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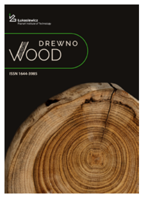

Tests of the Mechanical and Acoustic Parameters of Electric Guitar Bodies

Andrzej Ryniewicz[a]
Marcin Pietruch[a]
Anna M. Ryniewicz[b]
Łukasz Bojko[c] *

[a] Faculty of Engineering Sciences, University of Applied Science in Nowy Sącz, Poland
[b] Faculty of Health Sciences, University of Applied Science in Nowy Sącz, Poland
[c] Faculty of Mechanical Engineering and Robotics, AGH University of Krakow, Poland

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The aim of this work was to perform a mechanical and acoustic analysis of electric guitar bodies. Samples of ash, oak, walnut, lime tree, and fir were selected for mechanical tests – with constant moisture content, made of latewood, and free from defects. The tests were carried out on a Brinell device to determine the hardness of the wood, and on an MCT3 machine from Anton Paar to determine the microhardness and elastic moduli. The elastic properties of wood are determined by its anisotropy and have different values depending on the direction of force in relation to the fibers. The wood showed the greatest stiffness along the fibers; in the case of forces acting perpendicular to the fibers, the stiffness was much lower. Sound transmission tests of selected acoustic parameters were carried out. They involved measuring and analyzing the frequency and damping of vibrations of guitar bodies using a special vibration sensor. The acoustic parameters of a guitar body experimentally made from walnut were compared with those of a mass-produced Ibanez guitar made of ash wood. Each species of wood has its own characteristic blend of physical properties, such as grain structure, density, weight, and strength, which influence the final tonal power of the guitar. The test results of various wood species indicate significant differences in strength and acoustic-resonance properties, which determine the absorption of vibrations, sound amplification, and sound transmission. The use of a specific wood for a guitar body is dependent on the musician's artistic vision and the purpose of the instrument.

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Introduction

Each species of wood has its own characteristic mix of physical properties, such as grain structure, density, hardness, strength, and elasticity, which affect the ability to conduct sound and the tonal power of the guitar. Ahvenainen (2019) studied the anatomical and mechanical properties of wood for electric guitar bodies. Avram et al. (2023) studied the physical and mechanical properties of wood from three species of low-density, highly homogeneous hardwoods, including lime wood. Among other things, Brinell hardness in the transverse and tangential sections was studied. Asikuzun and Isleyen (2019) determined the changes in mechanical properties of new and aged wood using the Vickers microhardness test. Asikuzun and Kaymakci (2018) performed mechanical analysis in the form of XRD and Vickers microhardness studies of wood polymer nanocomposite materials (WPN). Pate et al. (2015a) experimentally assessed the variability of modal parameters of nominally identical electric guitars in an industrial context. Xolboboyevich (2023) presented a review of the species and properties

* Corresponding author: lbojko@agh.edu.pl

of wood used in the industry. Zoric et al. (2019) investigated the acoustic and mechanical properties of walnut and ash wood for the body of a solid-body electric guitar. Wood has the highest parameter values in the anatomical direction along the length of the fibers, and lower values in the transverse direction. Different wood species provide more low frequencies than others. Some provide more sharpness in the mid-range or high-end. The tone profile can add depth and texture to the sound of a guitar. Fleischer (2005) studied the vibration of a solid-body bass guitar and the effect of body vibration on string vibration. Fleischer and Zwicker (1998) conducted research on the mechanical vibration of electric guitars. He tested a simple measurement technique that would enable diagnosis of the causes of dead spots using two types of electric guitars. The causes and frequencies of dead spots in a typical electric guitar with a symmetrical headstock are also described in a book by Rossing (2010). Some musicians favor overtones and a sense of richness, while others prefer a focused sound. Certain types of body wood create a distinctive profile that is clearly perceptible when different musicians play the same guitar. Other genres are more neutral, allowing the musician to apply an individual touch. Le Carrou et al. (2014) attempted to quantify the influence of the guitarist on the vibration of the guitar. Navarret et al. (2009) evaluated how the material of the solid body of an electric guitar influences the sound produced. The study involved 32 guitarists. Bennett developed a model based on two mechanical properties of wood, density and Young's modulus, to determine the suitability of different types of wood for each part of the guitar. The model may serve as a guide for future wood selection for guitar components (Bennett, 2016). Jasiński et al. (2021) also investigated how the use of different types of wood in electric guitar bodies influences the sound produced by the instrument. Zoric and Kaljun (2018) evaluated the influence of the acoustic properties of walnut and ash wood on the production of solid-body electric guitars. Some musicians link the influence of the instrument's sound with the selection of appropriate wood for the guitar body. Studies focusing on the body of the instrument are nevertheless rare, and for this reason we selected this area for our research.

The aim of the work is to perform a mechanical and acoustic analysis of electric guitar bodies, in terms of assessing hardness, microhardness, and elastic moduli, as well as the amplitude and frequency of the vibrations generated.

An electric guitar itself emits very little sound, and so there is no need to transfer the energy of the vibrating strings to the body of the instrument. This means that the vibrations of the strings of a solid-body electric guitar do not decay as quickly as in the case of an acoustic guitar (Fleischer, 2005; Ray et al., 2021). Musicians express this by stating that an electric guitar has better sustain than an acoustic guitar (Navarret, 2009).

