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PARTICLE IMAGE VELOCIMETRY TECHNIQUE FOR ANALYSIS OF RETRACTIBILITY IN WOODS OF *Pinus elliottii*

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ABSTRACT

The aim of this work was to verify the ability to use the Particle Image Velocimetry technique for measurements of dimensional variations resulting from wood retractability of *Pinus elliottii* wood, initially saturated and with the surface marked with multiple dots of ink randomly distributed, was used in this work to apply the Particle Image Velocimetry technique. The specimens were dried and images were captured during the process. The images obtained were processed by the Particle Image Velocimetry algorithm and the deformations that occurred were calculated. For comparison, a conventional method (pachymeter) was used to measure the dimensions of the specimen during drying. The variation in dimensions obtained on the surface of the specimens from the Particle Image Velocimetry technique was 2,28 % for the radial direction and 0,20 % for the longitudinal direction of the fibers. With the standardized method, these values were 2,18 % for the radial direction and 0,21 % for longitudinal. The reduction in the average area of the specimens was 3,85 % by the Particle Image Velocimetry technique and 3,77 % by the conventional methodology. It was concluded that the Particle Image Velocimetry technique was able to accurately measure the displacements on the surface of the *Pinus elliottii* specimens, resulting in values statistically similar to those reached through the use of the conventional measurement method, demonstrating its reliability.

Keywords: Drying, image analysis, non-destructive techniques, physical properties, *Pinus elliottii.*

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INTRODUCTION

Technological advances in the field of materials science provide a theoretical basis to qualify the duration, behavior and especially the safety associated with wooden structures (ABNT NBR 7190 (1997), ASTM D143-94 (2014)). However, it is still necessary to advance techniques that facilitate the verification of the physical and mechanical properties of the wood in use. One of the important properties to be evaluated for the characterization of wood is retractability (Galvao and Jankowsky 1985). This property is inherent in wood, after all, it is a hygroscopic material, that is, because it has a great affinity for water, changing its dimensions from the variation of its moisture content (Brown *et al.* 1952, Kollmann and Coté 1968).

To measure the properties of solid materials, the test techniques recommended by the current regulations are the most used, however, these methods have some characteristics that can evolve, such as the high demand for time for processing and specific equipment. Thus, non-destructive testing techniques (END's) are alternatives for characterizing the materials, as they do not cause permanent damage to the specimens, and can be used on wood in use (Brashaw *et al.* 2009).

The Particle Image Velocimetry (PIV) technique is an optical, non-destructive technique that measures vector fields of velocities obtained by successive images from an assay or loading session. These images are processed in a computational algorithm that calculates the displacements that occurred on the surface of the object studied. This technique was originally developed in the field of fluids and gases, but authors have studied its application for solid materials (Braga Jr *et al.* 2015, Magalhães *et al.* 2015, Souza *et al.* 2014, Pereira *et al.* 2018, Pereira *et al.* 2019, Guedes *et al.* 2019). It is a technique capable of measuring deformations in situations where there is a variation between the final and initial position of the object and obtaining the mechanical properties.

This study investigates whether the PIV technique can be used to estimate retractability values in wood during drying.

MATERIAL AND METHODS

Drying and monitoring

For this work, *Pinus elliottii* was chosen for its low density (ρ = 0,430 g·cm^{-3}), which allowed for a faster saturation process. The specimens of *Pinus elliottii* without the presence of growth anomalies, from experimental planting of 20-year-old trees at the Federal University of Lavras was used. Six samples for the retraction tests were made with a circular saw in the dimensions of 10 cm × 10 cm × 1,85 cm (length x height x thickness); this dimension was defined to allow the observation and capture of the specimens in photographs.

The specimens were placed in a closed canister submerged in water and the air was removed with a vacuum pump until complete saturation (72 hours). The masses have been determined and dimensions verified with a balance with a precision scale of 0,001 g (Urano UA 220) and a pachymeter with a precision scale of 0,01 mm (Mitutoyo 500-197-30B).

