Article title

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ABSTRACT

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1. Introduction

In wood science, natural vibration analysis is being used to an increasing extent to characterise the longitudinal and the shear modulus of elasticity of various geometrical types of prismatic beams.

Natural vibrations are repetitive no sustained variations of a physical phenomenon around an average position– the so-called equilibrium position. The undulating movement is an energy transfer from one point to another via mechanical wave propagation without any mass transfer– mass particles simply oscillate around the equilibrium position while the vibration energy is propagated. Vibration analysis is a simple and efficient way of characterising the elastic properties of a mass.

When the natural vibration frequency f and the associated rank n are known, equation (5) can be used to determine the Young's modulus Ex. The following formula is used:

The accuracy of the well-known solution in longitudinal vibrations has not been discussed here, but it is important to note that considering this type of vibrations, the influence of the lateral motion of the parts of the rod not situated on the axis should not be neglected.

The MOE dictates the mechanical grade of the board. A board's market value is directly linked to its grade based on individual grading performance, with structural grade boards worth ≥ \$350 / m3 and non-structural boards worth approximately \$80/ m3 (Baillères et al. 2019). Moreover, stiffness measurements can also be used to improve breeding, planting, and silviculture management so that future forests have better properties (Legg and Bradley 2016a). This is critical for young, fast growing plantations, since the variation of the important wood properties is substantial within and between trees, even for trees of the same age and from the same stand (Huang et al. 2003; Zobel and Buijtenen 1989; Zobel and Jett 2012; Zobel and Sprague 2012). Therefore, accurate and early measurement of stiffness properties (modulus of elasticity, MOE) is essential to grade and sort logs allowing optimal use of wood resources.

Acoustic techniques are the most commonly and commercially used techniques and are inexpensive, fast, robust, and easily used in the field. Acoustic tools have been used to assess standing trees before harvest, enabling management, planning, harvesting, and wood processing to be carried out in a way that maximises extracted value from the resource (Schimleck et al. 2019). These methods measure stress wave speed through the stem, generated by tapping one end with a light hammer.

However, the constant density assumption often leads to large measurement approximation errors since the actual average density of the tree stems may vary significantly along the radius of the stem due to variations across the growth rings. This velocity measurement technique therefore has a potential source of error since the MOE is proportional to the square of the velocity. Moreover, the simplified equation used to calculate MOE using the acoustic method assumes that the vibration is in an isotropic, homogeneous and infinite continuous media (Strutt and Rayleigh 1945). The TOF acoustic tool can provide biased results in older stands as outerwood properties become more consistent in older trees.

Resonance approaches are more representative of a whole log and considered more accurate than TOF methods (Simic et al. 2019).

The non-destructive testing (NDT) of timber using the longitudinal vibration method is based on the natural frequency of wood which is in relation to its quality. The vibration equipment applied permits the measurement of the longitudinal natural frequency and mass of the specimen, and then the density and the dynamic modulus of elasticity can be calculated. There is a strong relationship between the static modulus of elasticity obtained from the bending test and the dynamic modulus of elasticity obtained by the NDT technique.

Acoustic measurements have become widely acceptable, and they have great potential for stress grading of coniferous timber. (G ö rlacher 1984 ; Bodig et al. 1993 ; Divos and Tanaka 1997 ; Brancheriau and Baill è res 2003 ; Chauhan et al. 2005 , 2007 ; Hanhij ä rvi et al. 2005 ; Í ñ iguez 2007 ; Í ñ iguez et al. 2007).

The main objective is to test non-destructive (ND) methods to complement the visual stress grading (Arriaga et al. 2006). The ND stress wave technique for wood quality assessment is based on the measurement of the velocity of propagation of a stress wave generated by an impact. This technique was developed at the Washington State University in the 1960s, among other tools to determinate the dynamic modulus of elasticity (MOE_{dyn}) of small clear specimens (Galligan and Courteau 1965 ; Pellerin 1965).

Sobue (1986) introduced a method of calculation of the MOE dyn by means of Fourier transformation (FT) of the power spectrum in the vibrating specimen. The parameter measured was the natural frequency of the piece. Strong correlation coeffi cients were obtained for both small clear specimens and structural size specimens. However, large cross-sections have not been studied. This ND method, based on frequency of the longitudinal stress wave, has been applied in Spanish grown coniferous species with large cross-sections with satisfactory preliminary results (Esteban 2003 ; Arriaga et al. 2005 ; Í ñ iguez 2007 ; Í ñ iguez et al. 2007).

The assessment of timber properties by means of nondestructive techniques (NDT) is not a new concept. After the fundamental hypotheses for wood had been suggested, the first research took place in the late 1950s, and since then good results have been achieved. Additionally, although much work has gone into developing industrial devices, it is clear that for in situ assessment portable equipment must be used. Due to previous experiences**.** portable devices are commercially available. The results recorded are not always comparable, due to the effects of different factors and the test methodologies used**.** The standardization process consists of the development of a common NDT procedure for the evaluation of structural timber properties. This process could be based on previous works [14] and should include the following features:

– Compilation of nondestructive test results from different research groups and studies, taking into account the species studied and devices used;

– The creation of a standardized data sheet to compare results, based on the adjustment factors proposed;

– Standardized equations.