Materials and methods

1. Mechanical tests

The research material includes various types of wood for use in electric guitar soundboards. Wood is an anisotropic and hygroscopic material with a nonuniform, variable structure. The study of mechanical properties requires consideration of many factors, among which the anatomical directions of the structure of wood of a certain density, free from defects, have a significant impact on its use.

The following wood species were selected for mechanical and micromechanical tests: common ash, English oak, walnut, small-leaved lime, and silver fir. Samples were subjected to technological procedures consistent with the production of electric guitar soundboards. They were obtained by mechanical processing in the form of milling, and the use of carpentry power tools to obtain the required dimensions and appropriate shape in accordance with the technology. The blocks are made of latewood, free of defects, with constant moisture content (Jiang et al., 2017; Pate et al., 2015a; Zoric et al., 2019). The samples were weighed on a laboratory scale, and the shape was measured to determine the density of the wood species tested (Jiang et al., 2018; Malaga-Toboła et al., 2019; Yilmaz Aydin and Ozveren, 2019).

Samples for Brinell hardness testing were cuboids with dimensions of 50 mm x 50 mm x 34 mm, and those

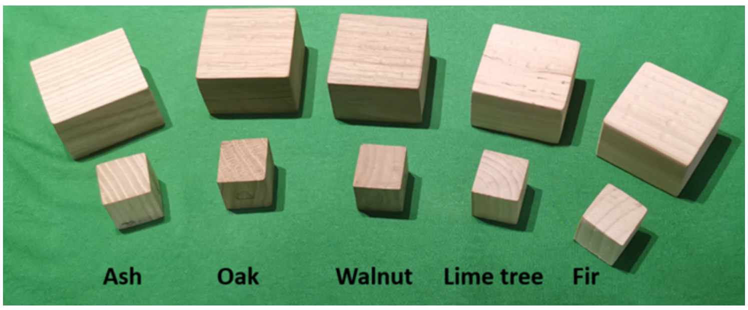

Fig. 1. Samples for mechanical and micromechanical tests

for testing microhardness and Young's modulus were cubes with an edge length of 20 mm (Fig. 1).

The hardness tests concerned deformations under the action of a static load related to the elastic-plastic properties of the material. A Brinell hardness tester was used for hardness tests (Fig. 2a). The test performed was a non-standard Brinell test for wood conducted according to the PN-EN ISO 6506-1:2008 standard. It consisted of pressing an indenter, in the form of a ball of a specific diameter, into the surface of the tested material at a given time. The test parameters were as follows: indenter load 306.25 N, ball diameter 10 mm. The diameters obtained from the indentations were measured on a Zeiss Stemi 508 stereoscopic microscope. On this basis, the average hardness values were determined according to the Brinell method in three anatomical directions: longitudinal to the fibers (W), transverse-radial (R), and transverse-tangential to the fibers (S) (Fig. 3a).

Micromechanical tests, which consisted of measurements of microhardness and Young's modulus in selected cross-sections, were carried out on the MCT³ device from Anton Paar (Fig. 2b). They were determined using a Rockwell R500 indenter. In the measurements, the force and penetration depth values were continuously recorded during the loading and unloading cycle. The maximum load value was 2 N, the loading and unloading speed was 4 N/min, and the maintenance time of the maximum load was 15 s. For each cycle, the indenter load was determined as a function of the penetration depth. Analysis of micromechanical properties was based on the Oliver and Pharr method, according to which the microhardness and elastic moduli of the tested materials were calculated from indentation curves (Bojko et al., 2015, 2022; Ryniewicz et al., 2016, 2018). The micromechanical parameters of various wood species were determined as the average of 10 measurements in three selected planes, in anatomical directions (Fig. 3).

2. Acoustic tests

The research material included two solid-body electric guitars. The body of the first was made of walnut wood. The second guitar is a factory design, mass produced by Ibanez, with a body made of ash wood. Both guitars have necks made of maple wood. To ensure the comparability of the results, uniform testing conditions were maintained.

A measurement system was developed that allowed us to determine the acoustic parameters of the guitars tested. It consisted of several devices, including a Huntek 6022B oscilloscope, a piezoelectric vibration sensor, an

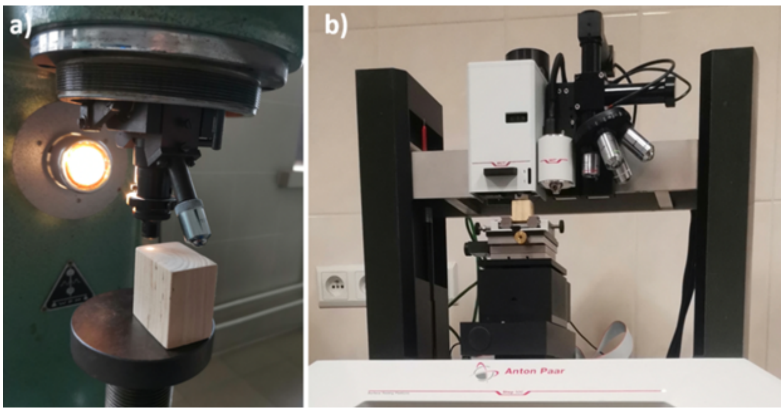

Fig. 2. Devices used in mechanical tests: a) Brinell hardness tester, b) MCT3 microhardness tester