The material was subjected to the process of drying in the open air for four days to dry to equilibrium moisture (temperature of 22 °C ± 2 °C and relative air humidity of 65 % ± 5 %), according to specifications adapted to ABNT NBR 7190 (1997).

The dimensional monitoring was carried out on the radial and longitudinal faces of the specimens by means utilizing of photographs, taken from a professional camera (Sony alpha a330 10,4 megapixels) fixed on a professional tripod (VX Case 625574). The mass of the specimens was measured at each drying stage to control the moisture content.

The images and measurements were taken until the moment that the mass of the specimens remained constant (moisture content approximately 12 %). After reaching equilibrium moisture content, the specimens were placed in a greenhouse until 0 % moisture content. After capturing the last image, the values of the dry masses and their dimensions were measured.

Estimation of dimensions with the PIV technique and the conventional method

For the execution of the PIV technique, the specimens had their surfaces marked with randomly distributed particles. To obtain the images, a professional camera (Sony alpha a330 10,4 megapixels) was used, perpendicularly to the sample surface at a distance of 0,90 m, in a previously assembled apparatus (Figure 1a). To measure the dimensions of the specimens, 20 vertical lines and 20 horizontal lines were made with the aid of a ruler, with a distance of 1 cm between them (Figure 1b).

The image capture process had an interval of 24 hours between sessions, totaling five sessions. After the sessions, the images obtained were processed using the computational algorithm PIV (PIV Make 0.0.1, 2019; GNU General Public License v3.0), in which the displacements, in pixels (converted to centimeters), of the previously defined interrogation windows on the entire surface of the specimen were calculated (Figure 1c).

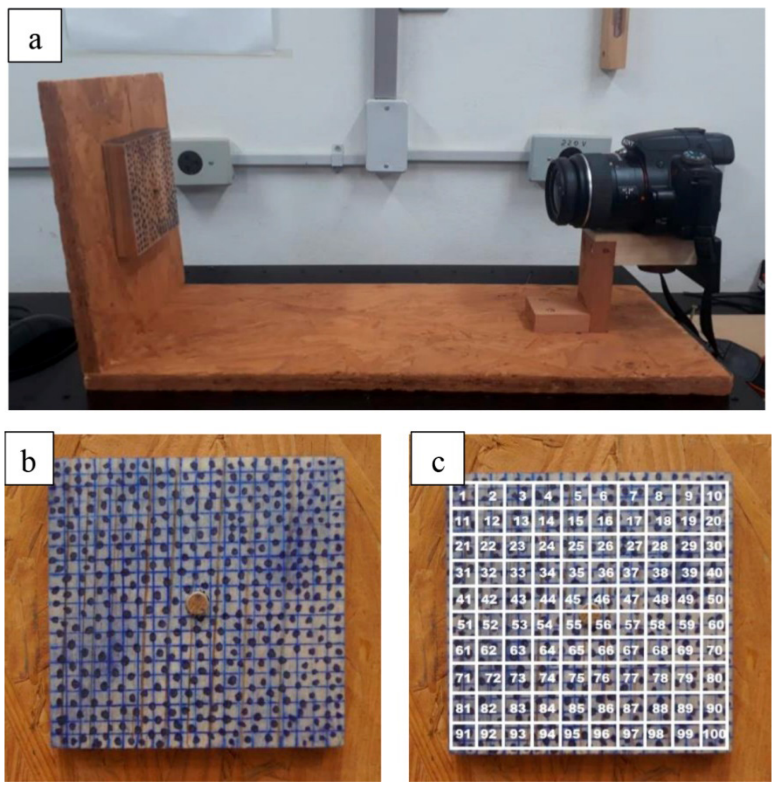

Figure 1: (a) General view of the apparatus assembled to conduct the test, (b) Layout of the horizontal and vertical lines in the specimens, (c) Representation of the selected interrogation windows on the surface of the tested specimens, in ascending order of numbering.

