DYNAMIC PROPERTIES OF WOOD OBTAINED BY FREQUENCY RESONANCE TECHNIQUE AND DYNAMIC MECHANICAL ANALYSIS

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Abstract. The study of the viscoelastic properties of wood involves the determination of dynamic parameters. Different methods can be used to determine these parameters, which bring the question of whether these parameters can be considered identical depending on the method used. This study compares the frequency resonance technique and dynamic mechanical analysis for determining the bending dynamic modulus of elasticity (MOED) and damping coefficient tan δ of dry and green wood. Groups of specimens of European beech (*Fagus sylvatica* L.), small-leaved linden (*Tilia cordata* Mill.), European oak (*Quercus robur* L.), and Norway spruce (*Picea abies* L.) wood at three levels of MC were tested with both methods. The bending dynamic modulus of elasticity decreased with increasing MC until the FSP. There were no significant changes in dynamic modulus with increasing MC above FSP. A strong linear correlation between MOED obtained through both methods was found ($r = 0.92$, $r^2 = 0.84$). For the damping coefficient tan δ, the relationship was weaker ($r = 0.57$, $r^2 = 0.32$), and each method showed a different influence of MC on the damping coefficient above the FSP, which leads to the conclusion that the damping coefficient is sensitive to the measurement method.

Keywords: Frequency resonance technique, dynamic mechanical analysis, dynamic modulus of elasticity, damping coefficient, wood.

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INTRODUCTION

Among the main parameters describing the response of a material under dynamic loading are dynamic moduli of elasticity and damping coefficients (Bucur 2006). Due to their high correlation with static moduli ($r = 0.82$) (Karlinasary et al 2008), and with the modulus of rupture ($r = 0.90$) (Hassan et al 2013), dynamic moduli of elasticity are used to predict the strength and stiffness of wood (Hein and Brancheriau 2018; Fernández-Serrano and Villasante 2021), wood-based composites (Hamdan et al 2010; Wang et al 2012), and standing trees (Wang et al 2001; Mora et al 2009). Density (ρ) and dynamic moduli of elasticity are used to calculate the acoustic impedance and the sound radiation coefficient (Wegst 2006; Ahmed and Adamopoulos 2018), and (in combination with the damping coefficient tan δ) to determine the acoustic conversion efficiency (Hossen et al 2018; Danihelová et al 2019). All these vibro-acoustic parameters are used for the selection of quality material for musical instruments (Wegst 2006; Bucur 2016; Ahmed and Adamopoulos 2018; Hossen et al 2018; Tronchin et al 2020). The dynamic parameters for the above-mentioned applications are determined using nondestructive tests (NDT) (Wang et al 2012). Among these NDT methods, the frequency resonance technique (FRT) is one of the most used. This method excites, detects, and analyzes the natural frequencies of the mode shapes arising on the oscillating specimen (Bucur 2006; Brémaud 2012; Baar et al 2016; Hamdan et al 2018; Teles et al 2018). The frequency of these oscillations depends on the material properties, the geometry of the tested specimen, and the way it is fixed. The bending dynamic modulus of elasticity (MOED) of longitudinal-tangential and longitudinal-radial bending mode shape, shear modulus, and Young's modulus is calculated from the first modes of certain oscillation shapes (bending, torsion, and longitudinal) (Bucur 2006; ASTM E1875–20 2020). From the amplitude decrease of free oscillations over time, the logarithmic decrement of damping (LDD) is determined, and the damping coefficient tan δ is further derived from it (Baar et al 2016). The FRT can be used on specimens of various dimension ratios, but standard ASTM E1876 states that the ratio of length to minimum cross-sectional dimension with a value of at least five (5) must be maintained, and a ratio of 20:25 is preferred (ASTM E1876–15 2016). Depending on the sensitivity of the measuring device, and the method of oscillation excitation, the FRT can be used on small samples (Cristini et al 2022), through sizes corresponding to standards for static laboratory tests (Yang et al 2003), and up to beams and logs (Papandrea et al 2022). Besides the described FRT, which is used for small to large samples, the dynamic mechanical analysis (DMA) method can serve for the assessment of small to micro specimens (Salmén et al 2016; Pizzo et al 2018). During the DMA, the oscillating force is applied to the clamped sample, and its response in time is analyzed (Menard 2006). From the force and displacement data, the storage modulus (E_S), which represents the elasticity, and the loss modulus (E_L), which represents energy loss by the internal friction, are determined (Pizzo et al 2018). These two components are used to determine the dynamic modulus of elasticity (complex modulus) as the ratio of stress and deformation (Menard 2006). The phase shift between the stress input and the strain response is the damping coefficient tan δ, and it is calculated as the ratio of E_L and E_S (Brémaud et al 2011). The main use of DMA is to observe the effect of environmental changes (temperature and RH) on the measured parameters of tested materials (Menard 2006). The test parameters (span length, deflection, loading force, and loading frequency) are also factors influencing the results (Ashaduzzaman et al 2020). The size of DMA samples is defined by the type of loading and the associated span of clamps, the internal dimension of a heating or climatic chamber, and the type of device used (Peng et al 2008; Chowdhury et al 2010; Kaboorani and Blanchet 2014). The MC is the factor frequently observed affecting the viscoelastic properties of wood. Below the FSP (approximately 30% MC), an increase of MC of wood causes a rapid decrease in dynamic moduli, and a significant increase in the damping coefficient (Bucur 2006; Matsunaga et al 2000; Lu et al 2012). Further increases above the FSP will not cause significant changes in the dynamic moduli (Bucur 2006, 2016; Barrett and Hong 2010; Nocetti et al 2014). For the FRT, the influence of increments of MC above FSP on the damping coefficient tan δ has not been described yet (Barré et al 2018). For the DMA, an increase of the damping coefficient tan δ was found when the MC increased above the FSP (Goken et al 2018). The main difference between the above-mentioned methods is the frequency at which the sample oscillates. The FRT is focused on individual resonant frequencies and the area of interest starts at the frequency of the first mode shape. The response in the case of impulse excitation is a combination of all the rising mode shapes (depending on the sensing and excitation point, and sample support). During continuous excitation, a frequency sweep is used to find the frequencies of resonance peaks, so the individual modes are separated (ASTM E1876–15 2016; ASTM E1875–20 2020). The frequency range of DMA starts basically in the static area (0.001 Hz) and ends, depending on the device used, at a frequency of approximately 100 Hz. Using a frequency sweep, the goal is generally not to find resonance peaks (on the contrary, resonance peak is undesirable for data collection), but to show the change in material response (Menard 2006). As the loading frequency increases, the material loses time to relax, and its behavior changes from viscous to elastic. Higher frequencies result in an increase in the dynamic modulus, while causing a reduction in the damping coefficient (Menard 2006).

