Metrological approach for Poisson modulus measurement of aluminium samples from 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, usually, they are 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 aluminium 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, 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 resources ultrasound test, was consistent with literature data and technical standards. Therefore, it is reinforced that nondestructive ultrasound testing is reliable, safe, and efficient in characterising the Poisson modulus, providing compliance and safety in using materials.

1 Introduction

Understanding the behavior 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 behavior, demonstrating its effectiveness compared to the longitudinal wave. To assess the de 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 intermetallic, 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 Materials 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. 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 turns at the specimen's center, which turn took five repetitions. It is worth mentioned all measurements followed the same setup including equipments, cables, measurement protocol, and volume of coupling material by repetition (about 1 ml of mineral oil).

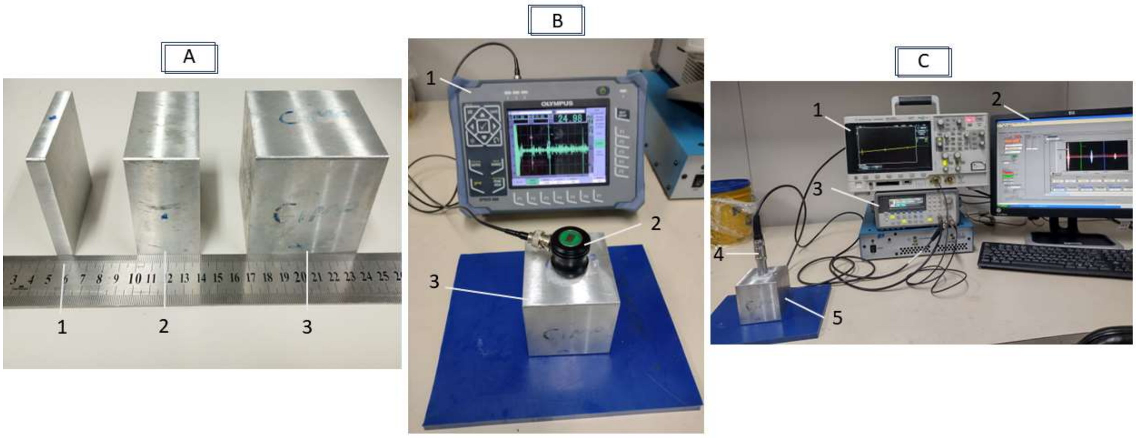
2.2 Tested specimens

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). Blocks should only be cleaned with flannel or paper towels to remove any residue on the parts that may interfere with measurements. 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 center 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) to measure the velocity and transit time of ultrasonic pulses in materials.

Figure 1. Measurement system. Samples used, signal generators, software and transducers.



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.

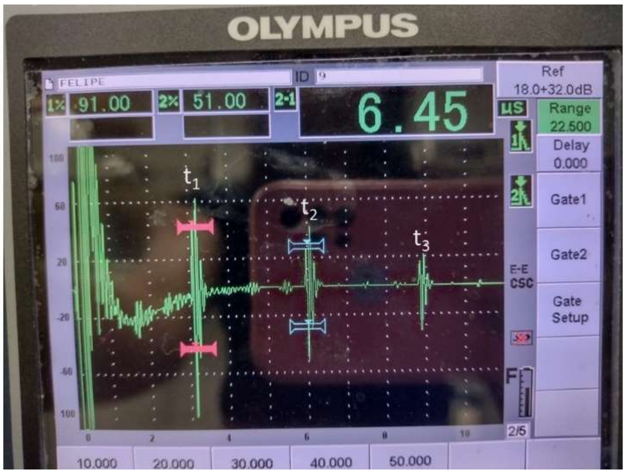
The time were captured in a software produced by LabView National Instruments (**Figure 1** C2).

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 to calculate the time it takes to travel back and forth between the sides of the block.

Let $t_{(1\text{-}2)}$ be the flight time between the signal of the first and second reflections, and $t_{(1\text{-}3)}$ the flight time between the signal of the first and third reflections, see **Figure 2**. The difference between them, resulting in flight time between the second and third reflections $t_{(2\text{-}3)}$ and the average of this difference with $t_{(1\text{-}2)}$, results in travel time in the sample and will be used to calculate, see Equation (4), the Poisson modulus.

