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Selection of Wood Based on Acoustic Properties for the Solid Body of Electric Guitar

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For the purpose of making of a solid body of an electric guitar the acoustic- and mechanical properties of walnut- (*Juglans regia L.*) and ash wood (*Fraxinus excelsior L.*) were researched. The acoustic properties were determined in a flexural vibration response of laboratory conditioned wood elements of 430 × 186 × 42.8 mm used for making of a solid body of an electric guitar. The velocity of shear- and compression ultrasonic waves was additionally determined in parallel small oriented samples of 80 × 40 × 40 mm. The research confirmed better mechanical properties of ash wood, that is, the larger modulus of elasticity and shear modules in all anatomical directions and planes. The acoustic quality of ash wood was better only in the basic vibration mode. Walnut was, on the other hand, lighter and more homogenous and had lower acoustic- and mechanical anisotropy. Additionally, reduced damping of walnut at higher vibration modes is assumed to have a positive impact on the vibration response of future modelled and built solid bodies of electric guitars. When choosing walnut wood, better energy transfer is expected at a similar string playing frequency and a structure resonance of the electric guitar.

Keywords: wood; acoustic properties; mechanical anisotropy; electric guitar.

1. Introduction

Wood is due to the indispensable physical and mechanical properties used for production of various music instruments. As an integral material of music instruments, it plays a significant role in their design and contributes to their acoustic and mechanical behaviour, as well as to the cultural identity. There are several wood species used to make music instruments. In this area not only an acoustic aspect is important (Mania *et al.*, 2017), but also a mechanical response (Mania *et al.*, 2015), physical stability, visual aesthetics and tangible properties are very necessary (Bucur, 2006). Different types of instruments can be made from several wood species, where very often various combinations of light- and high dense tonewoods are used in a single music instrument.

The function and impact of wood on electric string instruments has not been well studied so far. Actually, at the very beginning of making of electric guitars the upmost importance was dedicated only to an electro-acoustic chain (Lähdevaara, 2014). It has been shown later on the effect of strings end supports, since the end supports of the electric guitar also slightly follow the motion of the strings. The found mechanical coupling confirmed first studies of the guitar (Skrodzka *et al.*, 2011) and electric guitar with strings as a mechanically bound system (Pate *et al.*, 2015; Puszynski *et al.*, 2015; Mohamaad, Dixon, 2015; Issanchou *et al.*, 2018; Fleischer, Zwicker, 1998), however, it is well known from research in dynamic mechanical behaviour of violins (Skrodzka *et al.*, 2009; 2014).

The string/structure coupling has been for electric guitars well described by a driving-point conductance value at the fretting point of the neck, which is controlled by modal parameters (Fleischer, Zwicker, 1999). It has been shown, that a string playing frequency and a structure resonance may provoke substantial energy transfer from the string to the structure (Pate *et al.*, 2014). In this respect the alteration of resonance of corresponding strings was confirmed, followed by changes of decay time and timbre effects (Fleischer, Zwicker, 1998). The latter confirms that guitar strings and a body of the electric guitar represent a mechanically bound system.

Regardless of the demanding standards and industrial production of electric guitars, some guitar players claim they can notice differences between nominally identical solid body electric guitars. The differences were also confirmed in physical experiments. The authors found, for example, for nominally equal industrial electric guitars, the differences in weight up to 7%, in a modal frequency up to 8.6%, and in a modal damping ratio even up to 35.3% (Pate *et al.*, 2015). Due to the identical construction of studied guitars, these differences can mostly be attributed, in this case, to the variability of the intrinsic properties of used maple (*Acer* spp.) and rosewood (*Dalbergia* spp.). The difference in conductance in a mid-frequency range of an electric guitar was also a case when an ebony fingerboard was substituted with a rosewood one. Studies often report also on different vibration behaviour of an electric guitar due to various construction changes and construction junctions (Pate *et al.*, 2012; 2013). In addition, the results clearly show correlation between the dynamic and sound behaviour of electric bass guitar necks depending on the used wood species (Sprossmann *et al.*, 2013).