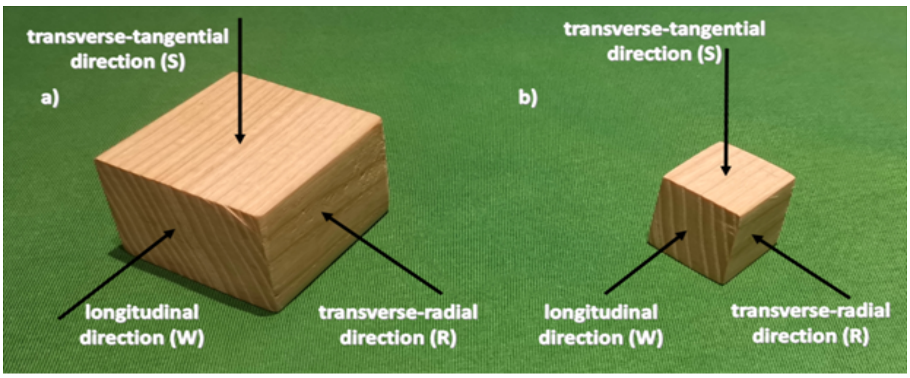

Fig. 3. Ash samples labeled with measurement directions for testing: a) hardness using the Brinell method, b) microhardness and Young's modulus using the Oliver and Pharr method

acoustic signal amplifier, a laboratory power supply, and a device forcing string vibrations (Fig. 4). The piezoelectric sensor is mounted approximately 20% below the guitar's steel bridge. In this area, the strings directly transmit their vibrations to the bridge. The sensor was connected to an acoustic signal amplifier, which is a necessary device because the tested guitars have solid-body structures and do not transmit vibrations clearly enough to allow measurements and reading of their frequencies on an oscilloscope. The oscilloscope was powered at 12 V using a laboratory power supply. The oscilloscope measurement probes were connected to the acoustic signal amplifier, transmitting an amplified vibration signal, which made it possible to obtain a graph of the vibration frequency of the guitar body. The impulse was generated using a device that forces string vibrations, specially constructed for the purpose of this research. This device consisted of a base block and an arm, at the end of which was mounted a pendulum with a guitar pick attached on rolling bearings. The regulating element that determined the impact force was an adjustable limiter, which made it possible to swing the pendulum to the same value each time. This ensured that the guitar strings were struck with the same force in each test.

Results and discussion

1. Mechanical tests

The density tests showed that this property depends on the wood species (Table 1). Among the wood samples tested, ash had the highest density. Oak and walnut had similar densities, that of oak being slightly higher. Lime and fir also had densities that were similar to each other and much lower than ash. It should be noted that the tested wood samples were stored in a dry room and had a moisture content of approximately 15%, measured using an electric moisture meter specially designed for use with wood. The basic elements that make up wood are carbon (49.5%), oxygen (43.8%), hydrogen (6%), nitrogen (2%), and others. The main compounds in wood are cellulose (~45%), chemicellulose (~30%), lignin (~20%), sugar, protein, starch, tannins, essential oils, rubber, and mineral substances. The micellar structure of cellulose is the reason for the anisotropy of wood (Shmulsky and Jones, 2019).

The resistance that wood offers to concentrated pressure forces characterizes its resistance to indentation. In the proposed method, it was determined