In this paper, MOED and corresponding damping coefficient tan δ, obtained using FRT and DMA, were compared on the same specimens made from different species and with different MC. The chosen sample size was a compromise meeting the maximum sample size for a DMA device and the ratio of the length to minimum cross-sectional dimension stated by the ASTM standard for FRT. In the case of comparable results, it would be possible to combine these methods in the future and predict parameters for a wide scale of wooden products with various dimensions. For an even wider use including green wood, it is also necessary to focus on deepening the knowledge about the influence of MC on dynamic parameters.

MATERIALS AND METHODS

Materials

Special orthotropic specimens with dimensions of $61 \times 8.4 \times 1.7$ mm (with coefficient of variation [cv] of dimensions = $0.9 \times 2.2 \times 9.6\%$), longitudinal × radial × tangential (Fig 1), were cut from European beech (*Fagus sylvatica* L.), Small-leaved linden (*Tilia cordata* Mill.), European oak (*Quercus robur* L.), and Norway spruce (*Picea abies* L.). Specimens were allocated into three groups of twenty pieces, and every group was conditioned to a different MC. One group had a low MC (LMC), and two groups were above FSP—a medium MC group (MMC), and a high MC group (HMC) (Table 1). The MC was determined using the oven-dry method. Basic density (ρ_b) was determined for all 240 specimens from the ratio of oven-dry mass and volume above the FSP (Table 2).

Measurements

Specimens for both measuring methods were loaded at the center span by longitudinal-tangent bending. To preserve the MC, measurements were done right after each other, FRT first, then immediately DMA, and FRT again (to monitor the impact of MC loss after each measurement). Before each stage of measurement, specimens were weighed. The entire measurement time for one sample was 12 min. Measurements were carried out in laboratory conditions at 24°C and 54% of RH.

Frequency resonance technique. Specimens were supported by flexible pads at the nodes of the first bending mode shape (0.224% and 0.776% of length). Specimen oscillations were excited at the specimen's midpoint by the rubber band. This excitation method was used due to the size and weight of specimens. The hit of a rubber band was sufficient to induce the first bending mode shape but also soft enough so that the loose sample did not reflect out or move on the pads. Vibrations were sensed in the middle of the

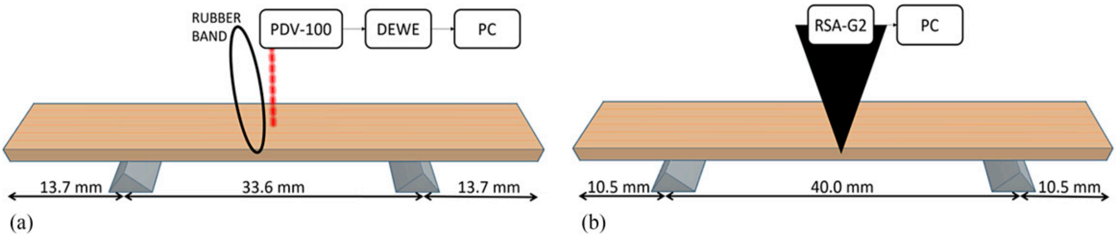

Figure 1. Setups of frequency resonance technique (a) and dynamic mechanical analysis (b).

specimen using a Doppler laser vibrometer PDV-100 (Polytec, Inc., Baden-Württemberg, DE), and recorded using a dynamic signal acquisition module DEWE-41-T-DSA and DEWESoft (DEWETRON Inc., Grambach, AT), with a sampling frequency of 20 kHz. A minimum of ten hits on the specimen were recorded. The test lasted under a minute.

Dynamic mechanical analysis. For the DMA, three-point bending was carried out using an RSA-G2 device (TA Instruments, New Castle, DE). Specimens were loaded by a spike in the middle and supported by a 40-mm-wide span. The samples were tested using the TRIOS software (TA Instruments), with an initial and minimum axial force value of 0.1 N (the axial force was set 30% higher than the dynamic force), and a displacement of 30 µm. The oscillation frequency was set as a logarithmic sweep from 0.1 to 100 Hz, with 10 points per logarithmic decade. This test was performed for 10 min per sample.

Data Analysis

Frequency resonance technique. For every specimen, the entire length of the signal recorded from FRT was transformed from the time domain into a frequency domain using the fast-Fourier transform processed using MATLAB (The MathWorks, Inc., Natick, MA). The highest peak with the lowest frequency belongs to the first bending mode. The bending dynamic modulus of elasticity obtained by this method ($\mathrm{MOED_{FRT}}$) was calculated from the frequency f using the following equation:

$$\mathrm{MOED_{FRT}} = \left(\frac{2f}{2.25\pi}\right)^2 \frac{\mathrm{ml}^2}{I} \tag{1}$$

where m is the mass and l is the length of the specimen. The moment of inertia I was calculated from width (w) and thickness (t) as a:

$$I = \frac{wt^3}{12} \tag{2}$$

Subsequently, five separate records (each for one of the five selected hits with the highest amplitude) were exported from the signal. For each record with a minimum of 25 periods of oscillation, the LDD was determined. From the LDD, the damping coefficient tan δ was calculated using Eq 3. As a representative damping coefficient of the specimen, a median from five tan δ was determined.

$$\tan\delta = \frac{\mathrm{LDD}}{\pi} \tag{3}$$

Dynamic mechanical analysis. The main results obtained by DMA were storage modulus

Table 1. Medians of MC of each sample group.

