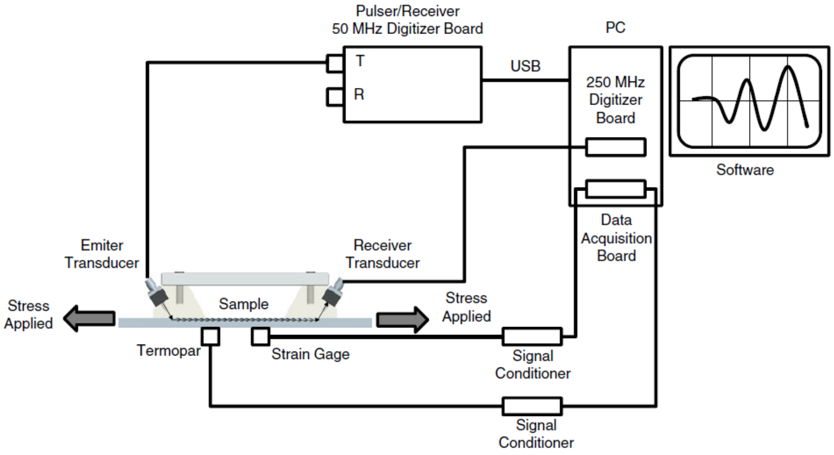


Figure 6 – Scheme of the system to measure the effect of stresses in the wave speed.

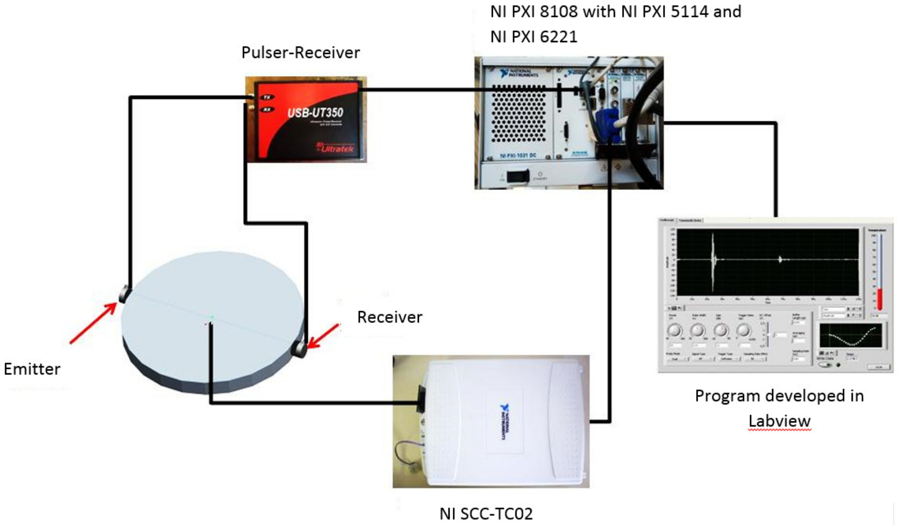


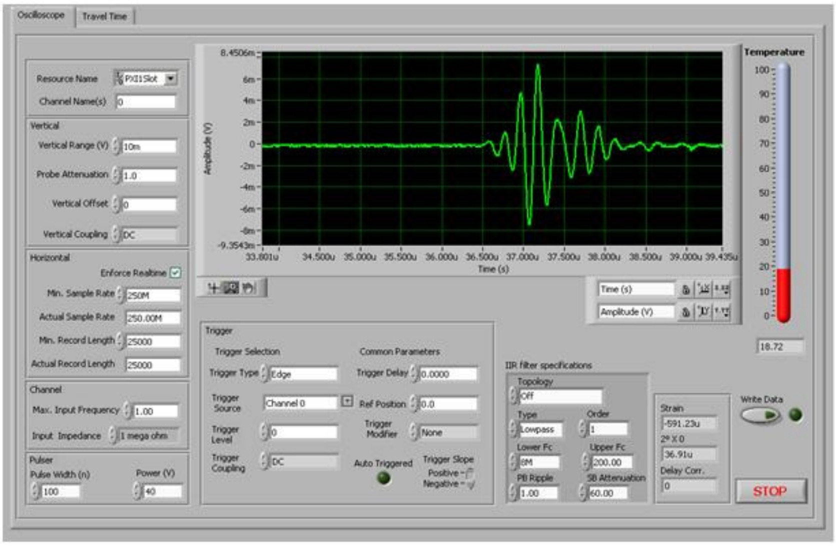
Figure 7 – Complete system used to measure the wave speed for composite polygonal samples.

d. Development of the routines for data treatment.