Authors also tried to directly measure the effect of vibrating strings on the pickup vibrations in a solid body of electric guitars, made of ash wood (*Fraxinus excelsior* L.). In this case, the measured pickup amplitudes were less than 1% of the total signal and did not significantly affect it (Puszynski, 2014). The study concluded, that wood can effect on sound only in string-wood feedback.

Studies were conducted as well in the direction of weight reduction of a solid body of music instruments, i.e. electric guitars. Thermal modification was used for a significant reduction of ash wood density (−6%), when the sound velocity and stiffness increased on average for 11% (Puszynski, Warda, 2014). Similar changes after dry thermal modification was confirmed also in beech wood (*Fagus sylvatica* L.), combined with significantly improved dimensional stability, being similar or better in acoustic properties comparing to hard maple (Zauer *et al.*, 2014; 2015; Pfriem, 2015). Positive changes, i.e. the decrease of density and increase of speed of ultrasound and specific stiffness is reported as well for beech after the thermal treatment in saturated vapour, to simulate accelerated aging of wood (Žveplan, Straže, 2017).

The aim of this research is to develop a fast and reliable procedure to determine relevant physical and mechanical properties of wooden elements used to make a solid body of electric guitars. The determined elastomechanical and modal variables will be afterwards used for optimisation of the construction, geometry and the shape of a final solid body of an electric guitar to achieve the optimum vibration response.

2. Material and methods

2.1. Material selection and processing

Air dried ash- (*Fraxinus excelsior* L.) and walnut woods (*Juglans regia* L.) (t = 30 years) were conditioned for 6 months in a laboratory (T = 20°C, RH = 50%), wherefrom elements were prepared (n = 2) for making of an electric guitar solid body. We selected longitudinally oriented wood elements 430 mm long (L), 186 mm wide (R) and 42.8 mm thick (T). The standard pickup hole was routed and 4 holes were drilled for bridge mounting (Fig. 1). Small prisms were additionally prepared in parallel, having dimensions $80 \times 40 \times 40$ mm (L, R, T; n = 2; Fig. 2). We

Fig. 1. Raw wood element for solid body of electric guitar with routed pickup- and bridge holes.

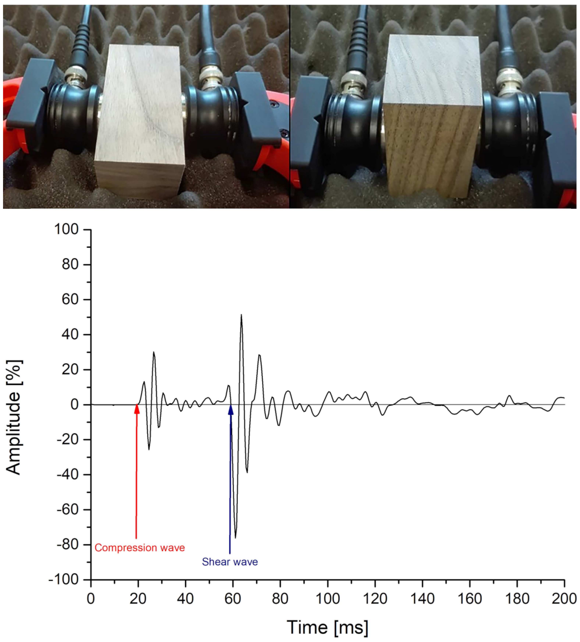

Fig. 2. Principle of measuring of velocity of ultrasonic waves (upper) and determination of time of flight of compression wave in T-direction and of shear TL-wave (bottom).

determined the mean density of 623 kg/m^3 for walnut (CV = 7.5%; CV – coefficient of variation), and 807 kg/m^3 (+25%, related to the density of walnut) for ash wood (CV = 9.3%).

