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A metrological approach to measuring the Poisson modulus of aluminium samples using longitudinal and transverse ultrasonic velocities

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ABSTRACT
Destructive tests are widely used in the industry to determine the mechanical properties of materials. However, they are usually time-consuming, expensive, and can cause damage to the materials. In this context, nondestructive ultrasound tests emerge as a viable alternative to determine mechanical properties without harming the material. The main objective of this study was to determine the Poisson coefficient of aluminum samples, using nondestructive ultrasound testing. Additionally, a metrological approach was implemented to assess the quantities, and their respective measurement uncertainty was presented, showing a high confidence level in the results. The study also highlighted the economic viability of nondestructive ultrasound testing, as it does not cause damage to the materials and allows for the evaluation of multiple mechanical properties in a single test, saving time and resources. Furthermore, the test contributes to quality control in the manufacturing and service of materials, by detecting flaws and variations in their mechanical properties. In this work, the Poisson modulus was determined as 0.3488 and associated with a measurement uncertainty of 0.0133. The results demonstrated that the Poisson modulus determined in this work, following the resources on ultrasound tests, was consistent with literature data and technical standards. Therefore, it is reinforced that nondestructive ultrasound testing is reliable, safe, and efficient in characterizing the Poisson modulus, providing compliance and safety in using materials.

Section: RESEARCH PAPER

Keywords: Poisson; metrology; ultrasound; steel; carbon steel; uncertainty

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1. INTRODUCTION

Understanding the behaviour of the physical properties of materials has motivated the deepening of research that better delimits such properties. Among them, the Poisson modulus is one of the most important, related to material deformations in orthogonal directions. One of the methods for determining this property uses longitudinal and transverse ultrasonic velocity information [1]. This work presents a metrological approach to the determination of that property.

As shown in the literature [2], the transversal wave is more appropriate for characterizing the mechanical properties of metallic alloys. It is also demonstrated that the transversal wave rate decreases when the longitudinal wave follows the same behaviour, demonstrating its effectiveness compared to the longitudinal wave. To assess the Poisson modulus, Kumar et al. [2] have shown a new correlation between the Poisson and transversal wave expressed by nondestructive tests (NDT). The work presented the variation in Poisson's ratio with shear velocity for intermetallics, where the slope curve was observed at 0.66. The interpretation of the curve slope is very similar to the other materials (0.61), and the correlation coefficient (R) has increased from 0.73 to 0.94.

2. MATERIAL AND METHODS

2.1. Theoretical background

The importance of Poisson's ratio in studying rigid body deformation lies in the effect of Poisson's ratio on the overall deformation of the body [3]. Poisson's ratio determines the lateral deformation when a body is subjected to an axial load. The literature does not present a metrological approach concerning the wave propagation/waveform and Poisson constant of metal alloys to different frequencies.

In addition, no research found a minimum frequency to assess the Poisson modulus or the frequency rate more appropriate. Besides this, the coupling conditions are also a concerning issue that may interfere on results [4].

It was measured five times at the specimen’s centre, which turns took five repetitions. It is worth mentioning that all measurements followed the same setup, including equipments, cables, measurement protocol, and volume of coupling material by repetition (about 1 ml of mineral oil).

2.2. Tested specimens

Three rectangular aluminium samples with the following dimensions were used to characterize the aluminium: 10 mm, 40 mm, and 70 mm (see Figure 1, A1, A2, A3).

The blocks should only be cleaned with flannel or paper towels to remove any residue on the parts that may interfere with measurements. The aluminium blocks have been previously calibrated, and the results were used for statistical analysis in this work.

2.3. Ultrasonic measuring system

To measure the longitudinal ultrasonic velocity, a longitudinal wave transducer (model V309, Olympus-NDT, USA; Figure 1 C4) with a diameter of ½” and centre frequency of 5 MHz, an oscilloscope model DSO-X 3012A (Agilent, USA; Figure 1 C1), a signal generator model 33250A (Agilent, USA; Figure 1 C3), and LabView® (National Instruments, Austin, TX, USA; Figure 1 C2) were used to measure the velocity and transit time of ultrasonic pulses in materials.

The experimental setup consisted of a 5 MHz shear wave transducer (Model V155, Olympus-NDT, USA; Figure 1 B2), a longitudinal wave transducer (Model V309-SU, Olympus-NDT, USA; Figure 1 C3) and an EPOCH 600 ultrasonic flaw detector (Olympus-NDT, USA; Figure 1 C1).

Due to the wave properties used, two supplying systems were used to emit signals performed on this work. For the longitudinal wave, the generator model 33250A (Agilent, USA; Figure 1 C3) emitted the signal, since the longitudinal wave does not need significant energy to travel through the specimen. Meanwhile, an EPOCH 600 ultrasonic flaw detector (Olympus-NDT, USA; Figure 1 C1) was necessary, since the phenomenon of dispersion (energy loss) through the medium occurs while employing the shear wave.