	LMC		MMC		HMC	
Group	MC (%)	cv (%)	MC (%)	cv (%)	MC (%)	cv (%)
Beech	11.7	4.6	49.7	6.4	78.8	6.2
Linden	10.2	7.0	47.9	10.0	81.5	7.1
Oak	11.1	3.0	50.5	8.1	82.8	10.6
Spruce	11.1	2.9	47.3	8.3	84.3	15.5

Table 2. Medians of basic density values of species.

Species	ρ_b (kg · m^{-3})	cv (%)
Beech (*Fagus sylvatica* L.)	558.8	3.5
Linden (*Tilia cordata* Mill.)	360.8	4.8
Oak (*Quercus robur* L.)	526.9	5.8
Spruce (*Picea abies* L.)	412.3	11.1

(E_L) and loss modulus (E_S), which are components of the stress (σ - E_L is 90° out of phase with the strain ε, and E_S is in the phase with the strain).

$$E_L = \frac{\sigma \sin \delta}{\varepsilon} \tag{4}$$

$$E_S = \frac{\sigma \cos \delta}{\varepsilon} \tag{5}$$

The damping coefficient tan δ represented a phase lag between the stress and the strain and was calculated as the ratio of E_L to E_S.

$$\tan \delta = \frac{E_L}{E_S} \tag{6}$$

The bending dynamic modulus of elasticity ($MOED_{DMA}$) is a complex combination of E_L and E_S.

$$MOED_{DMA} = \frac{\sigma}{\varepsilon} = E_S + iE_L = \sqrt{E_S{}^2 + E_L{}^2} \tag{7}$$

The MC of specimens decreased during the 10-min-long DMA depending on the moisture group, and (in the case of MC above the FSP) also depending on species (Table 3). Based on the weight method, MC loss was determined from known MC before and MC after the DMA test. For every specimen from groups MMC and HMC, the average of MC before and MC after the DMA test is given for the next data evaluation. DMA results were reported for each testing frequency. From all sample groups, the median for each testing frequency was calculated (Figs 2 and 3). For further statistical evaluation, the median value across frequencies was determined for each sample. The statistical comparison of data obtained by both methods was done using one-way ANOVA, with a significance level of 0.05 and 0.01, in the MATLAB environment. The steepness of the function (stp) was determined according to the first term (a) of the linear regression $y = ax + b$.

Table 3. Medians of MC loss during the DMA of each sample group.

	LMC		MMC		HMC	
Group	MC loss (%)	cv (%)	MC loss (%)	cv (%)	MC loss (%)	cv (%)
Beech	1.08	25.9	10.38	15.4	11.88	20.6
Linden	1.00	179.6	16.50	12.1	18.07	10.3
Oak	0.85	23.1	9.33	19.8	12.19	13.6
Spruce	0.87	24.1	15.81	14.9	20.61	15.3

RESULTS AND DISCUSSION

The MC loss during the DMA test was comparable for species in LMC groups, up to 1%. In groups with MC above the FSP, the differences between the species were observed. Wood species with lower ρ_b had a bigger MC loss during the experiment.

The DMA showed that the change from viscous to elastic behavior when changing frequency (Menard 2006) occurred earlier in dry wood than in wood at a higher MC (Fig 2). Resonance peaks at the same frequencies (39.8 and 63 Hz) were found in the data of E_L for all specimens, which affected the determination of $MOED_{DMA}$ and the damping coefficient at these frequencies. Since it concerns the same frequencies for all specimens (regardless of MC and species), which are far from their resonance frequencies found by FRT (from 1240 to 2708 Hz), a measurement error caused by a device or clamps resonance was considered. According to Bucur (2006), and Nocetti et al (2014), the modulus of elasticity decreases with increasing MC. The results from DMA show that compared with LMC, moduli of MMC and HMC decreased by: 40% and 52% for beech, 28% and 46% for linden, 27% and 43% for oak, and 37% and 52% for spruce respective. So, for species with a higher modulus of elasticity, there is a more significant decrease with increasing MC.

All samples showed a drop or lack of the damping coefficient values at the lowest frequencies, caused by very low or negative values of E_L (Fig 3). From the erroneous resonance peaks, described earlier, all damping coefficients followed an increase and convergence of all samples at the same value. The middle area of the measurement (0.5-10 Hz) showed a trend of a slight decrease with increasing frequency, which agrees with

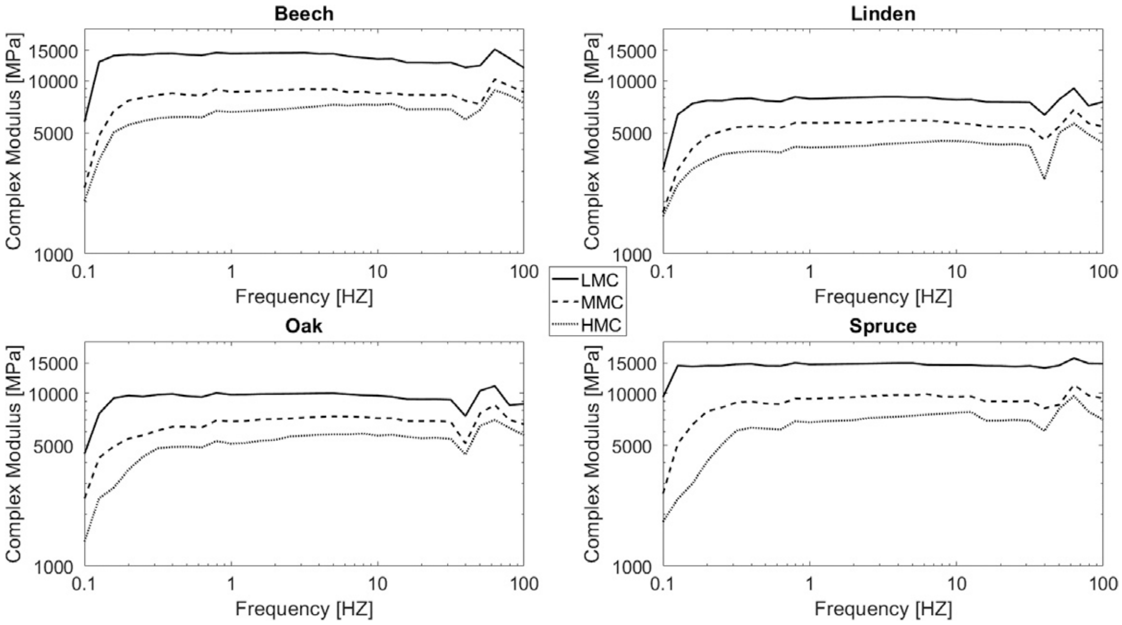

Figure 2. Medians of complex dynamic moduli of elasticity of species groups with different MC at varying load frequency—determined by dynamic mechanical analysis.

