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Technical & Applied Article **Open Access**

Ultrasound and Wood Science at the Forestry Research Centre in Nancy, France, for a period of twenty years, between 1979 and 1999

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Abstract – The aim of this article is to describe the development of the ultrasonic non-destructive velocity method for applications in Wood Science and Forestry. A key question addressed was the mechanical characterisation of wood on an increment core of 5 mm diameter bored from a standing tree. Theoretical considerations were studied for the characterisation of wood as an orthotropic solid. Acoustic invariants were introduced to characterise wood anisotropy. Wave propagation phenomena were related to macroscopic and microscopic particularities of wood structure. The mechanical characteristics of wood species for violins have been thoroughly studied. The detection of wood degradation by biological agents producing decay (fungi, bacteria), using the ultrasonic velocity method combined with X ray densitometry was studied. The ultrasonic velocity method was also applied to quality assessment of some wood-based composites. For applications in Forestry, it was demonstrated that on increment cores of 5 mm diameter bored from standing trees, it was possible to determine three stiffnesses and three shear moduli of wood and to assess the mechanical wood quality of standing trees. Other factors (the slope of the grain, pruning) affecting the quality of wood of standing trees were detected with the velocity method. In Forestry, seeds are important products. The capacity of the germinability of acorns was detected with the ultrasonic velocity method.

Keywords. Ultrasound, Wood, Wave propagation, Forestry

1 The background

I had the honour of collaborating with the National Forestry Research Centre in Nancy in France for twenty years, between 1978 and 1999. This prestigious institution and the "Qualité Bois" (Wood Quality) laboratory was world known, for the development of a non-destructive technique based on X-ray densitometry, by Dr. Hubert POLGE. The specificity of this technique was the use of a very small sized specimen, an increment core of 5 mm diameter extracted from living trees [1].

Based on my internationally recognised expertise and on my publications with RILEM (Réunion Internationale des Laboratoires pour l'Essaies des Matériaux) [2, 3], Dr. H. POLGE proposed I be recruited by the Forestry Research Centre in Nancy. At that time this organisation was part of INRA – Institute National de la Recherche Agronomique, in France. On the first of September 1978, the Honourable Pierre BOUVAREL – Chief Deputy of the Forestry Research Centre in Nancy, recruited me as – chargé de recherche contractual – (project leader for a contract period of five years). (I finished my career in this prestigious institution after 28 years of service and because of age limitations, in December 2005).

During the period 1979–1999, in "Qualité Bois" laboratory I was the sole scientific officer in charge of the development of ultrasonic techniques for wood and wood products and I had numerous colleagues and students working with me on mutual projects. Moreover, for the advancement of the methodology, I have to mention the excellent contribution made by the technical staff of the laboratory, the activity of students preparing for academic degrees and Master theses (called in France DEA – Diplôme d'études approfondies) and Doctoral theses (PhD) and the collaboration of the academic staff of universities and of the research organisations mentioned in the Acknowledgements. The international collaborations with colleagues involved in ultrasound generated the publications mentioned in the chronologic reference list existing in the archive of the laboratory and some of them are cited in the references of this article.

My task in the "Qualité Bois" laboratory was to develop an ultrasonic technique as a new non-destructive technique for mechanical characterisation of wood material and if possible, to extend it to other purposes

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important for Forestry. Moreover, the methodology for the mechanical characterisation of wood material required one important restriction, imposed by the small size of the specimen, the increment core of 5 mm diameter and 2 . . . 4 cm length, extracted from living trees (Fig. 1a). This specimen is a cylinder of elliptical section, because the size of 5 mm in the L axis is slightly larger (by about 1 mm) than in the T axis. This difference was explained by Polge and Thiercelin [5] as being due to existing growth stresses in trees. Using statistical regression analysis, it was confirmed by Bucur [6] that there is a relationship between the diameter of the increment core in the T and L anisotropic directions of wood as well as between the corresponding velocities of ultrasonic bulk P waves propagating in the increment core. It is important to bear in mind that the acoustical properties of wood species are determined by their anatomical structure [7].

In what follows I will describe my pioneering approach for mechanical characterisation of wood with the ultrasonic technique applied on increment core specimens of 5 mm diameter and on other types of specimens and the progress with the ultrasonic methodology in the field of wood science and technology during the last two decades of the XX th century in France, at the Forestry Research Centre in Nancy – "Qualite Bois" laboratory. This article is structured in three main parts. The first part is related to the theoretical approach for the development of an ultrasonic method for the mechanical characterisation of wood material with bulk waves. The second part introduces the acoustic parameters and elastic constants of some wood species and wood-based composite. The third part describes practical applications of the ultrasonic velocity method to sylvicultural practice and to timber industry.

