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Acoustic and elastic properties of wood used for musical instruments

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Abstract. This paper proposes an ultrasound method for determining the elastic properties of anisotropic orthotropic materials used stringed instruments (in our case violins) manufacturing. Samples from different wood species were subjected to the propagation of the ultrasonic wave front, the signal being received through a receiver. The sensors were placed successively on the three main orthogonal directions of the wood, obtaining the values of the ultrasound velocity in different directions. Subsequently, based on the mathematical relations, the values of elastic parameters were calculated.

1. Introduction

Elastic, acoustic, dynamic properties of the wood can be determined from sound waves velocity and the density of material using several experimental methods. One of the best known methods is to determine the resonant frequency of the wood, knowing the size of the sample. The wooden bar with a known length (L = 1m) is required to vibrate by means of an emitting electromagnetic transducer, and the sound waves generated in the wooden bar are received by a receiver (electromagnetic transducer) and transformed into electrical oscillations, amplified by an amplifier. During the oscillations of the sample, the vibration amplitude reaches a maximum corresponding to the resonant frequency. Subsequently, measurement techniques evolved, and in the literature [1–4] shows a measuring system based on an electric magnet as a transmitter and laser sensors to determine the displacements. At the first scan using a wide frequency band, the resonant frequency is determined, after which at a narrow frequency band analysis, the quality factor is determined. [1 – 2] uses the same principle of determining the resonant frequency, only uses a microphone as a transmitter, and uses an accelerometer to receive the signal. Figure 1 shows the principle diagram of the experimental installation for determining the resonant frequency according to the measurement principle proposed by [2].

Another method used to determine ultrasound (US) velocities in the material is based on the intrinsic transfer matrix method. The method consists in determining the eigenvalues of the intrinsic transfer matrix for a ternary system. This system consists of three media: two standard materials and the studied material. The experimental stand presented in Figure 2 is composed of the ternary bar system, the intermediate bar element being the studied sample (1) fixed elastically on a support (3). The excitation of the system is made dynamically in the longitudinal direction by means of an impact hammer (2), and at the opposite end is placed a light beam produced by a laser vibrometer (4).

Based on Doppler effect, the signal produced by the change of the received light wave frequency was measured compared to the frequency of the wave emitted by the light source due to the relative up-receiver movement. Measuring this frequency change with an interferometer allows the precise determination of the vibrational motion of the object and the transmission to the acquisition plate (5) [5 – 8].

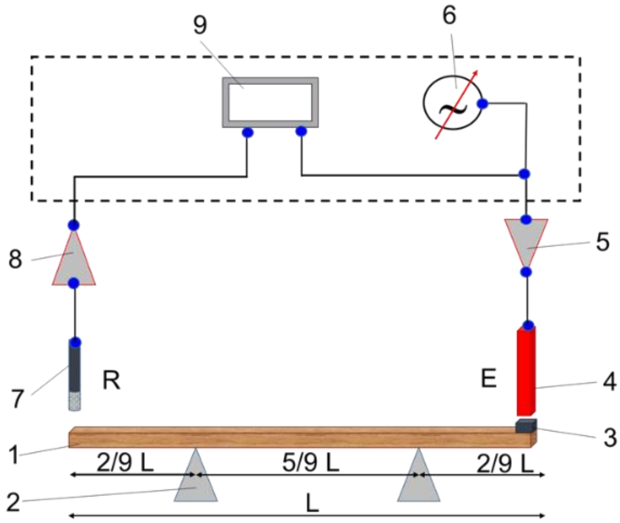

Figure 1. Experimental setup for determining the resonance frequency. Legend: 1 - wooden sample; 2 - supports: 3 - emitting electromagnetic transducer E; 4 – coil (4 Ω); 5 – amplifier (2 - 4 W); 6 – sine wave generator; 7 – microphone as R receiver; 8 – preamplifier for microphone or sound level meter; 9 – oscilloscope for visualizing signals.