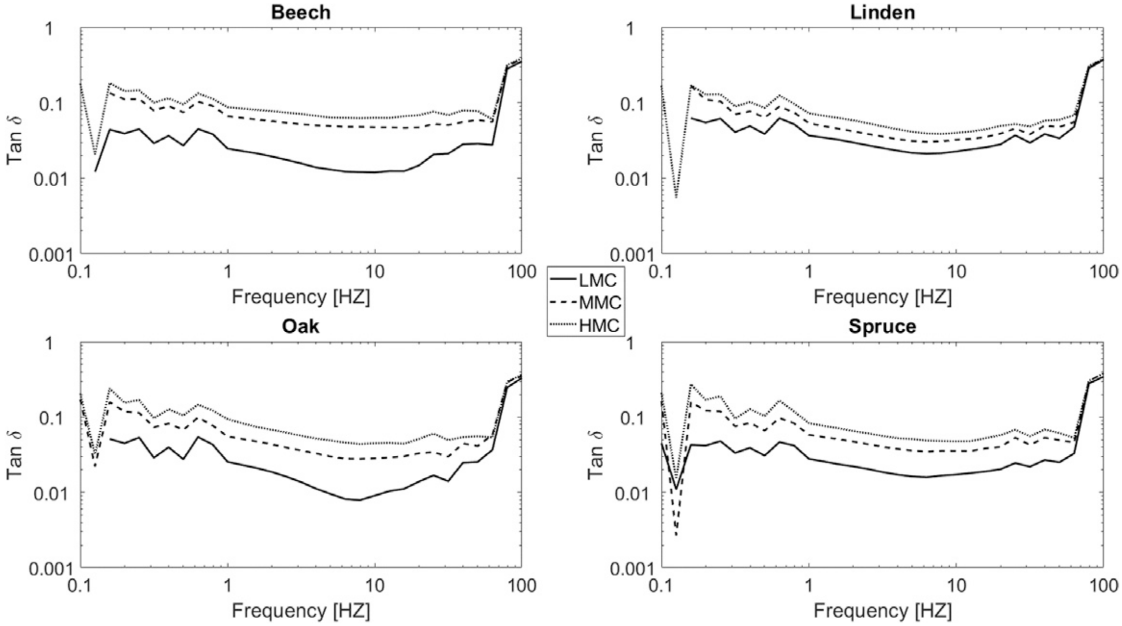

Figure 3. Medians of damping coefficients determined by dynamic mechanical analysis at varying load frequency.

Menard’s (2006) description of the influence of the loading frequency on material behavior determined by DMA.

As expected for DMA above FSP, the damping coefficient increased with rising MC (Goken et al 2018). For individual species, the DMA revealed a rising damping coefficient for MMC and HMC compared with LMC by: 161% and 253% for beech ($\text{stp} = 11\,\text{e}^{-4}$), 39% and 74% for linden ($\text{stp} = 4\,\text{e}^{-4}$), 107% and 204% for oak ($\text{stp} = 9\,\text{e}^{-4}$), and 95% and 167% for spruce ($\text{stp} = 6\,\text{e}^{-4}$) respective. This could lead to the conclusion that with higher ρ_b, the damping coefficient tan δ increases rapidly with increasing MC. Nevertheless, by focusing on individual species and their MC groups, no significant change was observed when the ρ_b changed. In case, there was any slight change observed, it was a decrease in the damping coefficient with increasing ρ_b (Fig 4), For the DMA, species with a higher ρ_b showed a faster increment of the damping coefficient with increasing MC. Brémaud et al (2009, 2010) stated that extractives content, chemical composition, and properties related to MC have a significant influence on the damping coefficient tan δ. This confirms that the steepness of the damping coefficient increases with increasing MC and is influenced not only by ρ_b, but also by the properties of the species itself.

Since the results were comparable for FRT in individual MC groups before and after DMA tests, values are stated (Table 4) as the unified medians from the average of LMC, MMC, and HMC before and after performing the DMA.

The bending dynamic modulus of elasticity obtained by DMA was statistically comparable within the individual species for both groups above FSP (MMC and HMC) with ($p = 0.01$), beech even with ($p = 0.05$). No species had statistically comparable MOED_{DMA} of the LMC group with MMC and HMC groups. Similar results were obtained for MOED_{FRT}. Individual species had comparable MMC and HMC groups with ($p = 0.01$), beech and oak even with ($p = 0.05$). No species had statistically comparable MOED_{FRT} of the LMC group with groups above FSP. Both methods agreed with the assumption that there is no statistically significant change in MOED above FSP, with increasing