2.2. Determination of acoustic and elastomechanical anisotropy of wood

The ultrasound technique was used for the acoustic characterisation of wood at the macroscopic level. We measured the velocity of compression and shear ultrasonic waves (Fig. 2) with a Pundit PL-200 device (Proceq, Schwarzenbach, CH) equipped with Panametric V150 shear wave ultrasonic probes at 250 kHz. The length of an ultrasonic impulse was 9.3 μs, at a voltage of 250 V, which was sent at frequency of 24 Hz. Three trials were performed on each specimen, with three repetitions in an every single anatomical wood direction (L – longitudinal, R – radial, T – tangential) and individual anatomical plane (*LR*-, *RL*-, *LT*-, *TL*-, *RT*-, *TR*-plane) of the specimen.

Elastomechanical variables were determined based on velocity of compression- (v_i) and shear ultrasonic waves (v_{ij}) (Fig. 2). Moduli of elasticity (E_L, E_R, E_T) and shear moduli (G_{LR}, G_{LT}, G_{RL}, G_{RT}, G_{TL}, G_{TR}) were calculated from the known relationship with the wood density (ρ) ($E_i = \rho \times v_i^2$; $G_{ij} = \rho \times v_{ij}^2$) (Bucur, 2006).

2.2.1. Determination of wood anisotropy by acoustic invariants

Anisotropy of a wood structure was evaluated by comparing compression and shear ultrasonic velocity between individual directions and planes. We introduced additionally the determination of acoustic invariants to verify the symmetry of a velocity tensor. The synthesized I-ratios are determined by planar anisotropy of the studied material (Eqs (2)–(4)), as well as by the total anisotropy of the material (Eq. (1)). For isotropic materials the I-ratio is equal to 1, and anisotropic materials have this value lower than 1. For spruce, which is very anisotropic from an acoustic point of view this ratio is 0.15, whereas for curly maple the value of 0.63 is reported (Bucur, 1988)

$$I\text{-ratio} = \frac{I_{23}}{(0.5\cdot(I_{12}+I_{13}))}, \tag{1}$$

where

- I_{12} is calculated as:

$$I_{12} = 0.5\cdot\sqrt{(v_{LL}^2 + v_{RR}^2 + 2\cdot v_{LR}^2)}, \tag{2}$$

- I_{13} is calculated as:

$$I_{13} = 0.5\cdot\sqrt{(v_{LL}^2 + v_{TT}^2 + 2\cdot v_{LT}^2)}, \tag{3}$$

- I_{23} is calculated as:

$$I_{23} = 0.5\cdot\sqrt{(v_{RR}^2 + v_{TT}^2 + 2\cdot v_{RT}^2)}. \tag{4}$$

2.3. Determination of mechanical and acoustic properties of wood in the frequency response at flexural bending

Longitudinally-radial oriented wood elements (Fig. 1) were laid on two nylon elastic supports which were positioned at the 1st nodal points of the flexural vibration mode (L = 22.4% of the element length or 96.32 mm from edge of the specimen). The pulsed elastic excitation with a rigid steel ball was performed in a geometric axis on the open-end of the element for the analysis of flexural vibration (Fig. 3). The condenser microphone PCB 130D20 was positioned on the opposite side of a specimen. The sound signal was acquired by NI-9234 DAQ module (National Instruments, Ltd.), in 24-bit resolution at 51 kHz sample rate. The measurements were carried out in a semi-anechoic room, with the acoustic absorption walls separating the room from the laboratory hall (the mean ambient noise level of 11.5 dB). Signals were further processed and analysed with LabVIEW software.