PART I

2 Theoretical approach for mechanical characterisation of wood material

The notations used in this article are as follows:

L, R, T anisotropic axes of wood noted also axis 1, axis 2, axis 3
$[\sigma]$ – stress tensor
$[\varepsilon]$ – strain tensor
ρ – wood density
$[C_{ijkl}]$ – stiffness tensor
$[S_{ijkl}]$ – compliance tensor
$[\Gamma_{ij}]$ – Christoffel tensor
$\Gamma^*_{kl}(\omega)$ is the complex Christofell tensor
$C^*_{ijkl}(\omega)\, n_j n_l$ – complex stiffness
$n_j n_l$ – propagation vector components
λ^* – eigen values of dispersion equation
δ_{kl} – Kronecker tensor; if $i = k$ then $\delta_{ik} = 1$ and if $i \neq k$, $\delta_{ik} = 0$
t – time
V_{phase} – phase velocity; V – group velocity
ρV^2 is the real part of the diagonal terms of stiffness matrix
$iV\omega^{-1}$ is the ratio of imaginary to real part of the stiffnesses
α – the attenuation coefficient of ultrasonic waves
ω – angular frequency
ν_{ij} = Poisson's ratios
E – Young modulus
G – shear modulus

The application of ultrasound to wood material characterisation was initiated by R.F.S. Hearmon – Forest Products Research Laboratory, Princes Risborough in the UK. In 1965 in the proceedings of the second symposium for the non-destructive testing of wood he published the first article on an ultrasonic velocity technique applied to the mechanical characterisation of wood as an anisotropic solid, of orthotropic symmetry [8]. The axes of elastic symmetry of wood correspond to the natural growth axes of a tree namely the L axis – the axial growing direction of a tree, and in the transverse plane, the R axis – radial and T – tangential versus the annual rings.

The elastic properties of solids can be defined by the generalized Hooke's law relating the volume average of stress $[\sigma_{ij}]$ to the volume average of the strains $[\varepsilon_{kl}]$ by the elastic constants $[C_{ijkl}]$ in the form:

$$[\sigma_{ij}] = [C_{ijkl}]\,[\epsilon_{kl}] \tag{1}$$

or

$$[\epsilon_{kl}] = [C_{ijkl}]\,[\sigma_{ij}]\,. \tag{2}$$

It is apparent that the stiffness matrix $[C]$ is the inverse of the compliance matrix $[S]$, as

$$[C] = [S]^{-1} \text{ and } [S] = [C]^{-1} \tag{3}$$

where $[C_{ijkl}]$ are termed elastic stiffnesses and $[S_{ijkl}]$ the elastic compliances, and i, j, k, or l correspond to indices 1, 2, 3, or 4. Stiffnesses and compliances are fourth-rank tensors. In his book, Hearmon [9] noted that "the use of the symbols for compliances $[S]$ and $[C]$ for stiffness is now almost invariably followed".

To fix the ideas, we know that the elastic behaviour of an anisotropic orthotropic solid is characterised by nine terms of the stiffness matrix and by nine terms of the compliance matrix noted $[C]^{-1} = [S]$. Stiffness matrix $[C]$ has six diagonal terms and three off diagonal terms. Generally speaking, the diagonal terms can be determined experimentally as a product of squared velocity and density. The procedure is straightforward with bulk waves, P waves and S waves. The determination of the off diagonal terms requires a more complex theoretic experimental approach. Experimentally, the specimens should be of "infinite solid" type, which means to be large compared to the wavelength of the ultrasonic waves. From these relationships can be deduced wood technical constants of an orthotropic solid namely: three Young's moduli, three shear moduli and the corresponding six Poisson ratios. A thorough explanation of these relationships is given in the reference books [10–12].

a).

b). wood anisotropic directions on the core : length in axis R, transverse surface is in plane LT