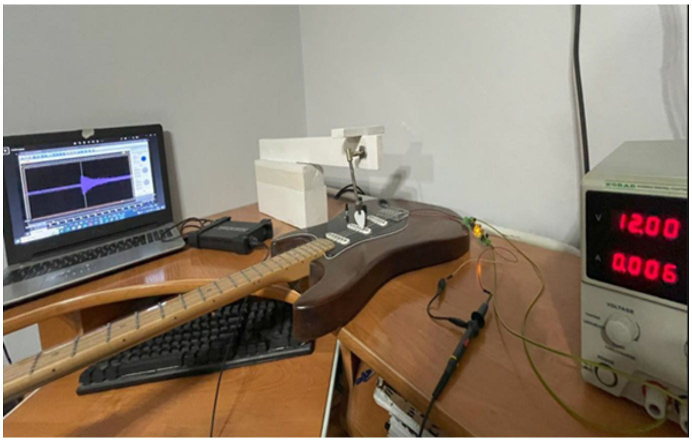

Fig. 4. Station for conducting acoustic tests

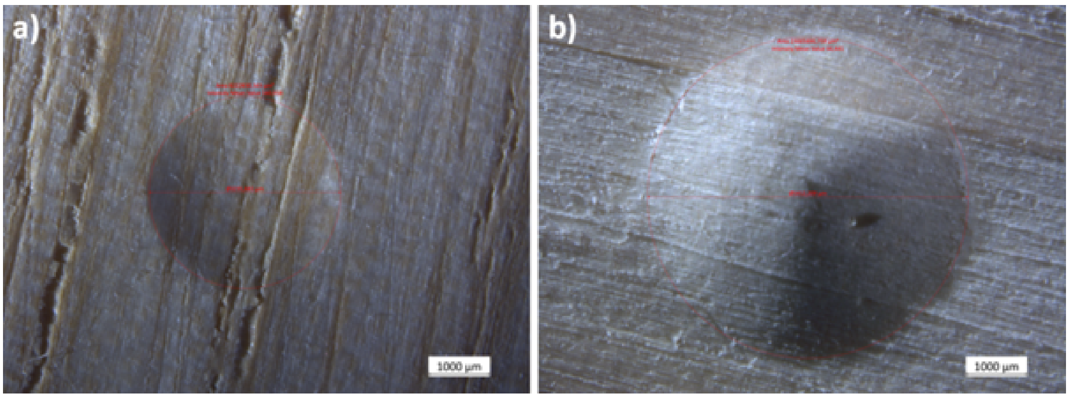

Fig. 5. Examples of indentations from Brinell hardness measurements measured on a stereoscopic microscope in the transverse-tangential direction with respect to the fibers: a) ash, b) fir

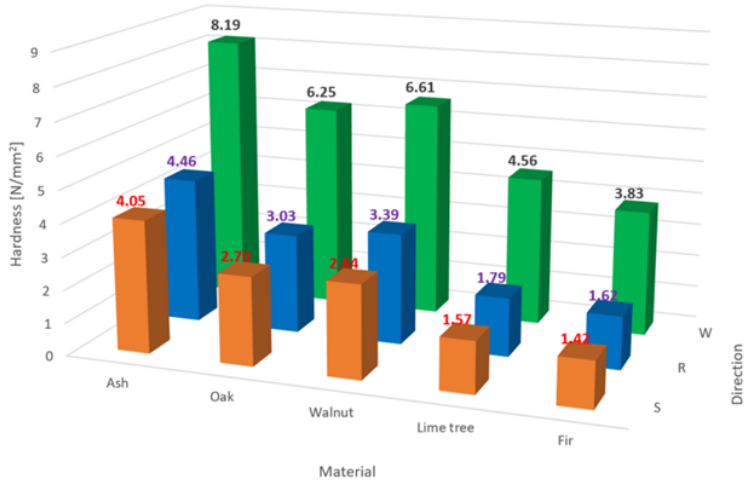

Fig. 6. Brinell hardness results for the tested wood species in the analyzed directions

on the basis of the average diameter of the indentation measured on the microscope (Fig. 5). Research indicates that it depends on the type of wood, on the direction of action of the penetrator (in this case the ball) in relation to the course of the fibers, and on the density of the wood (Table 1, Fig. 6). Ash had the highest hardness values: in the longitudinal direction (H_W) 8.19 N/mm^2, in the transverse-radial direction (H_R) 4.46 N/mm^2, and in the transverse-tangential direction (H_S) 4.05 N/mm^2. Walnut and oak had lower but still high hardness values – for walnut: H_W = 6.61 N/mm^2, H_R = 3.39 N/mm^2, H_S = 2.84 N/mm^2; and for oak: H_W = 6.25 N/mm^2, H_R = 3.03 N/mm^2, H_S = 2.70 N/mm^2. Lime wood had a hardness value in the longitudinal direction (H_W) of 4.56 N/mm^2 and much lower values in the radial and tangential directions (H_R = 1.79 N/mm^2, H_S = 1.57 N/mm^2). Of the wood species tested, fir had the lowest hardness, with H_W = 3.83 N/mm^2 and much lower values in the radial and tangential directions (H_R = 1.62 N/mm^2, H_S = 1.42 N/mm^2). Based on Brinell hardness tests, it can be concluded that the hardnesses in the radial direction in all tested wood species had higher values than in the tangential direction (Table 1, Fig. 6). This information may indicate the possible use of wood orientation in the guitar body. Lachowicz et al. (2021) conducted a multidimensional analysis of the Brinell hardness of silver birch wood in Poland. Hardness was measured in three directions: longitudinal, transverse radial and transverse tangential. Lykidis et al. (2016) evaluated a modification of the Brinell method for determining the hardness of solid wood, using six different solid wood species as an example. Pelit et al. (2015) investigated the effect of thermomechanical densification and heat treatment on density and Brinell hardness of Scots pine and eastern beech wood. Gasparik et al. (2016) determined the effect of wood species, thickness and degree of densification on the impact bending strength and Brinell hardness in the radial direction.

However, in terms of strength, the most preferred species for the guitar body are ash, walnut, and oak.

The hardness of wood, which is its response to concentrated elastic-plastic loads, should not have a significant impact on the vibroacoustic response of the body of a solid-body electric guitar, because it is the response to free vibrations that is analyzed. These vibrations remain in the range of elastic deformations. However, it should be noted that the results of Brinell hardness tests in anatomical directions, on selected wood species, confirmed significant differences depending on the type and density of the wood, but above all on the directionality of its structure.

The highest hardness, which varies depending on the species, was found in the samples tested longitudinally to the fibers. Hardness also varied in transverse directions, being different in the radial (higher) and tangential (lower) directions in all species. Note that the information provided in the literature regarding equal hardness in these transverse directions may be misleading.