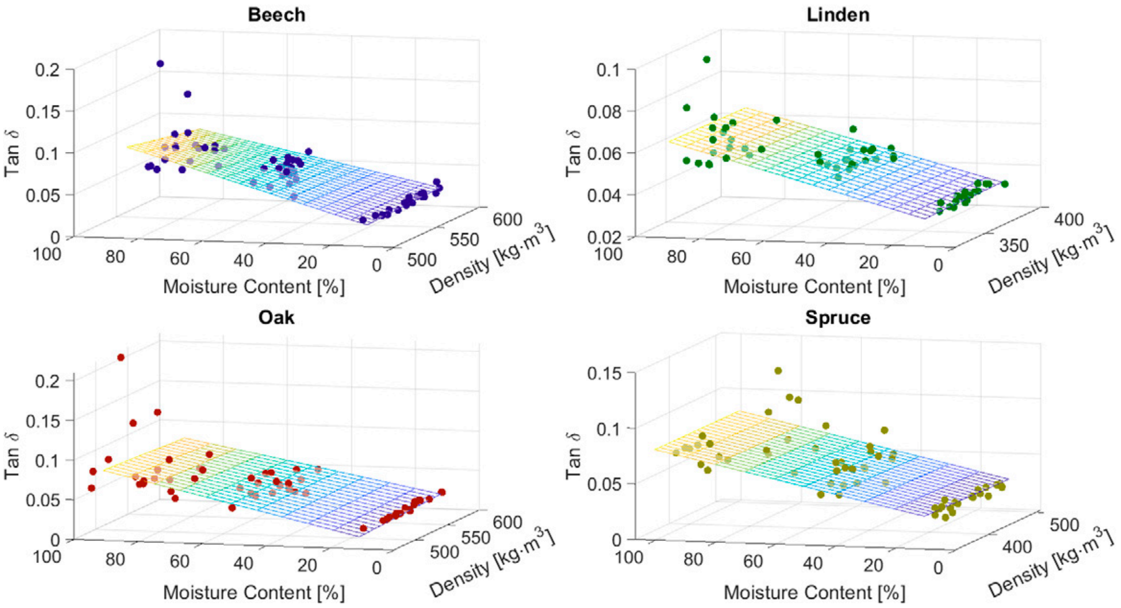

Figure 4. Increasing damping coefficient with increasing MC for individual species.

Table 4. Medians of MOED and tan δ for species with different MC.

		FRT				DMA			
Species	MC	MOED (MPa)	cv (%)	tan δ (−)	cv (%)	MOED (MPa)	cv (%)	tan δ (−)	cv (%)
Beech	LMC	17 297	8.9	0.0093	15.7	14 117	14.7	0.0227	12.9
	MMC	11 563	8.9	0.0206	30.6	8 448	14.2	0.0592	15.3
	HMC	10 721	12.6	0.0195	27.3	6 768	33.5	0.0800	35.5
Linden	LMC	10 222	9.9	0.0124	7.1	7 758	12.4	0.0339	5.3
	MMC	7 876	12.2	0.0162	16.2	5 616	12.1	0.0473	9.3
	HMC	6 467	17.0	0.0179	16.8	4 192	19.8	0.0589	17.7
Oak	LMC	12 088	19.9	0.0087	14.6	9 697	19.8	0.0222	10.1
	MMC	9 160	16.6	0.0137	24.8	7 048	15.4	0.0459	13.6
	HMC	7 976	17.5	0.0139	23.5	5 524	57.2	0.0676	49.5
Spruce	LMC	17 704	21.0	0.0073	12.5	14 595	24.0	0.0258	15.8
	MMC	11 541	10.9	0.0134	31.4	9 137	11.9	0.0502	16.2
	HMC	10 753	23.6	0.0148	31.2	6 935	42.4	0.0688	32.5

MC (Bucur 2006; Nocetti et al 2014). A comparison of MOED between both methods showed no statistical difference only for the spruce LMC group ($p = 0.01$), otherwise, the methods do not have comparable MOED within the species and their individual MC groups. Medians of $\mathrm{MOED_{DMA}}$ were smaller than $\mathrm{MOED_{FRT}}$, and were similar for all species, depending on the MC group: LMC of 18.4% for beech, 24.1% for linden, 19.8% for oak, and 17.6% for spruce; MMC of 26.9% for beech, 28.7% for linden, 23.1% for oak, and 20.8% for spruce; HMC of 36.9% for beech, 35.2% for linden, 30.7% for oak, and 35.5% for spruce. The data from both methods show that, as a function of MC, $\mathrm{MOED_{FRT}}$, and $\mathrm{MOED_{DMA}}$ copy a similar trend (Fig 5).

The damping coefficients obtained by DMA are higher than those obtained by FRT. Similar results were found in one of the few papers comparing DMA and FRT results of the damping coefficient tan δ on the mulberry wood with MC of 1.4% (Se Golpayegani et al 2012). Thus, these results for LMC groups were expected. Above FSP, a further increase was expected for DMA (Goken et al 2018), which again would be similarly steep for both methods (for FRT, it has not been described yet [Barré et al 2018]). This has been confirmed for DMA data only (Fig 6). The FRT results showed that above the FSP, the damping coefficients had similar trends as dynamic moduli, ie that there were no statistically significant changes with increasing MC. For all species, the damping coefficients tan δ were comparable between their MMC and LMC groups ($p = 0.05$). For the damping coefficient obtained by DMA, MMC and HMC groups were comparable only for spruce ($p = 0.01$).

As the results indicate, the methods are very similar in determining MOED, just with shifted values (Fig 7). Through multiple linear regression from all data (using function "regress"—Matlab) the coefficient $c = 0.7567$ to convert $\mathrm{MOED_{FRT}}$ to $\mathrm{MOED_{DMA}}$, and $c = 1.2813$ to convert $\mathrm{MOED_{DMA}}$ to $\mathrm{MOED_{FRT}}$ were calculated. $\mathrm{MOED_{DMA}}$ and $\mathrm{MOED_{FRT}}$ had strong linear correlations ($r = 0.92$, $r^2 = 0.84$). This correlation is very similar to the correlation between static bending MOE and dynamic bending $\mathrm{MOED_{FRT}}$ ($r = 0.98$, $r^2 = 0.96$) (Chauhan and Sethy 2016). The DMA operates at the boundary between statics and dynamics, with loading frequencies ranging from 0.1 to 100 Hz. As the static moduli have lower values than dynamic moduli, DMA corresponds to lower MOED values. A comparison of both methods for determining the damping coefficient tan δ showed a weaker correlation ($r = 0.57$, $r^2 = 0.32$). When comparing only the LMC groups (disregarding the influence of MC) the correlation coefficient remained almost unchanged. The correlation between MOED and the