The properties of wood vary with respect to species, growth rate, grain angle, moisture content, defects, anisotropies and many other factors. Stress induced waveforms in wood are very complex and so variable, that other resonance acoustic techniques successfully developed for other materials cannot be directly applied in the case of wood. Besides, sound attenuation is greater in wood than in other materials like ceramics or metals. Acoustic properties of many wood species have been studied due to their importance as materials for musical instruments [7–10]. In spite of the similarities with our experimental method, relatively few works deal specifically with the development of a classification system for wood using its acoustical properties. From a musical point of view, the main research goal is just the opposite, to characterize the acoustic properties of known wood species. Other acoustic approaches have been used for wood classification purposes: acoustic resonance spectrometry [11], and neural network analysis of ultrasonic signals [12]. Most stress-wave studies use ultrasonic frequencies [12–14]. Ultrasounds offer several advantages, but also some disadvantages, like a more costly equipment and low penetration depth in wood. The use of common low cost microphones and commercial PC sound cards for inspecting and identifying wood is studied in this work. These media reduce the accuracy and spectral range of the results, but allow for a very cost effective and flexible experimental setup. The obtained results indicate that this simple equipment could be enough for species characterization of many common wood species. Our technique is fully non-invasive and non-destructive. The stress induced waveforms are recorded while a low weight hard plastic pendulum is hitting a thin square veneer of wood at the centre

Mencionar brevemente correcciones MC.

Decir que este articulo habla de diferentes articulos ne españa de ensayos vibroacusticos, de la influencia de los factores a las medidas y de los equipos vibroacusticos mas usados en España.

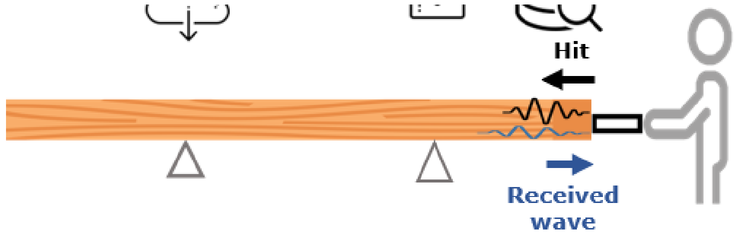
2. Teoria

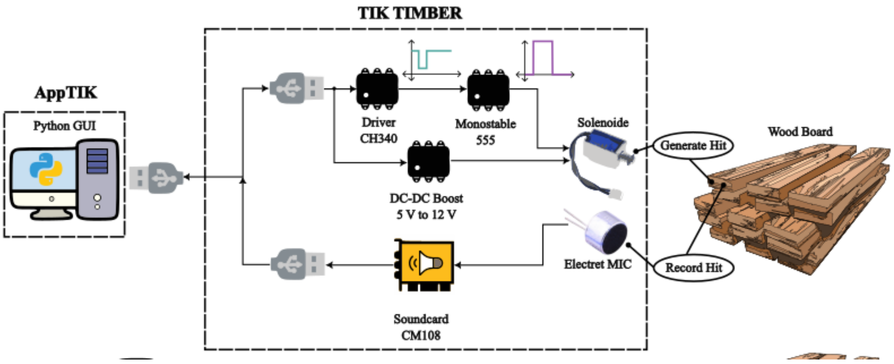
2.4.Vibrationtest

[26] showed that the Timoshenko bending theory can be applied to determine the dynamic longitudinal MoE and the shear modulus from the flexural vibration frequencies in free-free boundar condition. Indeed, they gave the following solution of the equation of motion of a vibrating beam at the first order: MoEdyn XW q MoEdyn XW KGXW xn¼yn ð1Þ where MoEdyn X W is the longitudinal dynamic MoE when bending is in edge wise or flat wise direction, ‘‘XW” being replaced by ‘‘EW” or ‘‘FW”, respectively; q is the density; K is the shear factor (K¼5=6 for a rectangular cross-section); GXW Is the dynamic shear modulus when bending is in edge wise or flat wise direction, ‘‘XW” being replacedby‘‘EW”or ‘‘FW”, respectively;xn and yn are parameters that depend on the vibrational mode frequency (see [26] for details). By plotting yn against xn for different vibration modes, a linear regression can be performed and the dynamic MoE and shear modulus can be found. The deviation of this equation is generally less than 1% if the length-to-depth ratio is between 10 and 20 (about 19 in the present work). Based on this theory, the BING device (Beam Identification by Non Destructive Grading, [27])was used to test all the samples in both EW and FW flexural vibrations, and thus obtain MoEdyn EW and MoEdyn FW.

3. Algoritmos

4. Materials & Methods





2.2 Experimental reference MOE (BING-MOE) by acoustic resonance technique

The MOE of each log was measured using Beam Identification by Non-destructive Grading (BING) (Paradis et al. 2017), which is a resonance acoustic method for estimating MOE. It consists of a microphone, an acquisition card (Pico Technology), two elastic supports, and a hand-held hammer (Baillères et al. 2009; Brancheriau 2014; Faydi et al. 2017). For longitudinal vibrations, the following equation was used to determine the axial modulus of elasticity: BING−MOE=4L2 fn n 2 . (1) Here, L is the length of the beam (m), ρ is the density (kg/ m3), and fn is the vibration frequency of rank n (1/s). This equation is valid for slender beams (L/h ≥ 10, where h is the height of the beam) and only for the fundamental frequency (Brancheriau and Baillères 2002).