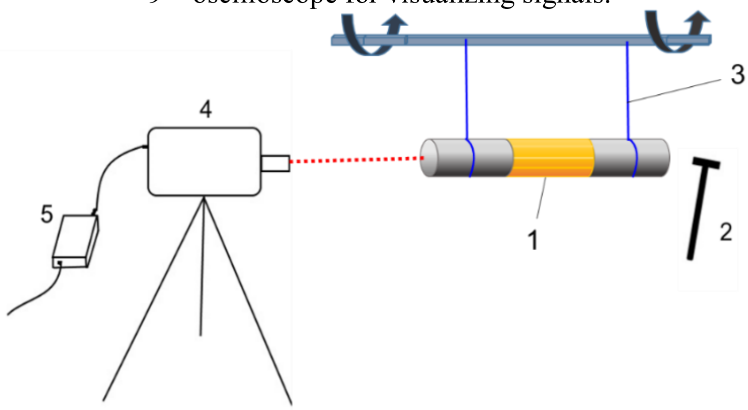

Figure 2. Experimental setup for determining the resonant frequency based on the intrinsic transfer matrix. Legend: 1 – sample from ternary system; 2 – impact hammer for exiting the structure; 3 – elastic elements for supporting the tests; 4 – laser vibrometer; 5 – signal acquisition device.

A modern and versatile method is the one based on measuring the ultrasonic propagation speeds in wood, a method studied and applied by [9 – 15]. This non-destructive evaluation method is based on a series of longitudinal and transverse propagation velocity measurements as well as attenuation measurements. The physical parameters to be determined are obtained with the help of mathematical formulas that link these quantities, some of which are also presented in this thesis. The method of measuring the speed of ultrasound in materials is standardized in ASTM E 494 [16–18].

The aim of the paper was to study different types of wood species using the US method. Thus, the US velocities in the wood's anisotropy directions were determined and then the longitudinal elastic modulus was calculated.

2. Materials and Methods

2.1. Materials

In this study, 14 wood species were analysed. The samples had a prismatic shape with the dimensions shown in Table 1. Figure 3 shows the types of samples investigated. For each sample the three main directions of the wood were identified - longitudinal, radial, tangential, the wood moisture was measured, the samples were weighed and then were tested with the ultrasound method.

Table 1. The physical properties of wood samples.

Wood species	Length L (mm)	Width in radial direction (mm)	Thickness in tangential direction (mm)	Density (g/cm^3)	Moisture content (%)
Ebony (*Diospyros crassiflora*)	119.16	49.70	48.95	1.143	12.00
Wenge (*Millettia laurentii*)	103.91	53.38	53.46	0.799	10.00
Mahogany (*Khaya ivorensis*)	100.11	49.05	48.92	0.698	10.20
Cherry (*Prunus avium L.*)	99.92	48.74	48.68	0.646	9.50
Elm (*Ulmus minor*)	100.84	50.19	49.81	0.804	13.30
Black Locust (*Robinia pseudacacia L.*)	98.66	44.84	44.95	0.812	9.00
Walnut (*Juglans regia L.*)	98.10	49.65	49.85	0.815	11.90
Maple/Sycamore (*Acer pseudoplatanus*)	99.14	46.25	45.65	0.547	10.00
Oak (*Quercus robur L.)*	99.71	42.91	44.48	0.820	10.00
Sapelli (*Entandrophragma cylindricum*)	128.16	49.99	49.59	0.540	8.40
European Lime (*Tilia cordata*)	99.85	42.43	42.52	0.507	8.40
European Beech (*Fagus sylvatica L.)*	100.102	41.943	41.92	0.723	8.53
Ash (*Fraxinus excelsior L.*)	99.857	42.030	42.04	0.809	8.90
Spruce (*Picea Abies K.*)	99.86	42.00	41.64	0.403	5.00

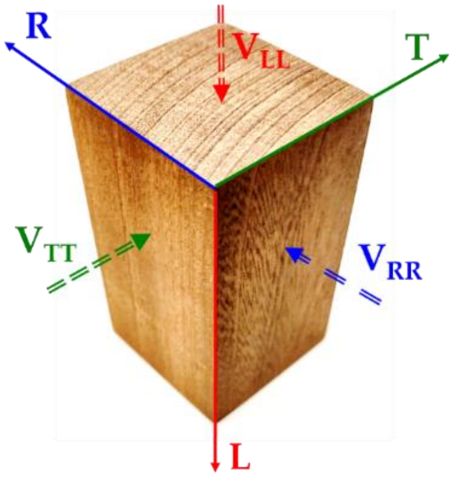

Figure 3. The type of studied wood sample (L – longitudinal direction; R – radial; T – tangential; V_{LL} – wood velocity in longitudinal direction; V_{RR} – wood velocity in radial direction; V_{TT} – wood velocity in tangential direction)