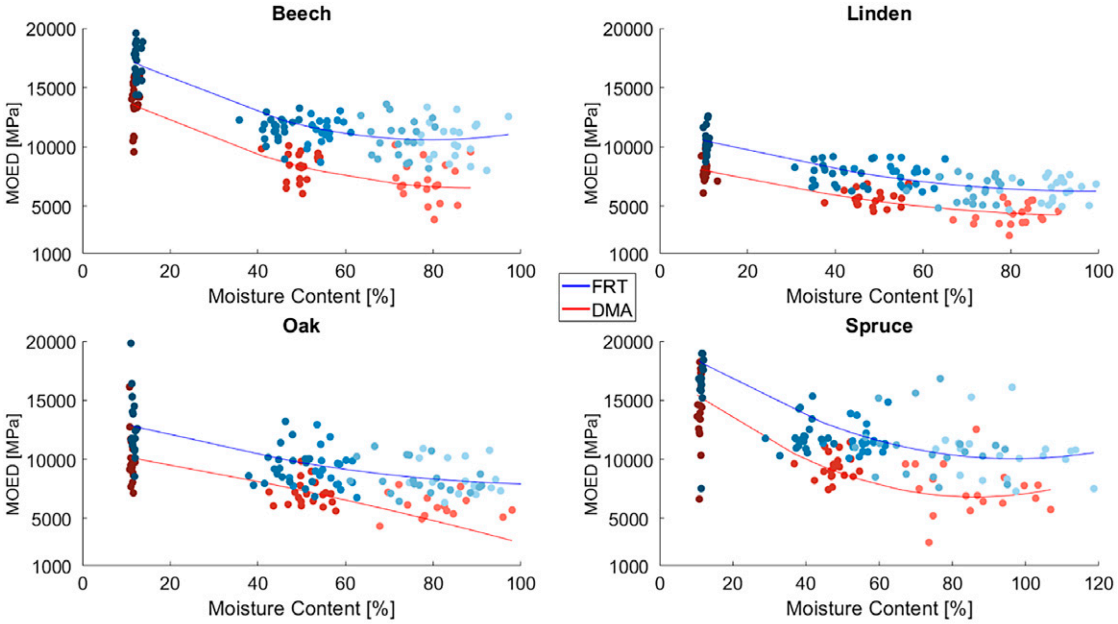

Figure 5. Comparison of bending dynamic modulus of elasticity (MOED) obtained by frequency resonance technique (FRT) and dynamic mechanical analysis (DMA).

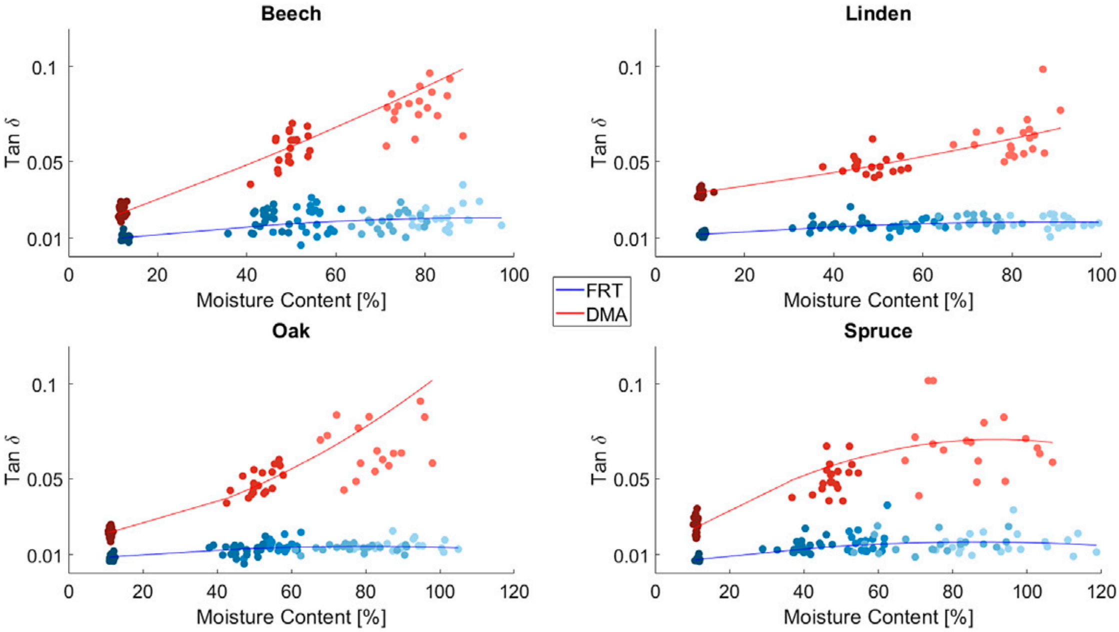

Figure 6. Comparison of damping coefficient obtained by frequency resonance technique (FRT) and dynamic mechanical analysis (DMA).

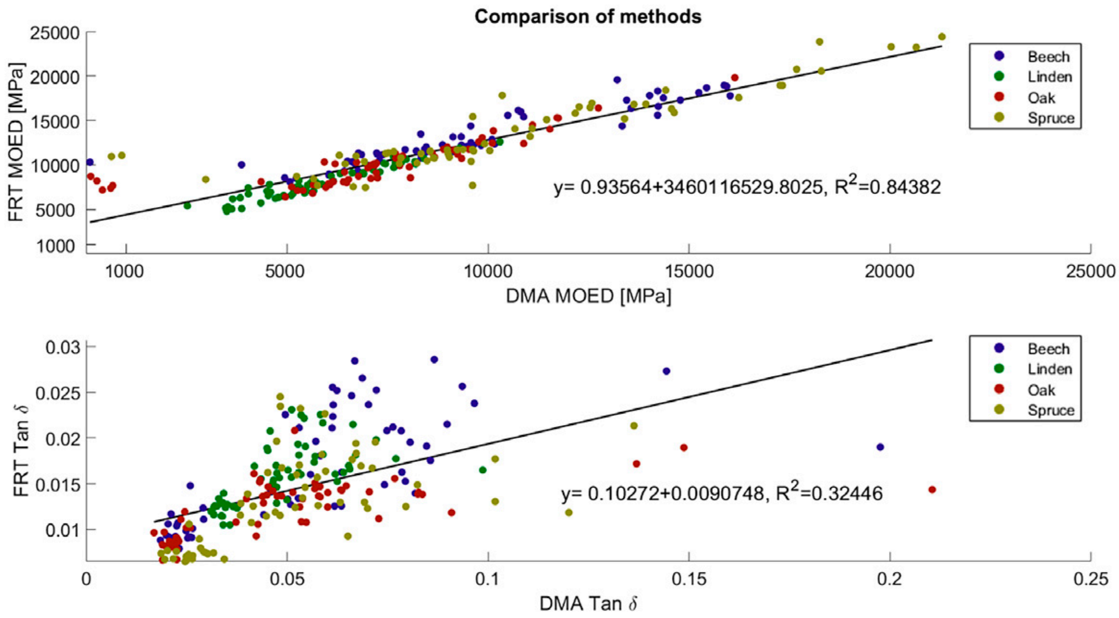

Figure 7. Comparison of dynamic parameters obtained by frequency resonance technique (FRT) and dynamic mechanical analysis (DMA).

damping coefficient tan δ was moderate for FRT (r = 0.42) and stronger for DMA (r = 0.65).