When we started to study the possibility of using L_{cr} waves to measure stresses in aerospace materials, we already have confidence (based on previous experiments and literature) that we could get results in Aluminum, but we would need to improve the method. However, the measurement in composites was totally new for our group. So, we had to study the ways to obtain useful data from the measurements. The result of this study generated a paper submitted to ASME IMECE 2013 (Comparison of signal filtering techniques for ultrasonic waves used in inspection of composite materials), attached to this report. There we compared the techniques based on digital filters IIR (Infinite Impulse Response), FIR (Finite Impulse Response), and Discrete Wavelet Transform (DWT).

The results showed that for the bulk longitudinal and L_{cr} wave propagating in most directions in the composite polygonal samples, the filters IIR and FIR presented better results than the DWT, aiming significant improvement in the Signal to Noise ratio (SNR). For bulk waves, the mean improvement in SNR where the FIR filters had the best results was 61%; for the IIR filters the improvement was 27% and 38% for the DWT. Only in one direction of propagation, 15° in relation to the fiber direction, the DWT had better results. However, analyzing the waveforms after the signal processing, it can be seen undesirable distortions in the waveform. This kind of effect does not happen when we use digital filters.

These findings were used to improve the programs developed for data acquisition employing the L_{cr} waves, as the one who the main screen is shown in Figure 8.



Resource Name PXI1Slot
Channel Name(s) 0

Vertical
Vertical Range (V) 10m
Probe Attenuation 1.0
Vertical Offset 0
Vertical Coupling DC

Horizontal
Enforce Realtime ☑
Min. Sample Rate 250M
Actual Sample Rate 250.00M
Min. Record Length 25000
Actual Record Length 25000

Channel
Max. Input Frequency 1.00
Input Impedance 1 mega ohm

Pulser
Pulse Width (n) 100
Power (V) 40

Time (s)
Amplitude (V)

Trigger
Trigger Selection
Trigger Type Edge
Trigger Source Channel 0
Trigger Level 0
Trigger Coupling DC
Common Parameters
Trigger Delay 0.0000
Ref Position 0.0
Trigger Modifier None
Trigger Slope
Positive - ☐
Negative - ☑

18.72

IIR filter specifications
Topology Off
Type Lowpass
Order 1
Lower Fc 8M
Upper Fc 200.00
PB Ripple 1.00
SB Attenuation 60.00

Strain -591.23u
2º X 0 36.91u
Delay Corr. 0

Figure 8 – Software developed to measure stress with L_{cr} waves.

e. Tests for influence factors.

The main factors identified for measurements with L_{cr} waves at the beginning of the research were temperature, texture (metals), and system characteristics, like transducer natural frequency, size, probe size, and so on. We would look for new factors and evaluate the influence of them with the already known.

After several studies, we reach the following conclusions:

i) The system characteristics influences for both Aluminum and Composites. So, any new equipment has to be calibrated to be used in wave speed measurements, for the resolution we require to get useful results. Notwithstanding, provided that we chose the equipment that responds adequately, we can get consistent results.

ii) Probe size influences on the how deep the wave travels. That information came from literature and our previous findings with API steel. In our evaluations for this research, all samples were tested under uniform traction. So, this factor would not influence. More studies are required to evaluate parts under bending.

iii) Texture for Aluminum was evaluated analyzing the differences in elastic properties in three main directions: the rolling one and two perpendicular ones. Table 2 shows the results determined using ultrasonic measurements. We employed two models to calculate them: Orthotropic and Isotropic, according with the literature. As can be seen, there is only small differences in the results. However, because L_{11} values are different, since they depend on third-order elastic constants, it is necessary to identify the rolling direction and correct the stress for any direction from it.

iv) Fiber direction is a major influence factor for composites, as expected. We built the polygonal specimens to evaluate it. The experimental plan of measurements allows us to know the influence of direction and temperature effects, simultaneously. Figure 9 shows the results. As can be seen, there is a huge effect of the direction, in comparison with the temperature. Because we are interested in the wave that propagates in the 0° direction, it is very important to identify it before the measurements.