Micromechanical tests, which included microhardness and Young's modulus of elasticity, were carried out using precise and innovative equipment. Due to the anisotropy of wood, they were also made in three directions: longitudinal (W), transverse-radial (R), and transverse-tangential (S) (Table 2, Fig. 7). Ash had the highest microhardness values: in the longitudinal direction (HiT_W) 45.72 MPa, in the transverse-radial direction (HiT_R) 39.32 MPa, and in the transverse-tangential direction (HiT_S) 32.95 MPa. Walnut had lower but still high microhardness values: HiT_W = 41.37 MPa, HiT_R = 32.97 MPa, and HiT_S = 26.34 MPa. The values for oak were slightly lower: HiT_W = 35.71 MPa, HiT_R = 30.05 MPa, and HiT_S = 25.62 MPa.

Table 1. List of density and Brinell hardness results for the tested wood species

Measurement direction	Material / Metrological parameter	Ash Average	Ash Standard deviation	Oak Average	Oak Standard deviation	Walnut Average	Walnut Standard deviation	Lime tree Average	Lime tree Standard deviation	Fir Average	Fir Standard deviation
	Density, kg/m³	859.88		696.95		650.01		486.56		413.52	
Transverse - tangential to the fibers	Indentation diameter, mm	3.10	0.14	3.79	0.27	3.69	0.20	4.95	0.57	5.15	0.39
	Hardness H_S	4.02	0.39	2.66	0.39	2.81	0.34	1.51	0.38	1.39	0.25
Transverse - radial to the fibers	Indentation diameter, mm	2.98	0.20	3.57	0.14	3.45	0.37	4.65	0.48	4.85	0.42
	Hardness H_R	4.37	0.79	3.02	0.26	3.24	1.11	1.73	0.42	1.58	0.30
Longitudinal to the fibers	Indentation diameter, mm	2.27	0.42	2.51	0.11	2.44	0.10	2.93	0.12	3.27	0.49
	Hardness H_W	7.59	2.44	6.21	0.55	6.58	0.52	4.54	0.38	3.63	1.00

Table 2. List of micromechanical parameters of the wood species tested, obtained using the Oliver and Pharr method

Measurement direction	Material / Metrological parameter	Ash Average	Ash Standard deviation	Oak Average	Oak Standard deviation	Walnut Average	Walnut Standard deviation	Lime tree Average	Lime tree Standard deviation	Fir Average	Fir Standard deviation
Transverse – tangential to the fibers	Microhardness HV	3.36	0.41	2.61	0.59	2.69	0.39	1.24	0.06	1.09	0.19
	Microhardness HiT_S [MPa]	32.95	4.02	25.62	5.77	26.34	3.80	12.12	0.56	10.64	1.90
	Young's modulus EiT_S	2.09	0.29	1.29	0.13	1.11	0.08	0.49	0.04	0.34	0.08
	Penetration depth, h_{max} [μm]	22.30	2.81	16.06	13.40	29.03	3.58	61.68	2.96	73.77	14.19
Transverse – radial to the fibers	Microhardness HV	4.011	0.54	3.06	0.28	3.36	0.41	1.20	0.03	1.35	0.40
	Microhardness HiT_R [MPa]	39.32	5.30	30.05	2.76	32.97	3.98	11.78	0.31	13.80	3.95
	Young's modulus EiT_R	2.64	0.16	1.74	0.22	1.87	0.16	0.47	0.01	0.94	0.20
	Penetration depth, h_{max} [μm]	18.69	2.27	24.48	2.22	22.52	2.58	63.40	1.34	59.84	22.17
Longitudinal to the fibers	Microhardness HV	4.66	0.73	3.64	0.40	4.22	0.36	1.68	0.18	1.64	0.54
	Microhardness HiT [MPa]	45.72	7.14	35.71	3.88	41.37	3.55	16.50	1.81	16.12	5.28
	Young's modulus EiT_W	5.38	1.57	2.81	0.34	3.25	0.15	2.38	0.69	2.05	0.20
	Penetration depth, h_{max} [μm]	15.59	2.77	20.32	6.10	17.35	1.35	42.58	4.69	47.21	15.91

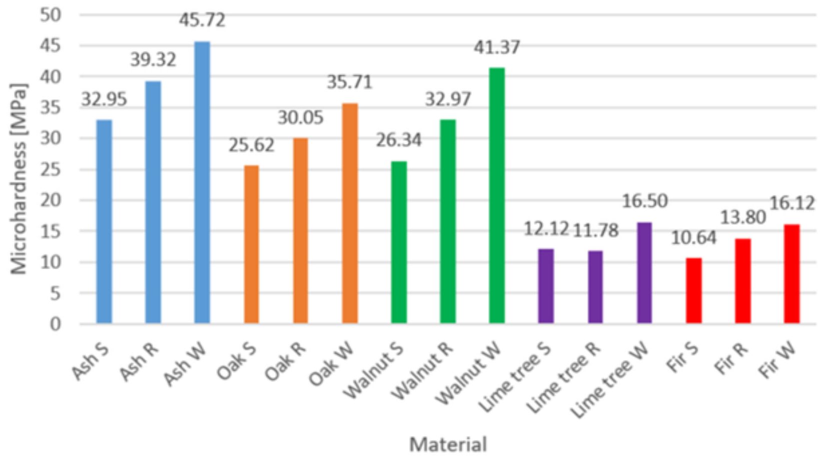

Fig. 7. Microhardness values for the wood species tested: in the longitudinal direction (W), in the transverse-radial direction (R), and in the transverse-tangential direction (S)