Computer design software

With the displacement values obtained, a graphical representation was built, using computer design software AutoCAD 2019 (Autodesk 2019), of all stages of the process. Representation was done separately (PIV and pachymeter). The value of the areas corresponding to each specimen was calculated and in possession of such values, the area reduction calculation was performed in each test session (Equation 1). Images representing all stages and their respective area loss were represented, both for the PIV technique and for the measurements with a pachymeter.

$$RA = \frac{Ai - Ad}{Ai} \text{x}100 \quad (1)$$

In which:

RA = Area Reduction (%).

Ad = Area of the specimen on the day analyzed (cm^2);

Ai = Area of the specimen on the first test day (cm^2).

Data analysis

The data obtained were processed and analyzed using Student's T-tests and linear regression to compare the mean values of retractability obtained by the PIV technique and measurement with a pachymeter. With the aid of drawing software, the specimens were represented with their average dimensions after each drying day. A reduction in the wood area was obtained in each analysis period. The reduction in wood area and moisture content was correlated.

RESULTS AND DISCUSSIONS

The moisture content values of the specimens during drying, as well as the dimensional variations in the longitudinal and radial directions, obtained by measurement (pachymeter) and estimated by the PIV technique, are shown in Table 1. All the test bodies were above the fiber saturation point ($\cong$ 30 %) on day 1 and between days 3 and 4 their moisture content stabilized with the relative moisture content of the air ($\cong$ 12 %). In the last stage, the specimens reached 0 % moisture content after drying in an oven.

Furthermore, the dimensional variation is smaller in the longitudinal direction of the fibers and higher in the radial direction. This is because the fibers in the longitudinal direction have greater resistance to this dimensional variation when compared to the radial direction (Brown *et al.* 1952).

Table 1: Daily length measurements of the radial and longitudinal direction of the pieces obtained together with the corresponding moisture content, for each technique used.

		Samples		
		A	B	C
Day 1	Moisture content (%)	89,44	61,21	61,16
	Pachymeter DR (mm)	101,66	101,99	102,42
	Pachymeter DL (mm)	100,22	100,11	100,17
Day 2	Moisture content (%)	50,85	35,25	32,80
	Pachymeter DR (mm)	101,43	101,63	102,03
	Pachymeter DL (mm)	100,20	100,08	100,14
	PIV DR (mm)	100,60	101,03	101,06
	PIV DL (mm)	100,17	101,00	100,11
Day 3	Moisture content (%)	12,45	12,81	12,98
	Pachymeter DR (mm)	100,18	99,67	100,12
	Pachymeter DL (mm)	100,13	100,06	100,12
	PIV DR (mm)	100,17	99,51	100,13
	PIV DL (mm)	100,02	99,97	100,08
Day 4	Moisture content (%)	11,60	11,91	11,99
	Pachymeter DR (mm)	99,87	99,54	99,78
	Pachymeter DL (mm)	99,84	99,85	99,79
	PIV DR (mm)	99,92	99,14	99,54
	PIV DL (mm)	98,25	99,74	99,85
Day 5	Moisture content (%)	0,00	0,00	0,00
	Pachymeter DR (mm)	99,63	96,93	97,01
	Pachymeter DL (mm)	98,26	99,66	99,68
	PIV DR (mm)	98,08	97,30	98,10
	PIV DL (mm)	98,14	99,57	99,54

DR = radial direction; DL = longitudinal direction.

The results of the descriptive statistical analysis for the total average displacement values of the three specimens obtained can be seen from Table 2, individually in the two directions analyzed with the help of horizontal and vertical reference lines, performed from the pachymeter and PIV technique, on all test specimens tested, and on all days of testing.

Analysis of variance (ANOVA) and F test was carried out. It was found that there is no statistical difference between the methods in the two directions analyzed, at 95 % confidence.

Table 2: Descriptive statistics of the measured values, with a pachymeter and the PIV technique, of retractability for the specimens during drying, in each direction analyzed.

Variable	Average (%)	Standard deviation (%)	CV (%)	Minimum (%)	Maximum (%)
Pachymeter DR	2,179	1,082	49,650	0,253	5,400
PIV DR	2,277	1,078	47,340	0,300	4,900
Pachymeter DL	0,206	0,180	87,410	0,000	0,640
PIV DL	0,204	0,205	100,310	0,002	0,880

DR = radial direction; DL = longitudinal direction. Significance Level - 95 %. CV = coefficient of variation.