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2.2. Methods
Non-destructive ultrasonic testing (US) consists in analysis of material's response at excitation with US waves for evaluation of material properties without inducing damages [13–15]. Ultrasound is an elastic wave that propagates in solid, liquid, and gaseous media in excess of 20kHz. In this study, the ultrasound device with trade name Lucchimeter was used. The physical principle of the method is based on the elastic properties of the media in which the US propagates. In solid materials two types of elastic waves are propagating: longitudinal waves and transverse waves (Figure 4).

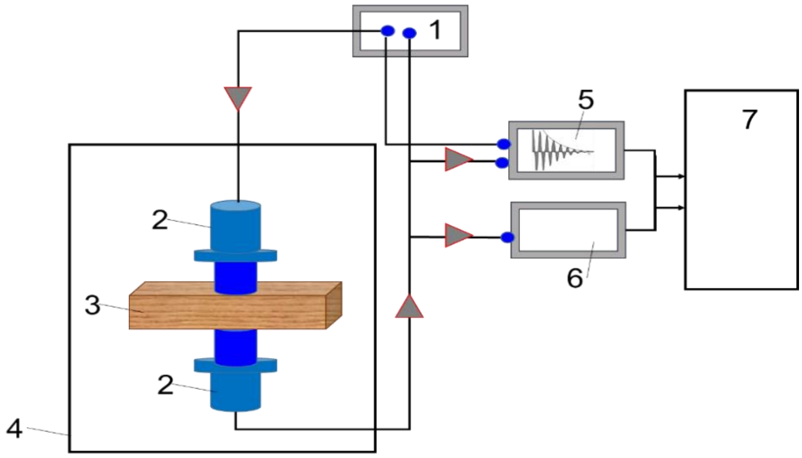

Figure 4. Experimental setup for determining the ultrasound velocity in wood. Legend: 1 – generator; 2 – transmitter/receptor; 3 – sample; 4 – connecters; 5 – oscilloscope 6 – conditioner; 7 – PC.

3. Results and discussions
Experimental research has shown the values of the velocities of propagation of wood sounds in the three main directions and subsequently the values of the Young modules in the three directions have been calculated. Figure 5 shows the variations of these parameters depending on the wood species tested. Thus, it was found that the samples of lime, sapelli and elm wood record the highest values of the US velocity in longitudinal direction, respectively along the wood fibres, respectively over 5200 m/s. Spruce wood has a relatively velocity of 5000 m/s. At the opposite pole are the species ebony, walnut, cherry and oak, with values ranging from 4200 to 4600 m/s. In the radial direction, the highest speeds are recorded in the samples of walnut, ebony, cherry and mahogany, of approximately 2200 – 2450 m/s, and the lowest values are recorded for lime, beech, spruce wood with values below 1800 m/s. In the tangential direction, the propagation speeds are lower than in the other two directions, but the highest values were obtained for acacia, walnut, ebony, wenge wood (1800 – 1900 m/s), compared to linden wood, maple, spruce and oak, in which the speed of sound propagation is below 1550 m/s.

Regarding the values of the elastic modulus, regardless of the direction of the fiber, ebony wood has the highest values (EL = 22.4 GPa; ER = 5.9 GPa; ET = 4.13 GPa). For the samples of spruce, cherry and lime wood, the elastic modulus are lowest.