Table 2. Elastic constants measured for Aluminum [21]

	Orthotropic	**Isotropic**		
Constant (GPa)	**Results**	**L^1_{11} averages**	**L^1_{11} maximum**	**L^1_{11} minimum**
C_{11}	111,4	111,3	112,1	110,3
C_{22}	112,1			
C_{33}	110,3			
C_{12}	57,0	57,4	57,0	57,9
C_{13}	57,9			
C_{23}	57,2			
C_{111}	-1.655	-1.655	-1.655	-1.655
C_{112}	-314	-374	-435	-314
C_{113}	-435			
L^1_{11}	**-3,95**	**-3,97**	**-3,75**	**-4,22**
Difference %		**0,4%**	**-5,2%**	**6,8%**

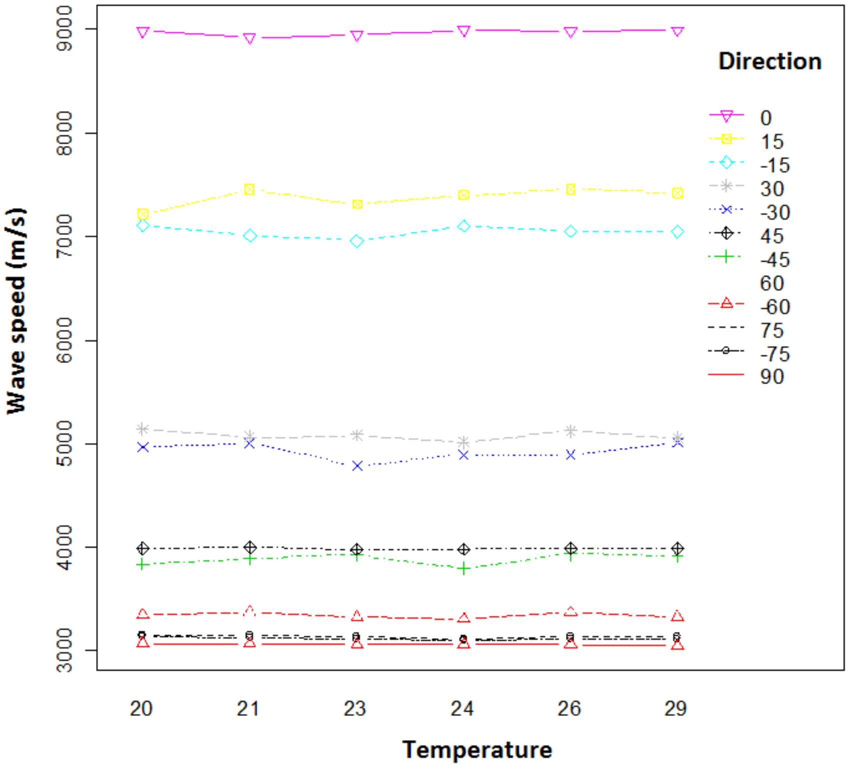


Figure 9 – Temperature (°C) and fiber direction effect on the wave speed for Composites of carbon fibers (HexTow® AS4), unidirectional, pre-impregnated (prepreg) with epoxy matrix (HexPly® 8552 from Hexcel®).

v) The lower effect of the temperature in comparison with the fiber direction does not mean that it is not important, for the resolution we need to measure the stresses.

So, several additional tests were performed to evaluate it. Figure 9 shows the effect of the temperature for fiber direction in two polygonal samples. In this case we used the time instead the speed, but the conclusions are the same, since the distance traveled by the wave is the same for all measurements. That distance can be slight different from one sample to another, what would explain why the results don't superpose each other. Beyond the limits showed we found larger differences and more studies need to be performed to evaluate why. Away from the fibers direction, there is a more intense effect of the temperature, but they are not required for stress analysis.