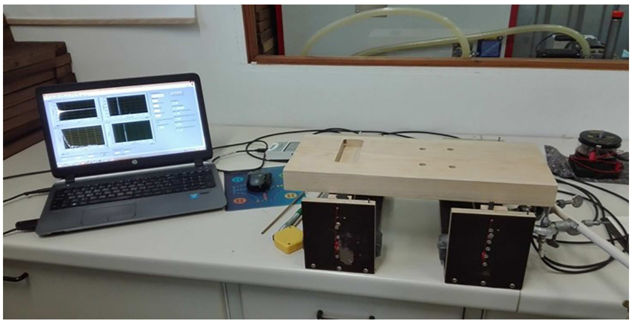

Fig. 3. Experimental setup of free-free flexural vibration measurements of wood elements.

To evaluate the flexural vibrations of the tested elements, the Timoshenko's vibration theory was used (Eq. (5)), which also takes into account the shear stresses in vibrating specimen. In order to determine the flexural bending modulus of elasticity (E_x) in an individual vibration mode and shear modulus (G_{xy}), Bordonne's solution was used (Eq. (6)) (Brancheriau, Bailléres, 2002)

$$E_X I_{GZ}\frac{\partial^4 v}{\partial x^4} - \rho I_{Gz}\left(1+\frac{E_X}{K_N G_{XY}}\right)\frac{\partial^4 v}{\partial x^2 \partial t^2} + \frac{\rho^2 I_{Gz}}{K_N G_{XY}}\frac{\partial^4 v}{\partial t^4} + \rho A\frac{\partial^2 v}{\partial t^2} = 0, \tag{5}$$

$$\frac{E_X}{\rho} - \frac{E_X}{K_N G_{XY}}\left[QF_2(m)\,4\pi^2\frac{AL^4}{I_{GZ}}\frac{f_n^2}{P_n}\right] = 4\pi^2\frac{AL^4}{I_{GZ}}\frac{f_n^2}{P_n}\left[1+QF_1(m)\right]. \tag{6}$$

Notation: E_X – bending modulus of elasticity [Pa], G_{XY} – shear modulus [Pa], I_{GZ} – moment of inertia [m^4], f_n – the bending frequency of the specimen in the i-th vibration mode, v – vibration amplitude [m], t – time [s], ρ – density [kg/m^3], x – distance in the longitudinal direction of the test piece [m], A – cross section [m^2], K_N – geometric constant ($K_N = 5/6$ for rectangular cross-sections), P_n – parameter to solve the Bernoulli constants (m), depends on the vibrational mode (n), L – length, $Q = \frac{I_{GZ}}{AL^2}$ – geometric constant.

The modulus of elasticity (E_X) at every individual bending frequency (f_n) of a known rank (n) was determined by Bernoulli's solution (Eq. (7)), which assumes a very high length-to-depth ratio ($L/h \gg 1$) and ignores shear and elastic support effects

$$E_x = 4\pi^2 \frac{\rho \mathrm{AL}^4}{I_{GZ}} \frac{f_n^2}{P_n}. \tag{7}$$

E_X and G_{XY} values were calculated via linear regression with parameters (x_n, y_n) (Brancheriau, Baillères, 2002), such that:

$$x_n = QF_2(m) 4\pi^2 \frac{\mathrm{AL}^4}{I_{GZ}} \frac{f_n^2}{P_n}, \tag{8}$$

$$y_n = 4\pi^2 \frac{\mathrm{AL}^4}{I_{GZ}} \frac{f_n^2}{P_n} (1 + QF_1(m)). \tag{9}$$

The parameters $F_1(m) = \theta^2(m) + 6\theta(m)$ and $F_2(m) = \theta^2(m) - 2\theta(m)$ depend on the vibration mode (n), and are calculated from Eq. (10).

$$\theta(m) = \frac{\tan(m) \times \tanh(m)}{\tan(m) - \tanh(m)}, \qquad \text{with} \quad m = \sqrt[4]{P_n} = (2n+1)\frac{\pi}{2}, \qquad n \in N. \tag{10}$$

2.3.1. Acoustic quality indicators

The damping of flexural vibration ($\tan\delta$) of tested elements was determined by measuring of the logarithmic decrement of the vibration signal. The influence of wood density and structure on mechanical stiffness was assessed by specifying a specific modulus of elasticity (E/ρ), and as well by the acoustic coefficient ($K = \sqrt{E/\rho^3}$. In addition we determined Acoustic Conversion Efficiency (ACE = $K/\tan\delta$) and Relative Acoustical Conversion Efficiency (RACE = $\sqrt{E/\rho^3}/\tan\delta$). The latter represents pure radiation of sound, and directly reflects the influence of material microstructure on sound radiation (Obataya *et al.*, 2000).