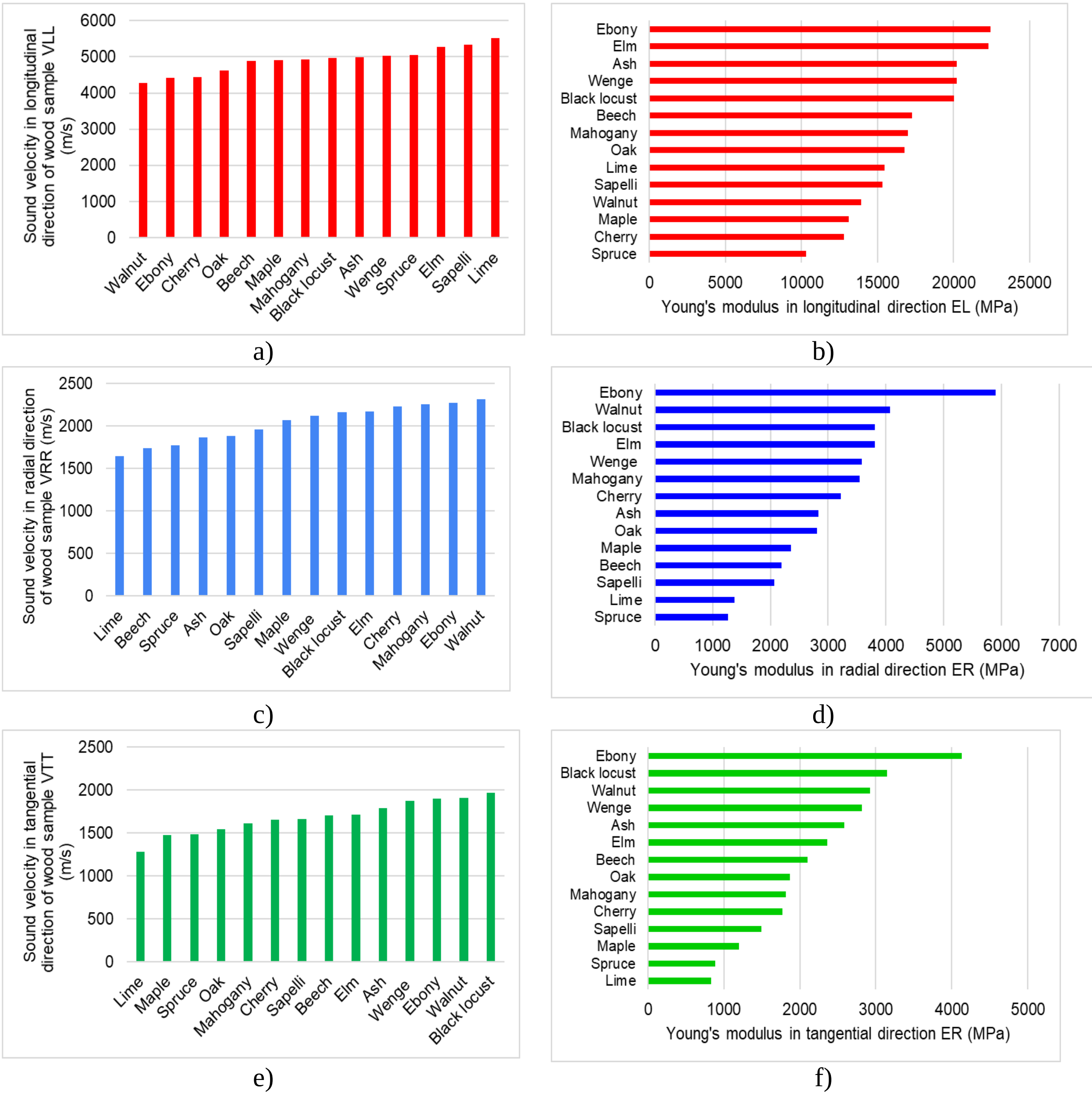

Figure 5. Acoustic and elastic features for several wood species: a) sound velocity in longitudinal direction; b) Young's modulus in longitudinal direction c) sound velocity in radial direction; d) Young's modulus in radial direction; e) sound velocity in tangential direction; f) Young's modulus in tangential direction

4. Conclusions

In conclusion, the paper presents the experimental investigations for determining the acoustic and elastic parameters by the ultrasonic method, on wooden samples of different species implied in manufacturing of stringed musical instruments.

It was found that the highest ratio of VLL / VRR sound propagation rates was for linden wood (3.355) and sapwood (2.720), and the lowest value was for ebony and walnut wood (1.853). Regarding the ratio of speeds on radial and tangential directions, the lowest ratios are in the case of beech (1.0220 and ash (1.047) samples, and the highest in the case of maple (1.402) and mahogany (1.398) samples.

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