2.4.1. General description of the test

Non-destructive transversal resonance tests (NDT) entailed placing the samples on two elastic supports in edgewise orientation and using a timber hammer as the impact tool (see Fig. 4). A t.bonne MM-1 Thomann microphone was used to capture the elastic wave and convert it to a signal, which was recorded by a Picoscope® 4424 oscilloscope with 80 Ms/s of maximum sampling frequency. The BING program (Beam Identification by Non Destructive Grading, [19]) was used to obtain the transversal modulus of elasticity (MoEdyn). This program is based on the theory proposed in [20] and relies on the flexural resonance frequency and the Timoshenko bending theory to determine the dynamic MoE and the shear modulus in free-free boundary conditions. Furthermore, [20] proposes the following first order solution for the motion of a resonance beam: MoEdyn ρ =MoEdyn KG ·xn+yn (1) where MoEdyn is the transversal dynamic MoE in edgewise position, ρ is the specimen density, K is the shear factor with a value of K =5/6 for a rectangular cross-section, G is the dynamic shear modulus and xn and yn are parameters dependant on the vibration mode. According to [20], the maximum relative errors of MoEdyn and G respectively remain <5% and 8%, considering a length-to-depth ratio between 10 and 20 (in our case L/h was set as 20).

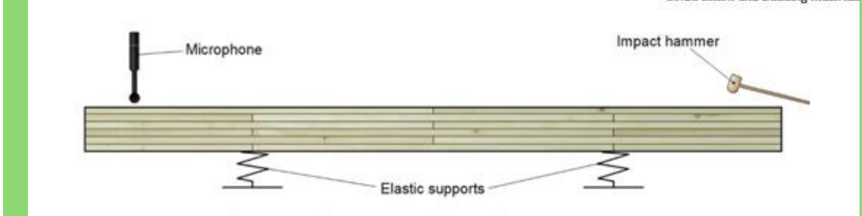


Fig. 4. General arrangement of the non-destructive resonance test.

2.3 Tests by vibration techniques

Tests carried out by vibration techniques with the Portable Lumber Grader (PLG of Fakopp) are based on measuring the resonance frequency of longitudinal vibration produced by the impact at one end of the piece, which crosses in its entirety. This vibration is affected by the content and position of knots, piece size, etc., within the specimen being studied. The way to produce vibration in the timber is to hit it at one end with a hammer while a microphone picks up the signal on the other.

After passing through an amplifier, the signal is processed by computer indicating the main frequency of vibration, velocity, dynamic and strength classification according to the EN 338:1999 standard.

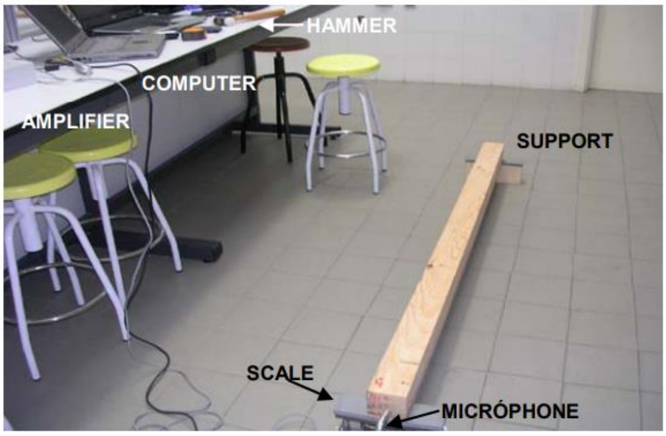


Figure 1.Outline of the PLG test.

The computer software determines the Dynamic modulus of elasticity through the following equation: Edyn = 0.92. U. (2. L. fi) 2 . (1 + ǻH/50) (1) Where: 0,92 is an experimental coefficient defined by the computer software. Therefore the objective of the analysis should be to test its effectiveness in different squared timber of Populus wood, U is the density, L is the length, fi is the frequency of longitudinal vibration and ǻH is the difference in moisture content compared to 12%. The software allows you to select some of the variables that influence the vibration wave, so much the environmental factors as the characteristics of the wood. After introducing all the variables and hitting the piece with a hammer, the classification appears on the screen followed by the detailed information obtained in the test such as: frequency, velocity, wave spectrum, elastic modulus, density, dimensions introduced and wood strength classification.