3. Results and discussion

3.1. The velocity of ultrasonic waves and elastomechanical properties of wood

The maximum velocity of compression ultrasonic waves was expected to be along the wood fibres, in ash wood, on average 4505 m/s, and 18% lower in walnut (v_L = 3684 m/s). The ultrasound velocities were in the transverse direction of both wood species between 1459 m/s and 1730 m/s, i.e. 15% greater on average at walnut. We did not confirm differences between the wood species in the radial wood direction (Table 1). The velocities of shear ultrasonic waves were always lower in all anatomical planes of wood comparing to velocities of compression ultrasonic waves. The mean shear velocities ranged from 848 m/s to 1686 m/s. If we compare only the shear velocities, we find generally greater values at walnut. The highest values were at both wood species in the LR plane, somewhat lower in the LT plane, and the lowest in the RT plane.

Table 1. Velocity of compression (v_i) and shear (v_{ij}) ultrasonic waves, modulus of elasticity (E_i) and shear modulus (G_{ij}) of walnut- and ash wood (CV% – coefficient of variation).

Direction	Walnut	Ash	Direction	Walnut	Ash
Velocity of compression ultrasonic waves v_i [m/s] and modulus of elasticity E_i [GPa]					
v_{LL}	3684	4505	E_L	8.60	17.20
CV%	8.2	8.4	CV%	15.40	16.60
v_{RR}	1459	1587	E_R	1.30	2.10
CV%	2.6	2.7	CV%	7.90	9.20
v_{TT}	1730	1500	E_T	1.89	1.91
CV%	2.2	4.6	CV%	5.60	8.40
Velocity of shear ultrasonic waves v_{ij} [m/s] and shear moduli G_{ij} [GPa]					
v_{LR}	1686	1382	G_{LR}	1.79	1.62
CV%	4.6	8.6	CV%	8.90	11.3
v_{LT}	1319	1155	G_{LT}	1.10	1.13
CV%	5.2	6.3	CV%	11.50	15.60
v_{RT}	834	862	G_{RT}	0.44	0.63
CV%	4.1	8.4	CV%	12.40	14.70
v_{RL}	1525	1182	G_{RL}	1.47	1.19
CV%	1.5	2.4	CV%	8.90	10.00
v_{TR}	846	848	G_{TR}	0.45	0.61
CV%	6.5	9.0	CV%	12.90	13.70
v_{TL}	1241	1164	G_{TL}	0.97	1.15
CV%	3.6	5.6	CV%	15.60	17.00

The modulus of elasticity of ash wood along fibres was twice greater than in walnut wood, 35% greater in radial direction, while in the tangential direction there were no significant differences between the wood species. Analysis of mechanical anisotropy confirmed for the wood species studied between 4.5 for walnut and 9 times greater moduli for ash wood along- than transverse to the wood fibres. Shear modulus ranged between 0.97 GPa and 1.47 GPa in LR- and LT-plane for both wood species. In general, slightly higher values were confirmed for walnut, but statistically insignificant. The lowest shear modulus, between 0.44 GPa and 0.63 GPa, was determined in the RT-plane in both wood species.

3.2. Acoustic and mechanical anisotropy of wood

Expected, due to essential differences in the velocity of compression ultrasonic wave, mechanical anisotropy was the highest when comparing the longitudinal and transverse stiffness of wood. Anisotropy in transverse direction (E_R/E_T) was significantly lower in the range from 0.71 to 1.12 (Table 2).