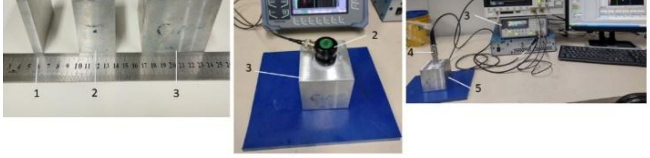

Figure 1. The measurement system: samples used, signal generators, software, and transducers.

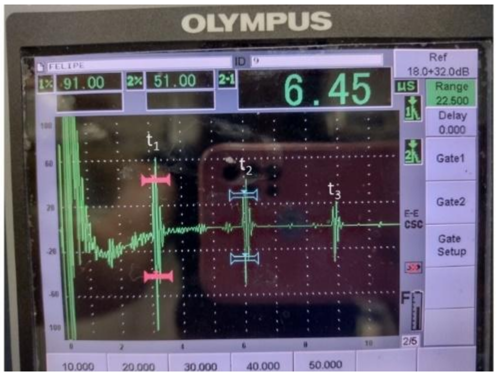

Figure 2. Multiple reflections throughout the block.

The times were captured in a software produced by LabView National Instruments (Figure 1 C2).

2.4. Measurements methods

The ultrasonic longitudinal propagation speed detection tests are performed using the pulse-echo method, where the propagation time of the ultrasonic wave received by the transducer assists in calculating the time it takes to travel back and forth between the sides of the block.

Let t_{1-2} be the flight time between the signal of the first and second reflections, and t_{1-3} the flight time between the signal of the first and third reflections, see Figure 2. The difference between them, resulting in the flight time between the second and third reflections, t_{2-3}, and the average of this difference with t_{1-2}, results in travel time in the sample and will be used to calculate the Poisson modulus, see equation (1):

$$\Delta t = \frac{(t_{1-2} - t_{1-3}) + t_{1-2}}{2}. \quad (1)$$

2.5. Environmental conditions

Tests were performed in a room with a temperature ranging from 23 °C to 25 °C and a humidity of about 50 % to 75 %. All measurements were performed simultaneously on the same day for each experimental condition.

2.6. Velocity assessment

From the time of flight, the time transmission velocity inside the specimens has been calculated by equation (2):

$$v = \frac{2\,d}{\Delta t}, \quad (2)$$

where:
d is the thickness of the aluminium block in meters;
Δt is the average double time spent by the ultrasound in the block.

2.7. Poisson’s assessment

The literature shows that the Poisson modulus can be determined by equation (3) [5], correlating the transversal and longitudinal waves:

$$\nu = \frac{1 - 2 \cdot \left(\frac{V_{\mathrm{s}}}{V_{\mathrm{L}}}\right)^2}{2 \cdot \left[1 - \left(\frac{V_{\mathrm{s}}}{V_{\mathrm{L}}}\right)^2\right]}, \quad (3)$$

where:
V_s is the shear wave velocity and V_L is the longitudinal wave velocity.

Using equation (2) on equation (3), it is possible to simplify the equation as shown in equation (4):

$$\nu = \frac{1 - 2\left(\frac{t_l}{t_s}\right)^2}{2 - 2\left(\frac{t_l}{t_s}\right)^2} . \qquad (4)$$

2.8. Uncertainty calculus

Calculating the expanded uncertainty (U) begins with determining the combined standard uncertainties. Measurement data evaluation was reported according to the literature [6], [7] as follows:

$$u_z^2 = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u_{xi}^2 \, , \qquad (5)$$

where u_z is the combined standard uncertainty associated with the outcome of the measurement (or calculation) f, and u_{xi} is the standard uncertainty associated with each variable xi, used to express the value of f. Therefore, since the velocity model rests only on the distance travelled and the time of flight, the velocity model for determining the standard uncertainty combined with the law of uncertainty propagation depends only on two independent variables:

$$\nu = f(t_l, t_s). \qquad (6)$$

Finally, the expanded uncertainty (U) can be calculated by:

$$u_c = \sqrt{\sum (u_v{}^2) + \left(c_{t_l}{}^2 \times u_{t_l}{}^2\right) + \left(c_{t_s}{}^2 \times u_{t_s}{}^2\right)} \, . \qquad (7)$$

Lastly, the combined uncertainty can be calculated by:

$$U = k \cdot u_z \, . \qquad (8)$$

The expanded uncertainty of the measurements (U_v) was calculated from the combined standard uncertainties (U_l) and (U_t) multiplied by the coverage factor $k = 2.0$, which corresponds to a coverage probability of 95 %.

3. RESULTS AND DISCUSSION

Figure 3 shows the capture of the reflected longitudinal wave signal in one of the measurement blocks to illustrate how the signals were measured using Labview software.