CONCLUSIONS

- The DMA showed that the damping coefficient increased with increasing MC, and increased faster with increasing MC for species with a high ρ_b (oak, beech with stp = $9e^{-4}$; $11e^{-4}$) than for species with lower ρ_b (linden, spruce with stp = $4e^{-4}$; $6e^{-4}$).
- The FRT showed that the damping coefficient values do not change significantly above the FSP.
- Same-size specimens showed that MOED determined using FRT was 24-28% more than MOED determined using DMA, with a strong linear correlation (r = 0.92, r^2 = 0.84). The influence of the scale while maintaining the ratio of dimensions and furthermore, the influence of the change of geometry should be verified.
- For further research, it is necessary to focus in more detail on the damping coefficient tan δ and the factors influencing it. Based on the results of this paper, the damping coefficient tan δ obtained by DMA and the damping coefficient tan δ obtained by FRT should not be confused.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Ahmed SA, Adamopoulos S (2018) Acoustic properties of modified wood under different humid conditions and their relevance for musical instruments. Appl Acoust 140:92-99. https://doi.org/10.1016/j.apacoust.2018.05.017

American Society for Testing and Materials, ASTM E1875 – 20 (2020). Standard test method for dynamic Young's modulus, shear modulus, and Poisson's ratio by sonic resonance. Philadelphia. https://doi.org/10.1520/E1875-20

American Society for Testing and Materials, ASTM E1876 - 15 (2016). Standard test method for dynamic Young's modulus, shear modulus, and Poisson's ratio by impulse excitation of vibration. Philadelphia. https://doi.org/10.1520/E1876-08.2

Ashaduzzaman M, Hale MD, Ormondroyd GA, Spear MJ (2020) Dynamic mechanical analysis of Scots pine and three tropical hardwoods. Int Wood Prod J 11(4):189-203. https://doi.org/10.1080/20426445.2020.1799910

Baar J, Tippner J, Gryc V (2016) Wood anatomy and acoustic properties of selected tropical hardwoods. IAWA J 37(1):69-83. https://doi.org/10.1163/22941932-20160121

Barré JB, Bourrier F, Brancheriau L, Bertrand D, Rey F (2018) Effects of fungal decay on elasticity and damping of small-diameter silver fir logs assessed by the transverse vibration resonant method. Wood Sci Technol 52(2):403-420. https://doi.org/10.1007/s00226-017-0961-2

Barrett JD, Hong JP (2010) Moisture content adjustments for dynamic modulus of elasticity of wood members. Wood Sci Technol 44(3):485-495. https://doi.org/10.1007/s00226-009-0292-z

Brémaud I (2012) Acoustical properties of wood in string instruments soundboards and tuned idiophones: Biological and cultural diversity. J Acoust Soc Am 131(1):807-818. https://doi.org/10.1121/1.3651233

Brémaud I, Gril J, Thibaut B (2011) Anisotropy of wood vibrational properties: Dependence on grain angle and review of literature data. Wood Sci Technol 45(4):735-754. https://doi.org/10.1007/s00226-010-0393-8

Brémaud I, Minato K, Langbour P, Thibaut B (2010) Physico-chemical indicators of inter-specific variability in vibration damping of wood. Ann For Sci 67(7):707. https://doi.org/10.1051/forest/2010032

Brémaud I, Minato K, Thibaut B (2009) Mechanical damping of wood as related to species classification: A preliminary survey. Pages 1–7 *in* Proceedings, 6th Plant Biomechanics Conference Cayenne, November 16–21, Cayenne, French Guiana. papers3://publication/uuid/80AA77A1-F445-4065-A76F-7AEFF49E3F1C

Bucur V (2006) Acoustics of wood. Theory of and Experimental Methods for the Acoustic Characterization of Wood. Pages 39–104 *in* TE Timell, R Wimmer, eds CRC Press, Boca Raton, FL. https://doi.org/10.1201/9780203710128

Bucur V (2016) Handbook of materials for string musical instruments. Mechanical Characterisation of Materials for String Instrument. Pages 93–126. Springer International Publishing, Switzerland. https://doi.org/10.1007/978-3-319-32080-9

Chauhan S, Sethy A (2016) Differences in dynamic modulus of elasticity determined by three vibration methods and their relationship with static modulus of elasticity. Maderas Cienc Tecnol 18(2):373-382. https://doi.org/10.4067/S0718-221X2016005000034

Chowdhury S, Fabiyi J, Frazier CE (2010) Advancing the dynamic mechanical analysis of biomass: Comparison of tensile-torsion and compressive-torsion wood DMA. Holzforschung 64(6):747-756. https://doi.org/10.1515/HF.2010.123

Cristini V, Tippner J, Nop P, Zlámal J, Hassan Vand M, Šeda V (2022) Degradation of beech wood by Kretzschmaria deusta: Its heterogeneity and influence on dynamic and static bending properties. Holzforschung 76(9):813-824. https://doi.org/10.1515/hf-2022-0039

Danihelová A, Spišiak D, Reinprecht L, Gergel T, Vidholdov Z, Ondrejka V (2019) Acoustic properties of Norway spruce wood modified with staining fungus (*Sydowia polyspora*). BioResources 14(2):3432-3444. https://doi.org/10.15376/biores.14.2.3432-3444