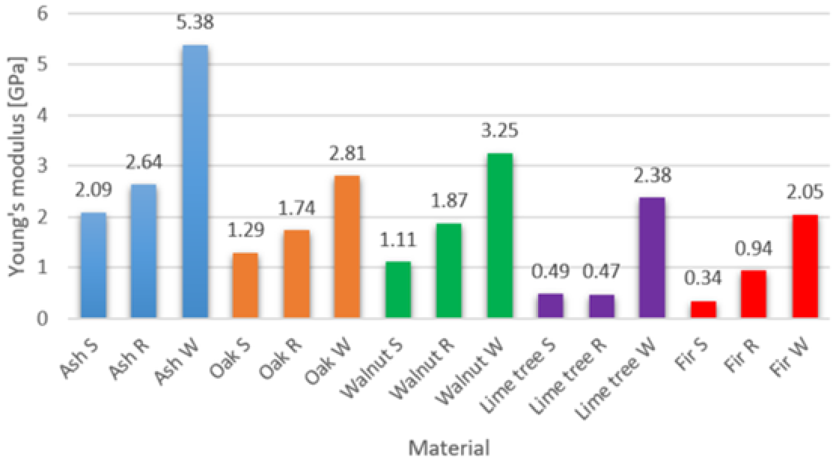

Fig. 8. Young's elastic moduli of the tested wood species: in the longitudinal direction (W), in the transverse-radial direction (R), and in the transverse-tangential direction (S)

Significantly lower microhardness values were recorded for lime wood (HiT_W = 16.50 MPa, HiT_R = 11.78 MPa, HiT_S = 12.12 MPa) and fir (HiT_W = 16.12 MPa, HiT_R = 13.80 MPa, HiT_S = 10.64 MPa). However, lime wood had a higher microhardness value in the tangential direction than in the radial direction, while fir had a higher value in the radial direction than in the tangential direction, which did not differ significantly from the longitudinal value.

The hardness and microhardness tests show that the hardness increases with increasing wood density. Wood has the highest hardness and microhardness in the direction parallel to the grain.

In micromechanical tests, Young's elastic moduli were also determined, depending on the anatomical directions of the tested wood (Table 2, Fig. 8). The elastic properties of wood are determined by its anisotropy. All wood species have the highest values of Young's modulus in the longitudinal direction (EiT_W in the range 2.05 GPa to 5.38 GPa). The higher the value of the modulus of elasticity, the higher the strength of the wood. Elasticity affects the ability to adapt to load. The higher the modulus value, the lower the deformation values of compressed and tensile elements. The highest values of elastic moduli were determined for ash wood; lower values were recorded for walnut, and then for oak. Much lower values of these moduli were found for lime wood and fir. However, for lime wood, the value in the longitudinal direction was much higher (EiT_W = 2.38 GPa) than the values in the radial and tangential directions (EiT_R = 0.47 GPa, EiT_S = 0.49 GPa). Fir had the values EiT_W = 2.05 GPa and EiT_R = 0.94 GPa, with the lowest value in the tangential direction (EiT_S = 0.34 GPa).

The determined distributions of elastic modulus values are beneficial for the guitar body, because the modulus in the longitudinal direction will ensure stiffness between the body's restraints, while lower modulus values in the transverse directions (radial and tangential) will favor vibroacoustic phenomena: resonance and sound-absorbance. Analysis of the elastic moduli values of the tested wood species indicates that ash and walnut will be the preferred acoustic materials. Therefore, these two wood species were selected for further tests to produce the bodies of two guitars (Carcagno et al., 2018; Pate et al., 2015b, 2015c).

In terms of geometry, construction, and functional design, both guitars were identical. There were differences in the following properties of the ash and walnut woods:
- density,
- hardness determined by the classic Brinell method in three anatomical directions (H_S, H_R, H_W),
- microhardness determined using the Oliver and Pharr method, in three anatomical directions (HiT_S, HiT_R, HiT_W),
- elastic moduli determined using the Oliver and Pharr method, in three anatomical directions (EiT_S, EiT_R, EiT_W).

2. Acoustic tests

In vibroacoustic tests, the vibrations of the bodies of the ash guitar and walnut guitar were determined in the form of frequency diagrams (Fig. 9). These graphs were divided into four intervals, and attenuation coefficients were calculated in each interval.

The first stage of the research included five tests on a guitar mass-produced by Ibanez, with a body made of ash wood. In all tests, the vibration frequency graphs of the guitar with an ash body were similar in nature. A similar range of vibration amplitude and damping was observed in all studies. From the moment the strings were struck, the vibration amplitude decreased evenly, which indicated good damping and, at the same time, good acoustics of the body (Fig. 9a). In a similar procedure, five tests were performed on a guitar with a walnut body. In all trials, the frequency graphs were also similar in nature (Fig. 9b). In each of the vibration frequency graphs obtained from the walnut body, a characteristic strengthening of the vibration amplitude was observed in the second phase, which may indicate the phenomenon of rumble.