Table 2. Anisotropy of velocity of compression (v_i) and shear (v_{ij}) ultrasound waves, moduli of elasticity (E_i) and shear moduli (G_{ij}) of walnut and ash wood specimens and plane acoustic invariants (CV% – coefficient of variation).

Direction	Walnut	Ash	Direction	Walnut	Ash
Anisotropy of velocity of compression ultrasonic waves					
v_{LL}/v_{RR}	2.52	2.84	E_L/E_R	6.37	8.06
CV%	9.30	10.40	CV%	18.70	19.70
v_{LL}/v_{TT}	2.13	3.00	E_L/E_T	4.53	9.03
CV%	7.50	8.40	CV%	16.30	17.10
v_{RR}/v_{TT}	0.84	1.06	E_R/E_T	0.71	1.12
CV%	5.10	6.20	CV%	9.40	10.50
Anisotropy of velocity of shear ultrasonic waves					
v_{LR}/v_{RL}	1.11	1.17	G_{LR}/G_{RL}	1.22	1.37
CV%	7.60	8.40	CV%	12.60	14.70
v_{LT}/v_{TL}	1.06	0.99	G_{LT}/G_{TL}	1.13	0.98
CV%	8.10	9.20	CV%	15.90	17.80
v_{RT}/v_{TR}	0.99	1.02	G_{RT}/G_{TR}	0.97	1.03
CV%	7.50	8.30	CV%	13.70	15.00
Plane acoustic invariants					
I_{12}	2312.30	2580.60	I_{23}	1276.10	1250.20
I_{13}	2238.60	2510.90	I-ratio	0.56	0.49

With ratios of the velocity of a shear ultrasonic wave in individual planes (v_{ij}/v_{ji}) varying from 0.99 to 1.17, i.e. different from 1, the study also confirms significant deviation of both tested wood species from mechanical orthotropy. This finding is further in agreement with the calculation of acoustic invariants. I-ratio was significantly less than 1 (1 = isotropic) for both wood species, and somewhat better was found at walnut wood (0.56).

For sound boards of acoustic musical instruments, such as violin and guitar, a great acoustic anisotropy of wood is desired (Bucur, 2006; Roohnia *et al.*, 2011). On the contrary, more isotropic materials having lower density are recommended for the building of a solid body of the electric guitar (Puszynski, Warda, 2014). From this point of view, as well as indicating the results, walnut turns out to be a more appropriate choice. The same conclusion can be obtained by synthesizing the velocity ratios in the I-ratio, where walnut also exhibits greater isotropy than ash wood (Table 3). Since, in general, the increase in the density of wood increases its acoustic isotropy (Bucur, 1988), due to the significantly higher density; better acoustic isotropy would be expected in ash wood. The reasons for better acoustic anisotropy of walnut are to be found in its more homogeneous microscopic structure. Walnut is semi ring porous wood and has lower density fluctuation in the transverse direction as ash wood (Wagenführ, 2007).

3.3. Frequency response and acoustic quality

In the frequency response of flexural excited specimens, the highest amplitudes were obtained for both wood species in the 1st vibration mode (Fig. 4). The fundamental bending frequency was 748 Hz for walnut, and in an ash specimen it was significantly higher (f_1 = 923 Hz) (Table 3). By studying higher bending modes, we determine the modal frequencies up to 3675 Hz in walnut and up to 3573 Hz in ash wood (Fig. 6).