Natural frequency of longitudinal vibration

The dynamic longitudinal elastic modulus MOE dyn was determined from spectral analysis of the natural frequency of vibration parallel to the grain produced by tapping at the ends of specimens resting on flexible supports. This technique is based on the relationship between the MOE dyn and the natural frequency of oscillation of a simply supported beam. The MOE dyn was calculated from the standard solution of the wave equation for longitudinal vibration of a slender rod with free-free support condition, according to Eq. (2) (Kollman and Krech 1960 ; G ö rlacher 1984):

$$MOE_{dyn} = \left(2 \cdot L \cdot \frac{f_n}{n}\right)^2 \cdot \rho \qquad (2)$$

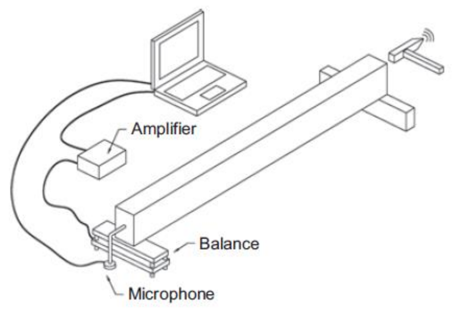


Figure 1 Test set-up.

where L is the total length of the piece, f n is the resonant frequency, n is the mode of vibration (1: fundamental mode, 2: first harmonic, etc.) and ρ is the density. The wave velocity in the longitudinal direction of the natural fundamental mode corresponds to the velocity of sound along a uniform bar and is given by:

$$V=2\cdot L\cdot f_1$$

to refer the velocity to a MC of 12 % , the value is multiplied by the factor k v,H = 1 + Δ H /80, being Δ H = H-12 % (the moisture difference to 12 %). The equation for this factor was obtained from adjustments given in the European standard EN 384 (2004a) for density and MOE (for Δ H = 1 % , k v,H = 1.0125). When the MC is higher than 12 % , the velocity should be increased by 1.25 % for every % -point difference in MC and, when the MC is lower than 12 % , the density should be decreased by 1.25 % for every % -point difference in MC, within the range of 5 – 30 % MC. In that way, the combined adjustment of density and square of velocity for the determination of MOE dyn is 2 % for every % -point of MC, as it is specifi ed for MOE in European standard EN 384 (2004a).

In this research, the test device for MOE dyn determination was developed at the Wood Laboratory of the University of Western Hungary, Sopron (Divos 2002). In the test procedure, the specimen is placed on two supports with soft polyurethane pillows to ensure free vibration. One of the supports is also a balance, which records the half-mass of each piece (Figure 1). The end of a specimen is hit by a hammer and the impact induces a stress wave of longitudinal vibration which is received as sound by a microphone set situated close to the other end of the test piece. The fundamental vibration frequency of the sound is analyzed by a fast FT sound analyzer.

NDT for timber assessment is based on the estimation of its main physical and mechanical properties. These are bending modulus of elasticity, E, bending strength, fm, and density, q.

2.1.2. Natural frequency

In this method timber pieces are made to vibrate longitudinally or transversely by means of an impact in the corresponding direction. The vibration of the piece occurs primarily in the system Eigen frequencies. These frequencies are related to the stiffness properties of the piece and its dimensions/geometry. In the case of longitudinal vibration, it is also possible to obtain the equivalent velocity of stress wave transmission. Some commercial devices which measure longitudinal vibration frequency are: the Portable Lumber Grader (Fakopp, Hungary), the Timber Grader MTG (Brookhuis Micro-Electronics, Holland) and the Hitman HM200 (Fibre-gen, New Zealand); and transverse vibration frequency: the Model 340 Transverse Vibration E-Computer (Metriguard, USA).

2.2. Factors affecting nondestructive variables

Nondestructive tests are easy and quick to perform, but it is important to note that several factors affect nondestructive variables. These factors can be divided into two categories, according to their origin: factors resulting directly from the wood sample, such as moisture content, temperature, quality, etc. and, on the other hand, factors relating to the test procedures and devices used, such as transducer coupling, path length and the size and shape of the specimen. 2.2.1. Moisture content The moisturecontent (MC) of timber dependson thehydrothermal conditions of the surrounding air. In a normal dry condition inside a building the MC of timber is from 8% to 12%; this is slightly higher, 10% to 16%, if the building is close to the coast. MC can be1168 G. Íñiguez-González et al./Construction and Building Materials 101 (2015) 1166–1171 measured with electrical resistance equipment, according to the [7] standard. A reference value of 12% MC is usually adopted. Under usual conditions the range of MC variation is about ±4% (12 ± 4%). The determination of the MC of timber is useful, not only to adjust the values of NDT variables, but also to detect abnormally high values that can be a sign of internal deterioration (fungi or insects). Stress wave velocity increases as MC decreases throughout the whole moisture range studied. In the interval from 20% to 12% MC the velocity decreases approx. 1.7% for each 1% increase in MC. For vibration technique (Viscan) data, correction factors with a decrease in ultrasound velocity of 0.60%, a decrease in dynamic modulus of elasticity for vibration of 0.87% and an increase in density of 0.42% for each 1% increase in moisture content in the range below 28% moisture content, were proposed for spruce [24].

The influence of temperature is generally less important than moisture content for stress wave propagation in the range from 6% to 18% MC [3,16]. In the case of longitudinal vibration it is possible to determine the velocity of the stress wave from frequency and the length of the piece. Piece length has no influence on the velocity obtained by longitudinal vibration.