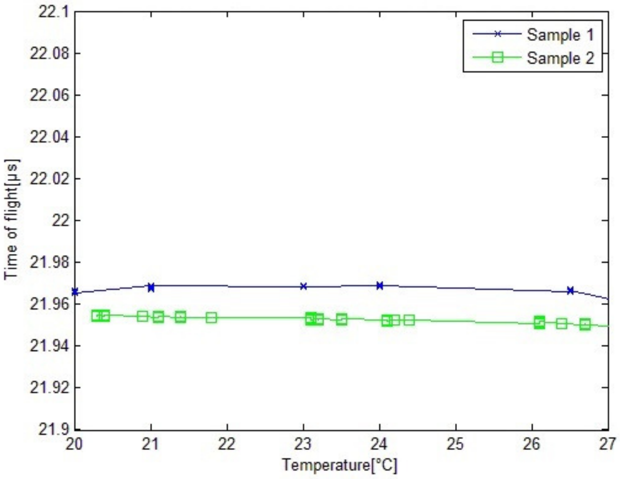


Figure 9 – Temperature (°C) effect on the longitudinal wave speed for Composites of carbon fibers (HexTow® AS4), unidirectional, pre-impregnated (prepreg) with epoxy matrix (HexPly® 8552 from Hexcel®).

vi) The effect of the temperature on longitudinal waves travelling in the Aluminum is shown in Figure 10. Differently from the composites, there is an identifiable effect of the temperature.

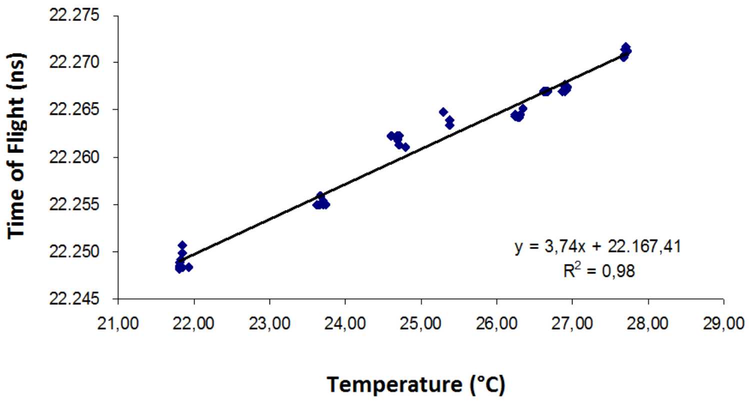


Figure 10– Temperature (°C) effect on the longitudinal wave time-of-flight for 7050 Aluminum.

vii) It is valuable to notice that the effect of the temperature is not only on the material under inspection, but also on the measurement system, especially the probe, which includes PMMA or Rexolite$^{@}$ shoes. That combined effect should be known and, in fact, it is more important than the effect on the particular material, because we want to correct our stress results for a particular system. The evaluation was performed for both materials and corrections are done. As an example, Figure 11 shows the effect of temperature for a particular system (and probe) on the Aluminum. That speed variation means 15.9 ns/°C and, by Figure 10, the parcel correspondent to the variation in the material is about 3.7 ns/°C.

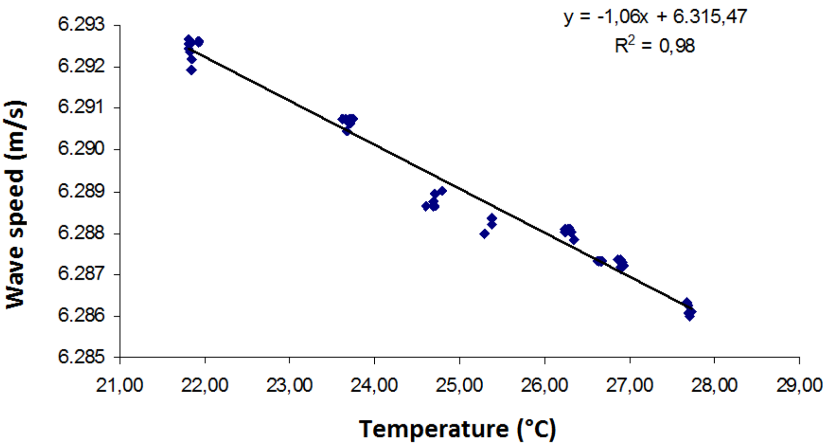


Figure 11– Temperature (°C) effect on the longitudinal wave speed and system of measurement for 7050 Aluminum.

f. Application of the system to evaluate the stress and strain in the structural components.

In this section we present the results for stress measurement using L_{cr} waves for Aluminum and the composite. The results shown are for experiments in which the influence factors were controlled or their effects are corrected.