Fernández-Serrano Á, Villasante A (2021) Longitudinal, transverse and ultrasound vibration for the prediction of stiffness using models incorporating features in *Pinus sylvestris* timber. Eur J Wood Wood Prod 79(6):1541-1550. https://doi.org/10.1007/s00107-021-01707-0

Goken J, Fayed S, Schafer H, Enzenauer J (2018) A study on the correlation between wood moisture and the damping behaviour of the tonewood spruce. Acta Phys Pol A 133(5):1241-1260. https://doi.org/10.12693/APhysPolA.133.1241

Hamdan S, Rahman MR, Jusoh I, Wahid HA (2018) Dynamic Young's modulus and moisture content of tropical wood species across Sap, median, and internal wood regions. BioResources 13(2):2907-2915. https://doi.org/10.15376/biores.13.2.2907-2915

Hamdan S, Talib ZA, Rahman MR, Ahmed AS, Islam MS (2010) Dynamic Young's modulus measurement of treated and post-treated tropical wood polymer composites (WPC). BioResources 5(1):324-342.

Hassan KTS, Horáček P, Tippnera J (2013) Evaluation of stiffness and strength of scots pine wood using resonance frequency and ultrasonic techniques. BioResources 8(2):1634-1645. https://doi.org/10.15376/biores.8.2.1634-1645

Hein PRG, Brancheriau L (2018) Comparison between three-point and four-point flexural tests to determine wood strength of Eucalyptus specimens. Maderas Cienc Tecnol 20(3):333-342. https://doi.org/10.4067/S0718-221X2018005003401

Hossen MF, Hamdan S, Rahman MR (2018) Investigation of the acoustic properties of chemically impregnated Kayu Malam wood used for musical instrument. Adv Mater Sci Eng 2018. https://doi.org/10.1155/2018/7829613

Kaboorani A, Blanchet P (2014) Determining the linear viscoelastic region of sugar maple wood by dynamic mechanical analysis. BioResources 9(3):4392-4409. https://doi.org/10.15376/biores.9.3.4392-4409

Karlinasary L, Wahyuna ME, Nugroho N (2008) Nondestructive ultrasonic testing method for determining bending strength properties of Gmelina wood (*Gmelina arborea*). J Trop For Sci 20(2):1-12.

Lu J, Jiang J, Wu Y, Li X, Cai Z (2012) Effect of moisture sorption state on vibrational properties of wood. Forest Prod Journal 62(3):171-176. https://doi.org/10.13073/0015-7473-62.3.171

Matsunaga M, Obataya E, Minato K, Nakatsubo F (2000) Working mechanism of adsorbed water on the vibrational properties of wood impregnated with extractives of pernambuco (*Guilandina echinata* Spreng.). J Wood Sci 46(2):122-129. https://doi.org/10.1007/BF00777358

Menard KP (2006) Dynamic mechanical analysis, 2nd edition. CRC Press, Boca Raton, FL. https://doi.org/10.1007/978-3-540-29805-2_1224

Mora CR, Schimleck LR, Mahon JM, Isik F, Mahon JM, Clark A, Daniels RF (2009) Relationships between acoustic variables and different measures of stiffness in standing *Pinus taeda* trees. Can J For Res 39(8):1421-1429. https://doi.org/10.1139/X09-062

Nocetti M, Brunetti M, Bacher M (2014) Effect of moisture content on the flexural properties and dynamic modulus of elasticity of dimension chestnut timber. Eur J Wood Wood Prod 73(1):51-60. https://doi.org/10.1007/s00107-014-0861-1

Papandrea SF, Cataldo MF, Bernardi B, Zimbalatti G, Proto AR (2022) The predictive accuracy of modulus of elasticity (MOE) in the wood of standing trees and logs. Forests 13(8):1273. https://doi.org/10.3390/f13081273

Peng Y, Shi SQ, Kim MG (2008) Effect of temperature on the dynamic mechanical properties of resin film and wood. For Prod J 58(12):68-74.

Pizzo B, Pecoraro E, Lazzeri S (2018) Dynamic mechanical analysis (DMA) of waterlogged archaeological wood at room temperature. Holzforschung 72(5):421-431. https://doi.org/10.1515/hf-2017-0114

Salmén L, Stevanic JS, Olsson AM (2016) Contribution of lignin to the strength properties in wood fibres studied by dynamic FTIR spectroscopy and dynamic mechanical analysis (DMA). Holzforschung 70(12):1155-1163. https://doi.org/10.1515/hf-2016-0050

Se Golpayegani A, Brémaud I, Gril J, Thevenon MF, Arnould O, Pourtahmasi K (2012) Effect of extractions on dynamic mechanical properties of white mulberry (Morus alba). J Wood Sci 58(2):153-162. https://doi.org/10.1007/s10086-011-1225-7

Teles RF, De Souza MR, Wimmer P (2018) Acoustical properties of 10 Amazonian hardwoods. Pages 1675–1681 *in* Proceedings 25th International Congress on Sound and Vibration 2018, ICSV 2018: Hiroshima Calling, July 3, 2018, Hiroshima, Japan.

Tronchin L, Manfren M, Vodola V (2020) Sound characterization through intensity of acoustic radiation measurement: A study of Persian musical instruments. Appl Sci 10(2):633. https://doi.org/10.3390/app10020633

Wang X, Ross RJ, McClellan M, Barbour RJ, Erickson JR, Forsman JW, McGinnis GD (2001) Nondestructive evaluation of standing trees with a stress wave method. Wood Fiber Sci 33(4):522-533.

Wang Z, Li L, Gong M (2012) Measurement of dynamic modulus of elasticity and damping ratio of wood-based composites using the cantilever beam vibration technique. Constr Build Mater 28(1):831-834. https://doi.org/10.1016/j.conbuildmat.2011.09.001

Wegst UGK (2006) Wood for sound. Am J Bot 93(10):1439-1448. https://doi.org/10.3732/ajb.93.10.1439

Yang JL, Ilic J, Wardlaw T (2003) Relationships between static and dynamic modulus of elasticity for a mixture of clear and decayed eucalypt wood. Aust For 66(3):193-196. https://doi.org/10.1080/00049158.2003.10674911