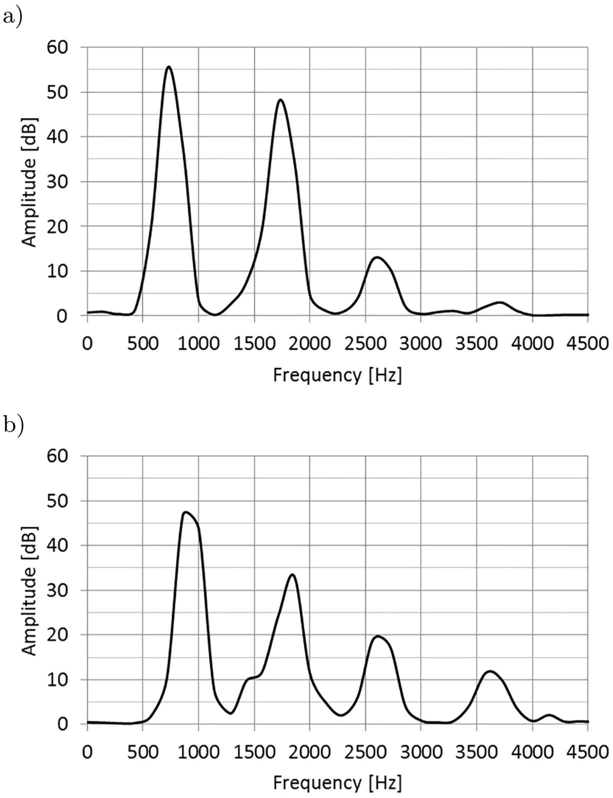

Fig. 4. Typical FFT spectrum of walnut- (a) and ash wood (b) elements for solid body of electric guitar after flexural excitation with present bending and torsion modal frequencies.

The Timoshenko's mean modulus of elasticity was 8.8 GPa in walnut and 16.6 GPa in ash wood, and it was not significantly different from the modulus of elas-

Table 3. Mean acoustic quality indicators of walnut and ash, determined by flexural frequency response of elements electric guitar solid body.

Indicator	Material	
	Walnut	Ash
f_1 [s^{-1}]	748	923
tan δ [–]	0.011	0.008
E/ρ [GPa]	9.79	14.93
K [m^4/(s · kg)]	5.04	4.81
ACE [m^4/(s · kg)]	246	261.0
RACE [km/s]	153	209.0

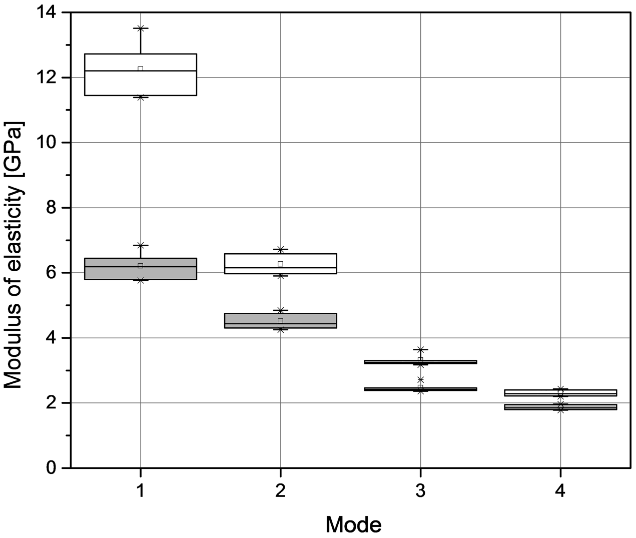

Fig. 5. Dependence of the modulus of elasticity (MOE) on vibration mode of walnut- (■) and ash wood (□) elements for electric guitar solid body.