Figure 2. Multiple reflections throughout the block.



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

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 Velocities assessment

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

$$v = \frac{2d}{\Delta t} \tag{2}$$

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.

$$\nu = \frac{1 - 2\left(\frac{V_s}{V_L}\right)^2}{2 \cdot \left[1 - \left(\frac{V_s}{V_L}\right)^2\right]} \tag{3}$$

Where:
V_s is the Shear wave velocity, and V_L is the longitudinal wave velocity.
Using Equation (2) on Equation (3) is possible to simplify the equation as shown on Equation (4).

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

Where:
t_s is the of shear wave flight time and t_l is the of longitudinal wave flight time.

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], following:

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

in which 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 x_i 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:

$$\nu = f(t_l, t_s) \tag{6}$$

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

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

Lastly, the combined uncertainty can be calculated by:

$$U = u_z\, k \tag{8}$$

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

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

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

Length [mm]	Poisson [adm]	Estimated [adm]	Error [adm]	Error [%]	U[adm]
10	0.3496	0.33	-0.0196	0.056	0.0192
40	0.3487	0.33	-0.0187	0.054	0.0251
70	0.3475	0.33	-0.0175	0.050	0.0273

Table 2 shows the result of the measurement and the data obtained from the literature in the columns below.

Figure 3. Poisson graphic results for three specimens.

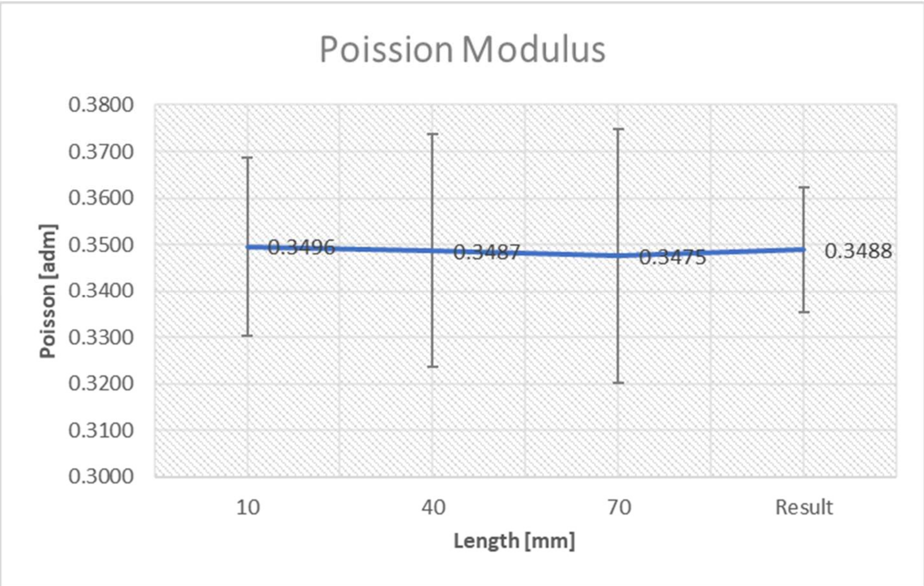


Table 2. Poisson results compared to the literature.

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	-

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 demonstrated in **Figure 3**, the uncertainty result calculated for the three blocks is above the maximum uncertainty of block 70 mm. It means the data is statistically correct since the specimens are from the same material.

On **Table 2**, it is observed that few studies present a quantitative assessment of how reliable their result was. Additionality, this work present beyond the Poisson modulus it brings together, associated to the measurement, its uncertainty with confidence level of 95%,

4 Conclusion

Based on the experiments and discussion presented in this work, it is concluded that the nondestructive ultrasound test effectively measured the Poisson modulus aluminium samples and possibly for another alloy.

The results obtained were consistent with the reference values in the literature, indicating the reliability and precision of the method used. This finding reinforces the relevance and usefulness of nondestructive testing by ultrasound as a viable tool for characterizing the mechanical properties of materials. The application of this method offers significant advantages, such as cost reduction, time efficiency and the ability to evaluate multiple properties. Therefore, this study contributes to advancing knowledge in the area and highlights the relevance of nondestructive ultrasound testing as a valuable technique in characterizing materials.

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 analyze 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.

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