For example, as the Wood Handbook (Forest Products Laboratory, [15] explains, wave velocity is a function of the modulus of elasticity and density. This velocity decreases with increasing temperature or moisture content in proportion to the influence of these variables on the modulus of elasticity and density. The velocity decreases slightly with increasing frequency and amplitude of vibration, although for most common applications this effect is too small to be significant. The species in question has no recognized independent effect on the velocity of wave propagation. Variability in velocity in wood is directly related to the variability of the modulus of elasticity and density. The following reference conditions proposed: 3.1.1. Moisture content 12% moisture content of timber is proposed as reference value to correct the nondestructive measurements (stress wave, ultrasound wave velocity and penetration depth). This value corresponds to the target MC for coniferous timber in service class 1 according to Eurocode 5 [8]. Service class 1 is characterized by a MC in the materials corresponding to a temperature of 20 C and a relative humidity of the surrounding air only exceeding 65% for a few weeks per year.

3.2. Modification factors In this section, equations and modification factors are proposed for the adjustment of ND variables to reference conditions. 3.2.1. Moisture content The reference velocity of stress wave propagation, v12 (referred to 12% MC)maybeobtained by Eq. (1), from velocity at H% MC, vH:

$$v_{12} = \frac{v_H}{1 - (H - 12)k_H} \qquad (1)$$

where kH is the adjustment factor for MC obtained as the ratio between the linear variation of velocity relative to MC (Dvelocity/DMC) related to velocity at 12% MC. A preliminary value of 0.01 (1% velocity decrease for every 1% MC increase) is proposed for this, as it is a common result in several research works. The reference depth penetration of the Pilodyn 6J Forest, P12 (referred to 12% MC) may be obtained by Eq. (2) from depth penetration at H%, PH:

$$P_{12} = \frac{P_H}{1 + (H - 12)k_P} \qquad (2)$$

where kP is the adjustment factor for MC obtained as the ratio between the linear variation (depth/MC) related to depth penetration at 12% MC. A preliminary value of 0.02 is proposed (approx. 2%depthpenetration increase for every 1% MC increase) for this factor. There are other experiences suggesting that its effect be neglected for practical purposes.

The sounds were recorded with several commercial low cost microphones in order to verify the consistency of the results. In general, the agreement was excellent. A common soundcard able to 192 kHz recordings, inside a PC, was used and controlled by the Praat program [15].The results were confirmed using a different soundcard.

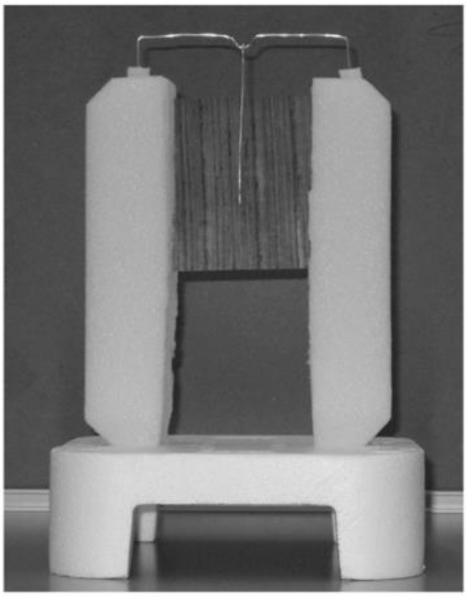


Fig. 1. Simple experimental setup for stress-wave studies in wood veneers.

Chevandier and Wertheim (1848) tested 14 wood species and obtained correction factors from 0.5% (ash) to 1.3% (Scots pine) per 1% MC change on longitudinal velocity obtained by resonance acoustic methods. Natural frequency data were recorded by means of two commercial devices: (1) the PLG (Fakopp Enterprise, Sopron, Hungary) equipped with a non-contact sensor (a microphone placed in front of one end) and (2) the MTG 960 (Brookhuis, Enschede, The Netherlands) equipped with an accelerometer contact sensor.

The results from the longitudinal vibration devices are almost identical, and the differences between the results are statistically insignificant. These observations are expectable, as the method consists of inducing vibration with a hammer and recording the natural frequency. As measurements with both devices were done simultaneously, the frequency was the same, but only the way how each device records frequency was different (PLG: microphone; MTG: contact accelerometer). Moreover, most of the measurements were done below FSP (except for Salzmann pine).

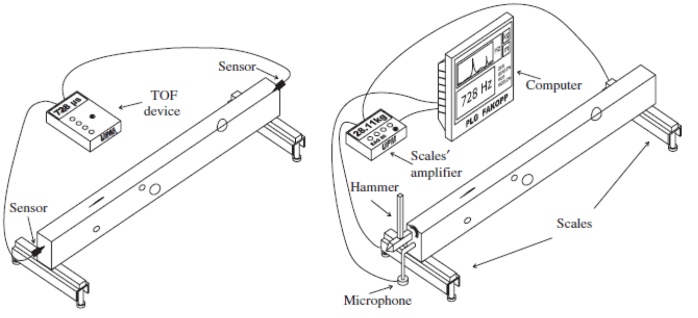
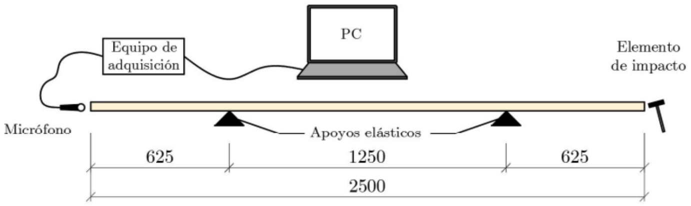


Figure 2: Measurement setup for NDT devices used.
(Left) time-of-fligth device, (right) PLG longitudinal vibration device.