To determine the vibration damping coefficients of the bodies of both guitars, the frequency graphs were narrowed to 1 ms. The periods of one complete vibration and the appropriate amplitudes for the selected periods were determined, and the damping coefficients in the first interval were calculated. The number of complete vibrations was counted, starting from the point where the amplitude was the highest. The red dots marked in maximum-amplitude vibrations denote the starting and ending times of counting periods (Fig. 10).

The damping coefficients of the tested bodies were determined from the formula:

$$\xi = \frac{1}{m-n} \ln \frac{A_n}{A_m} \qquad (1)$$

where:

$\ln \frac{A_n}{A_m}$ is the logarithmic damping decrement,

A_n is the amplitude of the n-th vibration,

A_m is the amplitude of the m-th vibration,

$m-n$ is the number of complete vibrations between amplitudes (i.e. period).

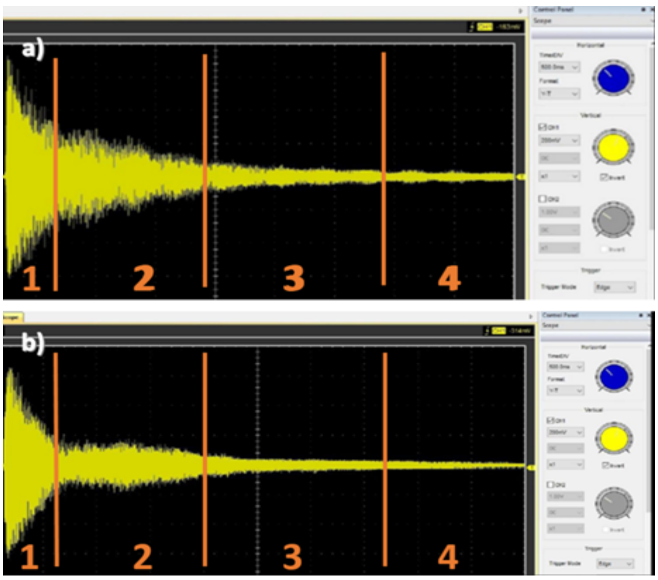

Fig. 9. Examples of vibration frequency charts for solid-body guitars, with marked intervals 1–4, used to determine the damping coefficients of bodies made of: a) ash, b) walnut

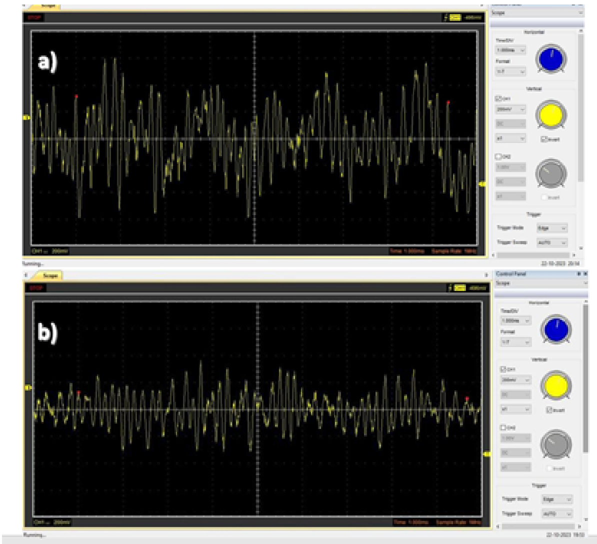

Fig. 10. Example graphs of guitar vibrations in the 1 ms range for the first interval, for bodies made of: a) ash, b) walnut

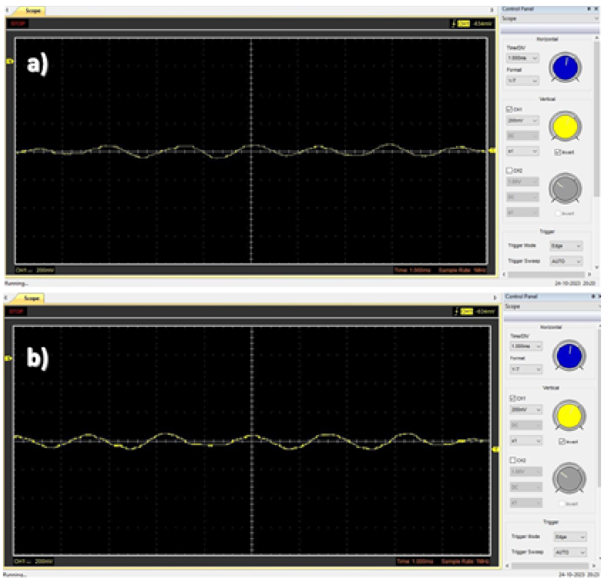

Fig. 11. Examples of frequency charts for the fourth interval in the final vibration cycle for bodies made of: a) ash, b) walnut

The next parameters analyzed were vibration frequency, amplitude, and period. To calculate the vibration frequency in the initial phase, the maximum amplitude and period were determined, and to determine the final vibration frequency, the amplitude in the final phase of body vibration and the period of full vibration were read (Fig. 11).

Table 3 lists the average values of the acoustic parameters of the guitars tested.

In the case of a guitar body made of walnut, a much higher damping coefficient was obtained: $\xi = 0.020$, compared with $\xi = 0.009$ in the case of a guitar body made of ash wood. These calculations confirm the thesis that the vibrations of the ash body decay much more slowly than in the case of the walnut body.