Figure 12 shows the Aluminum response to stress applied in the rolling direction. There is a clear tendency. The small values in the vertical axle are to show that our system is able to measure such small variations. The calculated response is about 4 ns/MPa. So, the system is able to measure stresses in Aluminum, provided the influence factors are taken in account.

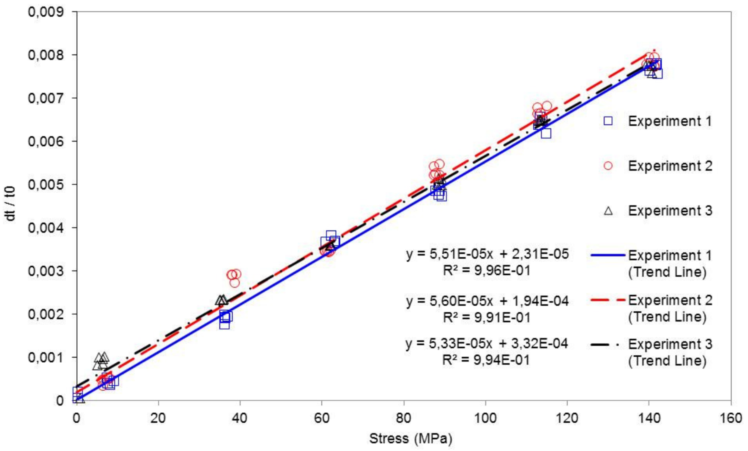


Figure 12 – Time of flight variation with the applied stresses for Aluminum 7050.

Figure 13 shows the Composite response to stress applied in the fiber directions. Three samples were tested. In that case, the plot show the time of flight variation multiplied by the longitudinal Elasticity Modulus (Table 1). The slope for all tendency curves ranges from 12 to 13. That is quite different from stresses applied at 45° and 90° from the fiber direction, which slope is about $3\ 10^{-3}$. This figure shows that the system is sensitive enough to be used as an alternative to measure stresses in similar composites.

Figure 13 also shows the main challenge still to be faced: the reference state, meaning "what is the time of flight for zero stress"? The difference of time between the zero stress and maximum stress for every sample is lower than the difference of the results for each of them at zero stress. Without knowing the time of flight reference (zero stress) for a particular sample we cannot calculate the magnitude of the applied (or residual) stress. At this time, we have no answer for that question.

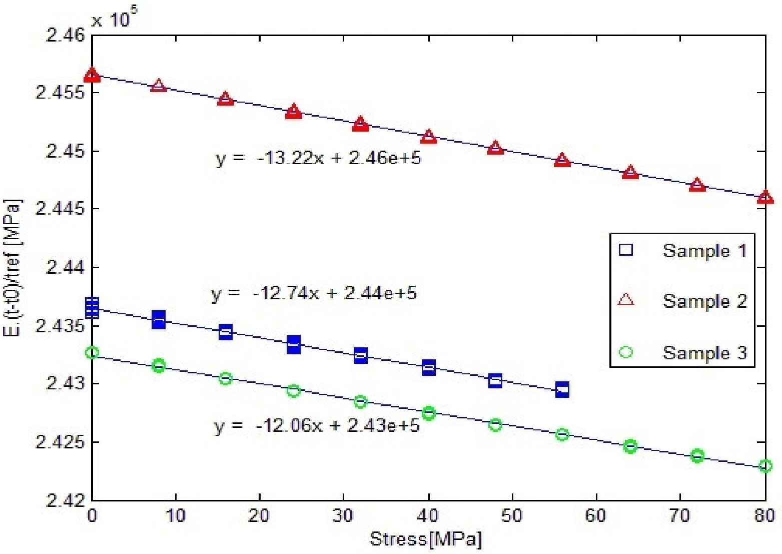


Figure 13– Time of flight variation with applied stresses for Composites of carbon fibers (HexTow® AS4), unidirectional, pre-impregnated (prepreg) with epoxy matrix (HexPly® 8552 from Hexcel®).

g. Final report and technical communications.

According the methodology proposed, this is the last report to be issued. Along the time of the development we submitted the papers listed below to be published. Some of them are directly linked to AFOSR, making use of the resources and personnel funding by this project.