The measured velocities decreased with MC increment up the FSP (in the 10–30% range), from 30 to 36 m s−1 per % MC change. Correction factors below FSP were proposed for the 12% reference MC. A wide range of MC correction factors are found in the literature due to different species, their densities, and specimen sizes. Further, errors in the MC determination may also cause deviations.



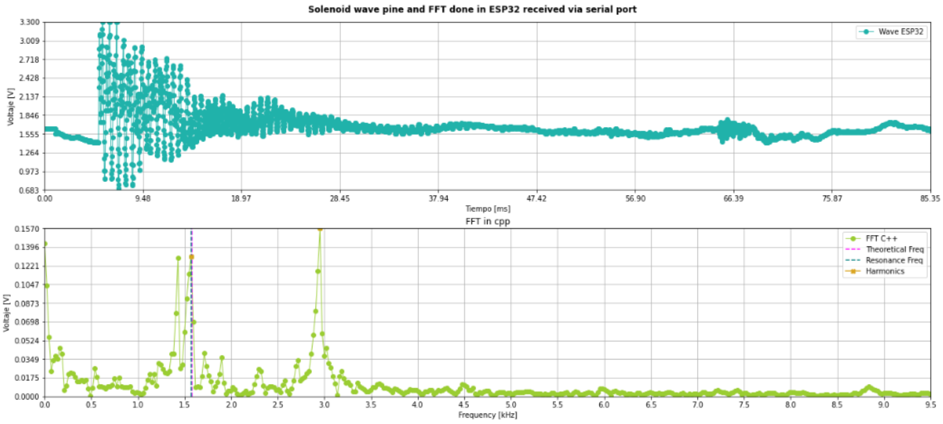
a) MTG (Brookhuis, Holanda) El Mechanical Timber Grader (MTG), desarrollado por Brookhuis Applied Data Intelligence, es un dispositivo aprobado para la clasificación de madera estructural según las normas UNEEN 14081-1:2016+A1:2020 y UNE-EN 338:2016. 3. Metodología 49 Este equipo mide la frecuencia fundamental de vibración de las tablas para predecir sus propiedades mecánicas. Utiliza un solenoide para golpear la tabla en una de las testas, generando una onda que se propaga longitudinalmente. Es posible realizar el ensayo golpeando la tabla externamente con un martillo. La frecuencia fundamental resultante se registra mediante el software especializado Timber Grader, v. 4.31.0.0, que calcula el módulo de elasticidad dinámico (MoEdin) a partir de la densidad y la velocidad de la onda. Este dispositivo es inalámbrico y se conecta a un ordenador mediante Bluetooth (Figura 36- a). El software Timber Grader facilita el análisis y reporte de los resultados, y puede predecir las clases de resistencia de la madera de acuerdo con diferentes normativas internacionales. Además, el sistema puede ampliarse mediante licencias adicionales para el análisis de diferentes tipos de madera, tanto coníferas como frondosas [43].

b) PLG (Fakkop, Hungría) El Portable Lumber Grader (PLG), desarrollado por la empresa Fakkop en Hungría, es un dispositivo diseñado para la clasificación de madera estructural, conforme a la norma UNEEN 338:2016 [44]. Este equipo mide la frecuencia fundamental de vibración del material mediante un golpe externo realizado con un martillo en una de las testas de la tabla, mientras que en la testa opuesta se coloca un micrófono que registra la respuesta en frecuencia. El sistema de control del ensayo está compuesto por un ordenador conectado al micrófono y, opcionalmente, a una báscula que mide el peso de la tabla para determinar su densidad. Si se han introducido previamente las dimensiones de la tabla, la báscula proporciona los datos necesarios para calcular la densidad (Figura 36-b). Alternativamente, se puede ingresar manualmente el peso o la densidad.

c) Tree Inspection Kit (TIK, Granada, España) El Tree Inspection Kit (TIK) es un dispositivo desarrollado en la Universidad de Granada para la caracterización de la madera en el marco del proyecto LIFE Wood for Future, tanto para la técnica de tiempo de vuelo (ToF) empleada en el Apartado 3.1 como para el método de resonancia. Este equipo dispone de dos herramientas específicas: TIK_tree, para realizar ensayos en árboles, y TIK_timber, diseñado para ensayos en tablas. El TIK_timber es un dispositivo autónomo que cuenta con un disparador interno para generar una onda en la tabla mediante un golpe en una de sus testas. Esta onda se propaga a lo largo del material, y la respuesta es registrada en la misma testa (Figura 36-c). Similar al MTG, se puede generar el golpe externamente con un martillo. El software integrado del TIK proporciona información sobre la frecuencia fundamental de vibración y los armónicos de dicha frecuencia. Con la longitud de la tabla y la densidad conocidas, el software también calcula el módulo de elasticidad dinámico (MoEdin).

igura 36. Dispositivos empleados para clasificación de madera estructural. a) MTG. b) PLG [44]. c) TIK.