It can be seen that when the strings of a walnut body guitar are struck, the amplitude is at the same level as in the case of an ash body guitar, but the vibrations of the walnut body are damped much faster. It can be added that, in the case of the walnut guitar, the amplitude decreases quite rapidly, then increases very slightly, and stops at a constant level, and then the vibrations are gradually damped.

Comparing the frequency charts of the tested guitars, it can be concluded that the branded guitar has better acoustics, because the vibration frequency response is much more evenly distributed (Fig. 9).

The frequency response for the two bodies differs slightly (Table 3). In the case of a walnut wood body this band ranges from 5000 Hz to 625 Hz, and for an ash

Table 3. List of average values of acoustic parameters of the guitars tested

Body vibration phase	Average values of acoustic parameters	Body material	
		Ash	Walnut
Starting	Amplitude [mV]	720	680
	Period [ms]	0.22	0.2
	Frequency [Hz]	4545	5000
Final	Amplitude [mV]	40	40
	Period [ms]	1.4	1.6
	Frequency [Hz]	714	625
Damping factor, ξ		0.009	0.020

wood body the range is from 4545 Hz to 714 Hz. These differences are so small that they may have a negligible impact on the tone of these guitars. However, the differences in the damping coefficients of these two bodies are so large that they may have a significant impact on the length and quality of the sound of the instrument.

The evaluation of the acoustic responses of both guitars involved the identification of modal parameters to the same input signal that constituted their free response. Analysis of these responses indicates that the micromechanical and mechanical parameters of the material used for guitar bodies influence the acoustic properties of the instruments.

This is confirmed by the authors of other publications, who also point out that an important area in the study of solid-body guitars is the material properties of the body, which affect the vibration characteristics of the instrument and its acoustics. Ray et al. (2021) investigated whether the material properties of a solid-body electric guitar have a significant effect on the vibration characteristics of this instrument and its acoustic behavior. Henriques et al. (2022) identified the orthotropic elastic properties of wood using the synthetic image method based on digital image correlation. Bilko et al. (2021) determined the shear strength of pine wood in two directions of fiber orientation. Miyoshi et al. (2018) evaluated the effect of density and anatomical features on the mechanical properties of different wood species in the transverse direction.

A particularly important issue analyzed with regard to the correlation of micromechanical and vibroacoustic tests is differences in elasticity resulting from the anatomical anisotropy of the tested bodies (Fig. 8, Table 3). The stiffness of the structure is proportional to the elastic moduli. The highest modulus values were found for ash wood in all three directions. The highest stiffness was in the longitudinal direction; values were lower in the transverse directions. It can be assumed that an appropriate arrangement of body fibers will generate vibrations with higher amplitude in the transverse directions than in the longitudinal direction. Dackermann et al. (2016) conducted a comparative study using static and ultrasonic methods of materials testing to determine anisotropic material properties of wood. Malaga-Toboła et al. (2019) evaluated the effect of wood's anisotropy on its mechanical properties with respect to the scale effect. Guntekin and Aydin (2016) investigated the elasticity constants of black pine using ultrasonic waves. They determined three Young's moduli, three Kirchoff moduli and six Poisson ratios at constant moisture content. A much lower damping coefficient was found for the ash wood body than for the walnut body. With respect to the areas analyzed relating to the flow of acoustic energy from the body to the surroundings, the most suitable wood for the body of a solid-body electric guitar is ash.

Conclusions

Based on Brinell hardness tests, it can be concluded that the information provided in the literature regarding the equal hardness of wood in the transverse-radial direction and in the transverse-tangential direction is not precise. Hardnesses in the radial direction in all tested wood species had higher values than in the tangential direction.

Brinell hardness and microhardness tests using the Oliver and Pharr method show that hardness increases with increasing wood density. Wood has the highest hardness and microhardness in the direction parallel to the fibers, and lower values in transverse cross-sections.

Analysis of the elastic moduli values of the tested wood species using the Oliver and Pharr method indicates that the preferred acoustic materials are, in order, ash wood, walnut, and then oak. The micromechanical testing method seems justified because of the possibility of assessing the elasticity parameters of wood.

Based on vibroacoustic tests of guitars made of ash and walnut wood, it can be concluded that the Ibanez guitar has better acoustics, because the vibration frequency response is more evenly distributed and the vibration damping coefficient is lower. The vibrations of the ash body decay much more slowly than those of the walnut body.

Micromechanical and vibroacoustic tests of the wood used for the body of a solid-body electric guitar confirmed a mutual correlation in all analyses, which permits assessment of the acoustic properties of the constructed instrument.

The results of micromechanical tests may provide guidance for electric guitar manufacturers in terms of fiber orientation in the bodies. Body length should be in the direction along the grain (W), body width in the transverse-radial direction to the grain (R), and thickness in the transverse-tangential direction to the grain (S).

The mechanical and acoustic test results presented in this work in the form of density, hardness, microhardness, Young's modulus, as well as amplitude, frequency of generated vibrations and vibration damping coefficients of the body, will enable designers of electric guitars to make an appropriate selection of the material and its fiber orientation when developing electric guitar bodies.

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