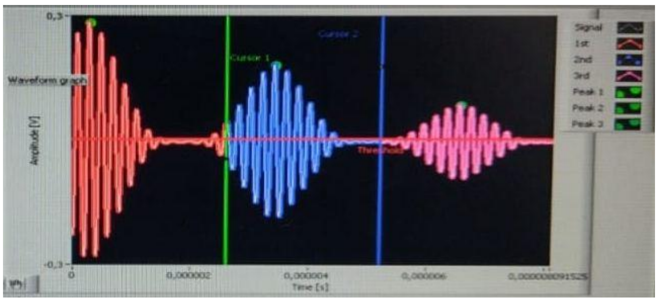

Figure 3. Three reflections displayed on the Labview screen for the longitudinal wave.

Table 1. Results of Poisson modulus for aluminium blocks with 10 mm, 40 mm, and 70 mm.

Length mm	Poisson adm	Estimated adm	Error adm	Error %	*U* adm	*U*/2 adm
10	0.3496	0.33	-0.0196	0.056	0.0192	0.0096
40	0.3487	0.33	-0.0187	0.054	0.0251	0.0126
70	0.3475	0.33	-0.0175	0.050	0.0273	0.0137
Result	0.3488		0.0107		0.0133	0.0067

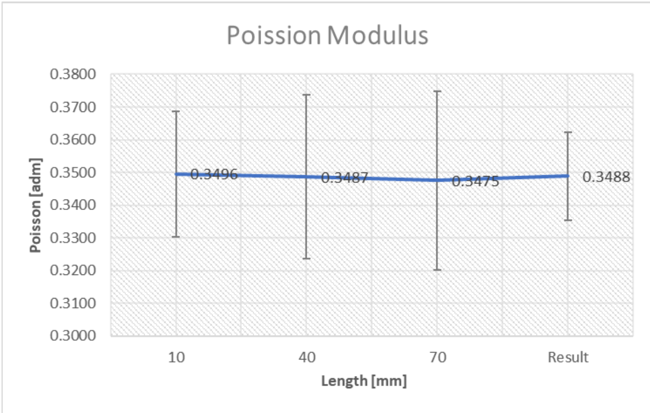

Figure 4. Poisson graphic results for aluminium specimens.

The Poisson modulus was calculated and presented in Table 1 with the times of flight values. Note that each aluminium block was calculated from the given equations.

It is observed that the Poisson modulus determined by the ultrasound technique remained within the expected value when compared to data from the literature and the standard on the test.

As shown in the graph in Figure 4, the statistical evaluation of the measurement data and uncertainty for the three blocks used in the tests yielded statistically similar values. This outcome was anticipated, as the samples originate from the same parent material.

Table 2 shows that few studies provide a quantitative assessment of the reliability of their results. Additionally, this work presents the Poisson's ratio along with its associated measurement uncertainty, at a 95 % confidence level.

4. CONCLUSION

Based on the experiments and discussions presented in this work, it is concluded that the nondestructive ultrasound test effectively measured the Poisson's ratio of aluminium samples, and may also be applicable to other alloys.

The results obtained were consistent with the reference values in the literature, demonstrating the reliability and precision of the method used. This reinforces the value of nondestructive ultrasound testing as an effective tool for characterizing the mechanical properties of materials. The method offers significant advantages, including cost reduction, time efficiency,

Table 2. Poisson results compared to the literature.

Source	Poisson [adm]	U [adm]
Presente study	0.3488	0.0133
ASTM E 494-95 [5]	0.3361	-
WEI *et al* [8]	0.33	-
FRANCO *et al* [3]	0.347	-
KUMAR *et al* [2]	0.35	-

and the ability to assess multiple properties in a single test. As a result, this study contributes to advancing knowledge in the field, and highlights the importance of nondestructive ultrasound testing as a valuable technique for material characterization.

As a suggestion for future studies, the method can be extended to characterize other materials with more applicability, such as carbon steel, stainless steel, and other metallic alloys [9]. In addition, it is possible to analyse other mechanical properties and evaluate the material when subjected to specific conditions of use or service, such as heat treatments, under specific stresses and loads, among others.

AUTHORS' CONTRIBUTION

E. W. Santos, M. K. M. de Assis, and T. C. Dourado—conceptualization: they designed the overall research framework and objectives; methodology: they developed the methodological approach and experimental design; writing: they drafted the initial manuscript and analysed preliminary results.

S. A. Miqueletti and T. C. Dourado—data curation: they managed and curated the datasets used in this study; formal analysis: they conducted statistical analyses and validated the findings; visualization: they created figures and graphs to represent the data.

A. Justen and M. K. M. de Assis—investigation: they performed experiments and collected data; software: they developed and maintained custom code used in the analysis.

T. C. Dourado, S. A. Miqueletti, and R. P. B. Costa-Félix—supervision: they oversaw the research activities and guided the team throughout the project; funding acquisition: they secured funding to support the study; project administration: they coordinated tasks among authors and managed timelines.

M. K. M. de Assis and E. W. Santos—writing review & editing: they critically reviewed and revised the manuscript for intellectual content and clarity; resources: they provided essential resources and access to tools for the research. All authors approved the final version of the manuscript and agree to be accountable for its content.

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