5. Results



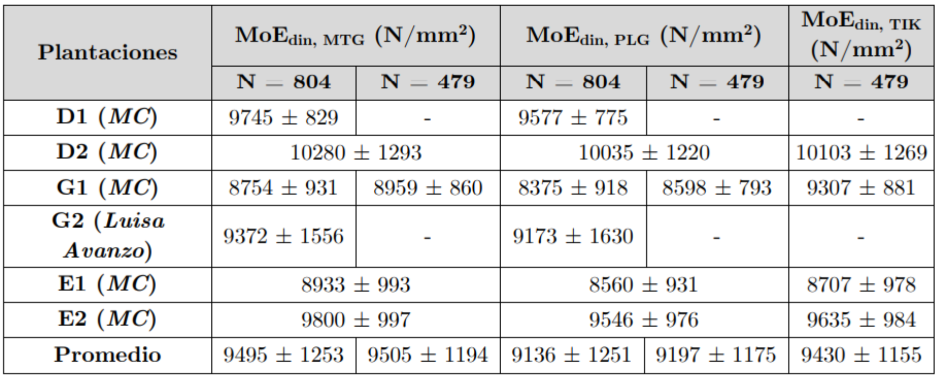
4.1.2. Dispositivos de medida

En este Apartado se presenta una comparación entre los resultados obtenidos mediante los dos dispositivos de medición: el equipo comercial Microsecond Timer (MST) y el equipo de laboratorio. El objetivo de esta comparación es evaluar la precisión y consistencia de los datos registrados por ambos dispositivos, y determinar si existen diferencias significativas en la estimación del módulo de elasticidad dinámico en árbol con densidad verde (MoEdin,árbol,ρverde Lab). La Figura 111 muestra los valores medios de módulo de elasticidad medidos para el registro de todas las plantaciones en el mismo árbol con los distintos dispositivos: el equipo de laboratorio y el equipo comercial MST. El ajuste lineal entre las medidas de ambos dispositivos presenta una fuerte correlación, indicada por un valor de R2 de 0,95.

4.3.3. Ensayo no destructivo en tabla (MTG, PLG y TIK)

En la Tabla 26 se presentan los promedios y desviaciones estándar de MoEdin para cada dispositivo (MTG, PLG y TIK) y plantación, obtenidos de los ensayos descritos en el Apartado 3.3.3. Cabe aclarar que el análisis de los datos incluye todas las probetas ensayadas, sin aplicar los criterios de clasificación visual MEF, lo que implica que no se excluyeron probetas a causa de defectos visuales. Por otro lado, debido a que con el dispositivo TIK se realizaron 479 mediciones, la Tabla 10 recoge la comparativa de los 3 equipos para esta población (N=479) y la comparativa global para los equipos MTG y PLG (N=804). Es importante destacar que, aunque el MTG está incluido en la norma UNE-EN 14081-1:2016+A1:2020, este no posee ajustes específicos para evaluar la especie Populus x euramericana. A pesar de esto, se ha optado por utilizar los datos del MTG como referencia debido a su prevalencia en la industria. Los datos representados tienen realizadas las correcciones pertinentes por humedad tal y como quedó descrito en el Apartado 3.3.5.

Tabla 26. Módulos de elasticidad dinámicos de los dispositivos MTG, PLG y TIK según la plantación. (Valores promedio ± desviación estándar).



Plantaciones	**$MoE_{din,\ MTG}$ (N/mm^2)**		**$MoE_{din,\ PLG}$ (N/mm^2)**		**$MoE_{din,\ TIK}$ (N/mm^2)**
	N — 804	**N — 479**	**N — 804**	**N — 479**	**N — 479**
D1 (*MC*)	9745 ± 829	-	9577 ± 775	-	-
D2 (*MC*)	10280 ± 1293		10035 ± 1220		10103 ± 1269
G1 (*MC*)	8754 ± 931	8959 ± 860	8375 ± 918	8598 ± 793	9307 ± 881
G2 (*Luisa Avanzo*)	9372 ± 1556	-	9173 ± 1630	-	-
E1 (*MC*)	8933 ± 993		8560 ± 931		8707 ± 978
E2 (*MC*)	9800 ± 997		9546 ± 976		9635 ± 984
Promedio	9495 ± 1253	9505 ± 1194	9136 ± 1251	9197 ± 1175	9430 ± 1155

En la Figura 125-a, correspondiente a los ensayos realizados sobre 804 probetas con los dispositivos MTG y PLG, se observa que los valores de los módulos de elasticidad dinámicos obtenidos con MTG son ligeramente superiores a los de PLG. Esta tendencia ya se destaca en la Tabla 26, con diferencias que varían desde un 1,7% hasta un 4,4%, donde el valor promedio de MoEdin del MTG refleja una superioridad del 3,9% con respecto al PLG. Por otro lado, en la Figura 125-b, que corresponde a la campaña de 479 probetas con los dispositivos MTG, PLG y TIK, se puede ver que MTG y TIK muestran resultados similares. El dispositivo PLG presenta valores que son ligeramente inferiores, siendo un 3,3% y 2,5% menor a los dispositivos MTG y el TIK, respectivamente. La plantación donde se produjo mayor diferencia entre los tres dispositivos fue la plantación G1. En este caso, el TIK registra un valor que supera en un 3,9% y 8,2% a los valores registrados por el MTG y PLG, respectivamente. Esto puede ser a causa de que la muestra G1 la conforman secciones de tabla pequeñas (20x80 mm y 25x100 mm), donde la presencia de nudos puede generar alguna imprecisión en la realización de los ensayos.