Regression analysis of the methods

The Figure 2 shows the behavior of the estimated values during the pine wood retractability as a function of the values of all reference values of all specimens measured with a pachymeter.

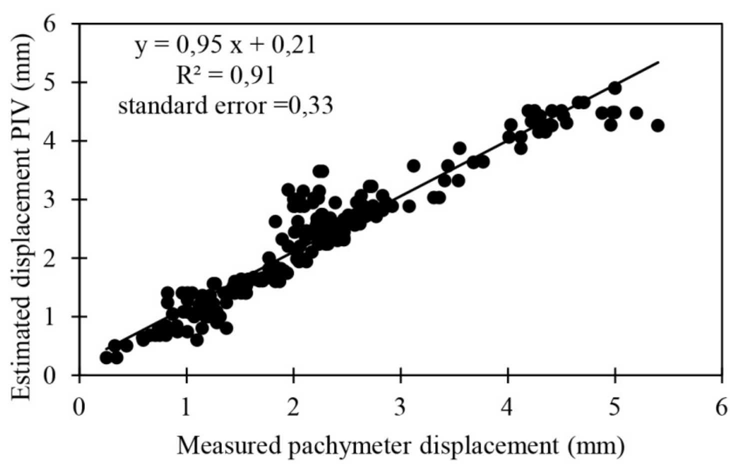

Figure 2: Behavior of displacement values obtained by the PIV technique as a function of the values measured with a pachymeter.

According to the regression determination coefficient ($R^2 = 0,91$), the adjusted linear model is able to explain 91 % of the total variation of the values estimated by PIV from the measured variation, indicating a high association between the methods, associated with a low associated standard error (33 %).

Graphical demonstration of the effect of retractability

The displacement values resulting from the two techniques were designed in design software in order to show the percentage of area reduction per test day. Figure 3 shows the representation of the area reduction that occurs each day in the specimen by means of measurements made with the pachymeter and the PIV technique.

It can be seen that the smallest reductions in area were in the direction parallel to the fibers (longitudinal direction of the wood), because in these regions, there are greater forces against displacement, created by the presence of the wood fibers. The average area reductions, in percentage, in the three tested specimens, were: 3,85 % for the PIV technique and 3,77 % for the pachymeter. Very similar values are observed between a conventional method (pachymeter) recommended by ABNT NBR 7190 (1997) and the PIV technique.