- Stress analysis in carbon/epoxy composites using Lcr waves. Journal of Composite Materials. Recommended for publication after minor revisions (on the way).
- Influence of Anisotropy Generated by Rolling on the Stress Measurement by Ultrasound in 7050 T7451 Aluminum. *Experimental Mechanics*, March 2013, V. 53, Issue 3, pp 415-425.
- Application of Acoustoelasticity to Measure the Stress Generated by Milling in ASTM A36 Steel Plates. Accepted to be published: *Journal of the Brazilian Society of Mechanical Sciences and Engineering* (Impresso).
- Signal Processing Techniques for Ultrasonic Waves to Measure Stresses in Oil Pipelines. *ASME 2013 International Mechanical Engineering Congress & Exposition - IMECE 2013*. San Diego, CA, USA, Novembro de 2013. Accepted.
- Comparison of Signal Filtering Techniques for Ultrasonic Waves Used in Inspection of Composite Materials. *ASME 2013 International Mechanical Engineering Congress & Exposition - IMECE 2013.* San Diego, CA, USA, Novembro de 2013. Accepted.
- Desenvolvimento de um Goniômetro Ultrassônico para Estudo de Orientação Preferencial dos Grãos utilizando Ondas Longitudinais Criticamente Refratadas (LCR). *XI Congresso Ibero-Americano de Engenharia Mecânica (CIBIM).* La Plata, Argentina, Nov. 2013. Abstract accepted and full text submmited.
- Theoretical and Experimental Evaluation of the Penetration Depth for Lcr Waves in API 5L X70 Steel. *2012 Spring World Congress on Engineering and Technology (SCET2012),*

Xi'an, China. Proceedings of the 2012 Spring World Congress on Engineering and Technology. Piscataway, EUA: IEEE eXpress Conference Publishing, 2012. v. 2. p. 50-56.

- Effect if Mean Grain Size in The Time of Flight for Lcr Waves. *Proceedings of the ASME 2012 International Mechanical Engineering Congress and Exposition IMECE2012.* Houston, Texas, USA, 2012.
- Application of Critically Refracted Ultrasonic Longitudinal Waves (LCR) for the Inspection of Aluminum Alloys. *21th International Congress of Mechanical Engineering (COBEM 2011).* Proceedings of COBEM, 2011. Natal, RN, Brasil
- Analysis of the behavior of Lcr Waves propagating in Steel bars using Taguchi Method. *21th International Congress of Mechanical Engineering (COBEM 2011).* Proceedings of COBEM, 2011. Natal, RN, Brasil.
- Application of Design of Experiments to Evaluation the Propagation Speed of Lcr Waves. *5th Pan American Conference for NDT*, 2011. Cancum, Mexico. Proceedings of 5th Panndt.

As mentioned before, the results of this research allow the developing of three MSc. Theses, two Undergraduate Scientific Researches and two undergraduate final works

CONCLUSIONS AND FUTURE DEVELOPMENTS

At the beginning of study we intend to "evaluate stress in aircraft structural components based on the acoustoelastic effect", focusing in Aluminum and Composites. Based on this report, this research reach the objectives proposed. Besides, seven students were benefited using the resources of this project. Six of them received sponsorship and one used the equipment and knowledge. We also published part of the results.

As expected for any research, there are new challenges to be pursued until the time we can have a technique that can be employed for field measurements. The main one is certainly the reference time for stress measurement. Because all remaining influence factors were controlled, only the non-uniformity of the material is left to cause the zero stress dispersion. So, we will now focus on find nondestructive ways to evaluate the material, mainly using ultrasound, to correct this effect. The most promising technique at this time is the total focusing method (TFM), already used in commercial products for other applications. We would like to use it to "look inside" the material and see the differences that cause the dispersion. Them we intent to correct their effect in the stress measured, allowing calculating its right magnitude.

We already started the process of searching for the answers: a Ph.D. will work as a Post doctorate affiliate to the Lab in this subject and one of our Ph.D. students will stay at University of Bristol next year, both of them working with TFM and Phased Array applications. Besides, the main researcher of this project will stay at University of Michigan, Department of Aerospace Engineering, to study with some experts how to transform our technique in a product with field applications. We expect to have some interesting results in a couple of years.

The work with AFOSR was a very enriching experience. The technical staff was very professional and demonstrated to have knowledge about research. They were always at disposition to help to solve the difficulties, like when the Brazilian Financial Systems delays the transfer of the funds to the project. I hope to have many opportunities to work with them in the future.

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