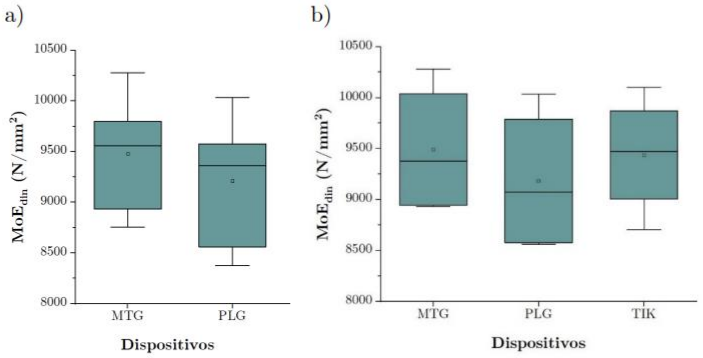


Figura 125. Módulos de elasticidad dinámicos (MoE_{din}). a) Campaña de 804 probetas con los dispositivos MTG y PLG. b) Campaña de 479 probetas con los dispositivos MTG, PLG y TIK.

En la Tabla 27 se presentan los valores de elasticidad dinámicos y estáticos (Apartado 4.3.2) por sección de probeta y plantaciones para los distintos dispositivos empelados (MTG, PLG y TIK). En términos globales, el módulo de elasticidad dinámico fue un 10,1% y un 6,6% superior en comparación con el módulo de elasticidad estático para los dispositivos MTG y PLG, respectivamente. En el caso del TIK (479 probetas), el valor de MoEdin ���������� obtenido fue un 9,3%

superior respecto de los ensayos estáticos. Estos resultados resultan acordes con las conclusiones ofrecidas por estudios previos [89,90], donde se menciona la obtención de valores dinámicos superiores a los estáticos.

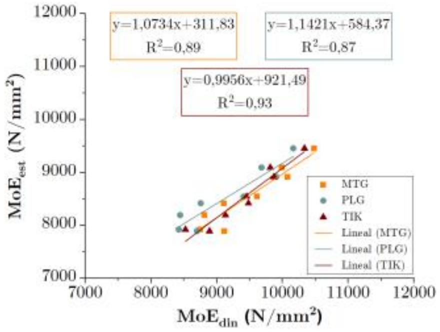


Figura 126. Relación entre los módulos de elasticidad estáticos y dinámicos promediados por sección de probeta en los distintos dispositivos (MTG, PLG y TIK) sobre las 479 probetas de la Tabla 11.

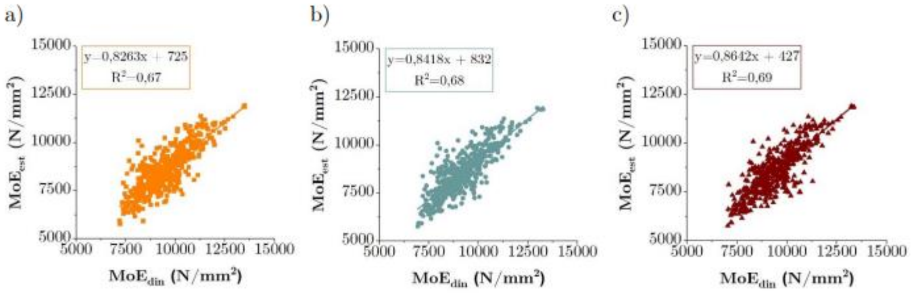


Figura 127. Relación entre los módulos de elasticidad estáticos y dinámicos promediados por sección de probeta en los distintos dispositivos sobre las 479 probetas de la Tabla 11. a) MTG. b) PLG. c) TIK.

Con respecto a los coeficientes de correlación de los distintos dispositivos con respecto al módulo de elasticidad estático, los valores obtenidos son de 0,89, 0,87 y 0,93 para los dispositivos MTG, PLG y TIK, respectivamente. La correlación más alta del TIK (R2= 0,93) indica una mayor precisión en la predicción del MoEest, lo cual es respaldado por su pendiente cercana a 1. Pese a que los dispositivos MTG y TIK obtienen valores bastante próximos en la mayoría de las muestras (Tabla 27) la correlación del TIK es un 4,5% superior a la del MTG. En la Figura 127, se presentan las nubes de puntos para cada dispositivo, mostrando la relación entre MoEest y MoEdin en las 479 probetas individuales. Aunque la dispersión es mayor que en los promedios, el dispositivo TIK mantiene la mejor correlación (R2=0,69), confirmando su precisión incluso a nivel individual.

6. Conclusions

Acknowledgements

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[12]

Comentado [IG1]: Este articulo es el que se hizo cuando desarrollaron el PLG