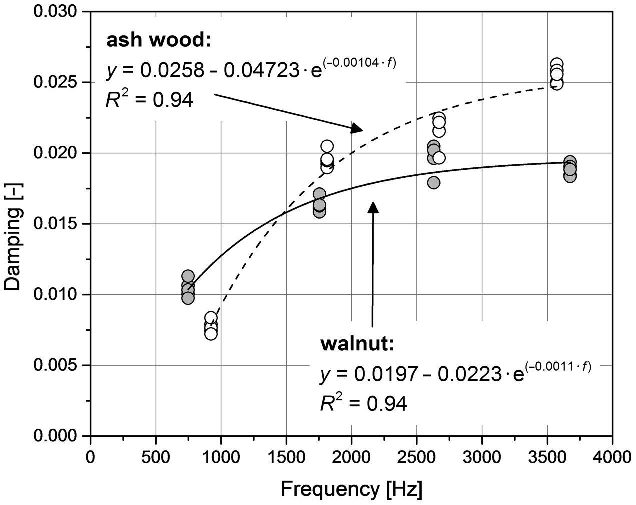

Fig. 6. The dependence of vibration damping on vibration mode frequency of walnut- and ash wood elements for electric guitar solid body.

ticity obtained by the ultrasonic method (Table 1). The shear modulus (G_{XY}) determined from Bordonne's solution by regression line (Eq. (6)) was 0.42 GPa and 0.46 GPa for the walnut and ash wood, respectively. The modulus of elasticity was reduced at higher vibration modes of tested specimens at both wood species, but more significant in ash wood (Fig. 5).

The difference in the reduction of the modulus of elasticity with the increase of vibration mode (Fig. 5) is expected between wood species and is related to the difference in microstructure homogeneity of tested wood and to the difference in shear stiffness. The latter is confirmed also by ultrasonic testing, where G_{LT} and G_{TL} moduli in ash wood were higher comparing to walnut (XY plane in bending is LT orientation of wood; Table 1). The shear moduli measured by ultrasound were about twice as high as for flexural vibrations. One of the reasons for lower shear modulus and shear stress determined from flexural vibration is due to reduction of cross sections of tested elements by routing of a standard pickup hole (Fig. 1). The second reason is related to the measuring method, since similar differences are also found by other studies. The difference is in this case attributed to a smaller characteristic time in the ultrasonic method, due to the higher frequency used, which reduces the impact of the viscoelasticity of the wood (Bucur, 2006; Divos, Tanaka, 2005).

The differences in some indicators of the acoustic quality, i.e. the acoustic coefficient K and in acoustic conversion efficiency ACE were between the tested wood species negligible. Values were quite low and similar to results in other studies (Table 3) (Bucur, 2006; Brémaud *et al.*, 2012; Straže *et al.* 2015). A significantly greater value was confirmed in ash wood for RACE, which neutralizes the difference in density in the studied samples (Obataya *et al.*, 2000), and proposes that radiation of sound energy that is somewhat better in ash wood.

We confirmed in addition the increase in vibration damping at higher vibration modes of both tested wood species (Fig. 6). In the fundamental vibration mode, a slightly smaller damping was confirmed for ash wood (tan δ = 0.008) compared to the damping in walnut (tan δ = 0.011). In the case of higher vibration modes this difference is reduced, whereas walnut is proven to be a less damped material comparing to ash wood.

Smaller vibration damping of walnut at higher modes and frequencies than in ash wood, related with its significantly lower density, could positively impact on vibrating of a future built solid body of an electric guitar. It can be expected in this case the higher energy transfer at the similar string playing frequency and a structure resonance of the electric guitar. In this respect the alteration of resonance of corresponding strings and of timbre effects is expected, followed by the reduced decay time, as was confirmed in related studies (Fleischer, Zwicker, 1998; Pate *et al.*, 2014).

4. Conclusions

To sum up, the authors despite the great variability of wood can statistically prove differences in acoustic and mechanical properties of tested two hardwood species, i.e. walnut and ash wood, for use in making of an electric guitar solid body. The research confirmed the better mechanical properties of ash wood, that is, the larger modulus of elasticity and shear modules in all anatomical directions and planes. At the same time, some indicators of acoustic quality were better in ash wood, but only in the basic vibration mode. Nevertheless, in ash wood, greater acoustic and mechanical anisotropy was determined. It has also proved to be less homogeneous and, consequently, poses great differences between vibrating modes.

Acknowledgment

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