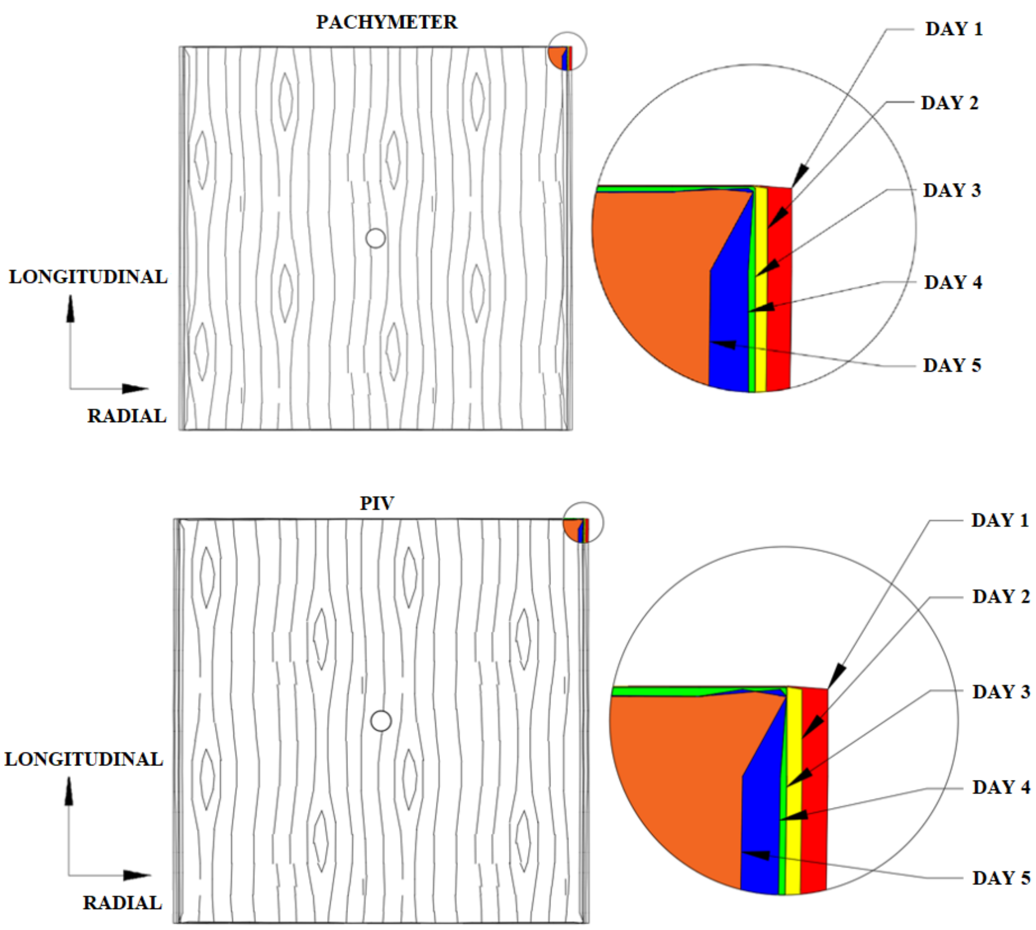

Figure 3: Graphical demonstration of the area reduction undergone by the specimen.

Correlation between moisture content and area reduction during drying

In all specimens, the correlation between the area reductions between the techniques and the moisture content obtained similar behaviors, with high values of linear correlation. Furthermore, in two specimens, the values of determination coefficient (R^2 = 0,76) of the PIV technique correlated with moisture content were higher than the respective values of determination coefficient (R^2 = 0,70) obtained by the correlation of the values measured by pachymeter against moisture content. This, again, demonstrates the reliability of the PIV technique compared to a conventional method already consolidated. Thus, we arrived at the correlation equation between the reduction of area and moisture content by the two methods (Equation 2 and Equation 3).

$$y_{PIV} = -0,0467x + 3,193 \quad (2)$$

$$y_{pachymeter} = -0,0444x + 3,0438 \quad (3)$$

Where *y* is the area reduction and *x* is the moisture content.

Using the equations, it is possible to estimate the reduction in the area of *Pinus elliottii* wood during drying. Research has shown satisfactory results of the PIV technique compared to conventional methods, with respect to physical and mechanical parameters in wood (Braga Jr *et al.* 2015, Pereira *et al.* 2018, Guedes *et al.* 2019). In the literature, a value of 3,85 % and 3,44 % was found for the radial contraction of *Pinus elliotttii* wood in a natural drying process until equilibrium moisture content, measured with a pachymeter (Acosta *et al.* 2019, Juizo *et al.* 2015). The values obtained in this work were made until the wood dried at 0 %.

CONCLUSIONS

The PIV technique proved to be able to characterize the materials present in this study with precision, demonstrating that this technique has results compatible to conventionally used methods.

The percentage values of retractability between the PIV technique and the conventional method were 2,28 % and 2,18 % for the radial direction and 0,20 % and 0,21 % for the longitudinal direction of the fibers. Such results are statistically equal, according to the F Test and by the analysis of variance (ANOVA), at 95 % confidence. A linear determination coefficient greater than 0,90 was obtained.

The equations generated by the correlations obtained by linear regression between the values of percentage loss of area and the values of moisture content, were similar between the two techniques (PIV and pachymeter).

It was feasible to obtain an equation with reliable R^2 to estimate the retractability of *Pinus elliottii* wood using the two methods studied from moisture.

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