c) Effect of sample size on velocity V_{LL}

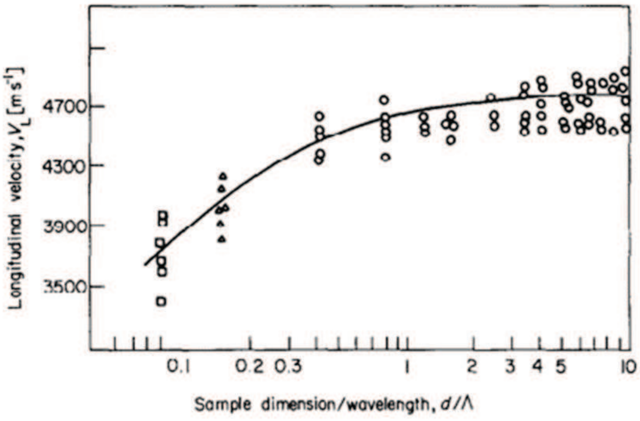


Figure 1. Effect of specimen size on ultrasonic velocity V_{LL} of a P wave. Legend: (a) Boring of an increment core from a tree (`https://i0.wp.com/haglofsweden.com/wp-content/uploads/2020/05/Core550x840.jpg?w=840&ssl=1` accessed 4 May 2023). (b) An increment core of 5 mm diameter in the L and T axes and of several centimetres in the R axis on which are seen the annual rings and the earlywood and the latewood zones of each annual ring (`https://patrimoines.laregion.fr/uploads/pics/IMG_7216_m.jpg` accessed 10 August 2023). (c) Effect of sample size and wavelength on velocity V_{LL} for standard specimens and for 5 mm diameter cores and 10 mm diameter cores, and standard specimens of various lengths and transverse sections of 2 cm × 2 cm and 30 cm length (□ – 5 mm core, Δ – 10 mm core and o – standard sample). Ultrasonic frequency 80 kHz ([4], Fig. 9, p. 119).

2.1 Preliminary approach

Having in mind the size of the increment core of 5 mm diameter, it was necessary to understand the difference in the response of this specimen to ultrasonic wave propagation compared with a large specimen corresponding to an infinite solid. It was known from preliminary tests on a large specimen of wood in the L direction that the P wave velocity V_{LL} is about 5000 m/s for a frequency of 1 MHz, which means a wavelength of about 5 mm. In the direction R the velocity V_{RR} is about 2000 m/s and in the T direction the velocity V_{TT} is about 1000 m/s. Ultrasonic velocimetry depends strongly on the relationship between the ultrasonic frequency and the size of the specimen. The wavelength should be small compared to the size of the specimen, to fulfil the theoretical condition of the propagation of progressive ultrasonic waves in an infinite solid.

To understand the physical condition of an increment core specimen in an ultrasonic field it was necessary firstly, to compare the values of the velocity of P waves in the L direction on specimens of various sizes ranging from cubes of 16 mm to bar type standard specimens of 30 cm length and $2 \times 2\,\mathrm{cm}^2$ section. Figure 1c illustrates the effect of the size of the sample on the ultrasonic velocity V_{LL} of a P wave, measured with a transducer of 80 kHz frequency in the longitudinal direction L of wood. The samples were of various sizes, starting with – increment cores of 5 mm and 10 mm diameter and finishing with standard specimens of 2 cm × 2 cm transverse section having various lengths up to 30 cm, along the L axis. From this figure one notes that bulk waves propagate in samples of size d, for which $d/\lambda > 0.4$ fulfilling the condition of an infinite solid. If the size of the tested specimen compared to wavelength is $d/\lambda < 0.4$, then we have another type of wave propagating in specimens, like surface waves of various types. This experiment confirms that the geometry of an increment core of 5 mm diameter does not satisfy the condition of an infinite solid for the propagation of ultrasonic P waves. The regression equation between V_{LL} and the ratio of the sample dimension and wavelength is given by the expression:

$$V_{\mathrm{LL}} = e^{\frac{0.02936}{d/\lambda}}. \tag{4}$$

On the other hand, the measurements of the velocity V_{LL} on increment cores of 5 mm diameter with transducers of P waves of various frequencies showed an increase in the velocity value with frequency (Tab. 1). This means that wood is a dispersive material having different behaviour in the L, R and T axes. This also means that the anatomic structure of wood interacts differently with ultrasonic waves, depending on anatomic element patterns. The heterogeneity of wood material is observed at the macroscopic level and by reference to the layered structure of the annual rings with earlywood and latewood. At the microscopic level heterogeneity is introduced by anatomic elements like fibres, tracheids, the layered structure of the cell wall, cellulosic and lignin components, etc.

Table 1. Effect of frequency on P wave velocity on increment cores measured at 80 kHz and 2 MHz [4].

Statistical parameters	Units	P wave velocity on increment cores (m/s)		
		V_{LL}	V_{RR}	V_{TT}
Average	80 kHz	4150	1949	1462
	2 MHz	4685	1949	931
Difference	%	11	9	36
Coefficient of variation	80 kHz	0.0682	0.0518	0.0395
	2 MHz	0.0765	0.0498	0.0618

The first effective possible approach to validate ultrasonic measurements on increment cores was to use statistics, a familiar tool for the biological sciences.

The regression equations for the P wave velocity on increment cores measured at 80 kHz and 2 MHz are statistically significantly related and are given by:

$$V_{\mathrm{LL}}^{2\,\mathrm{MHz}} = 2185 + 0.5976\, V_{\mathrm{LL}}^{80\,\mathrm{kHz}} \quad \text{and correlation coefficient } r = 0.474^{***} \tag{5}$$

$$V_{\mathrm{TT}}^{2\,\mathrm{MHz}} = 347.1 + 0.399\, V_{\mathrm{TT}}^{80\,\mathrm{kHz}} \quad \text{and correlation coefficient } r = 0.400^{*}. \tag{6}$$

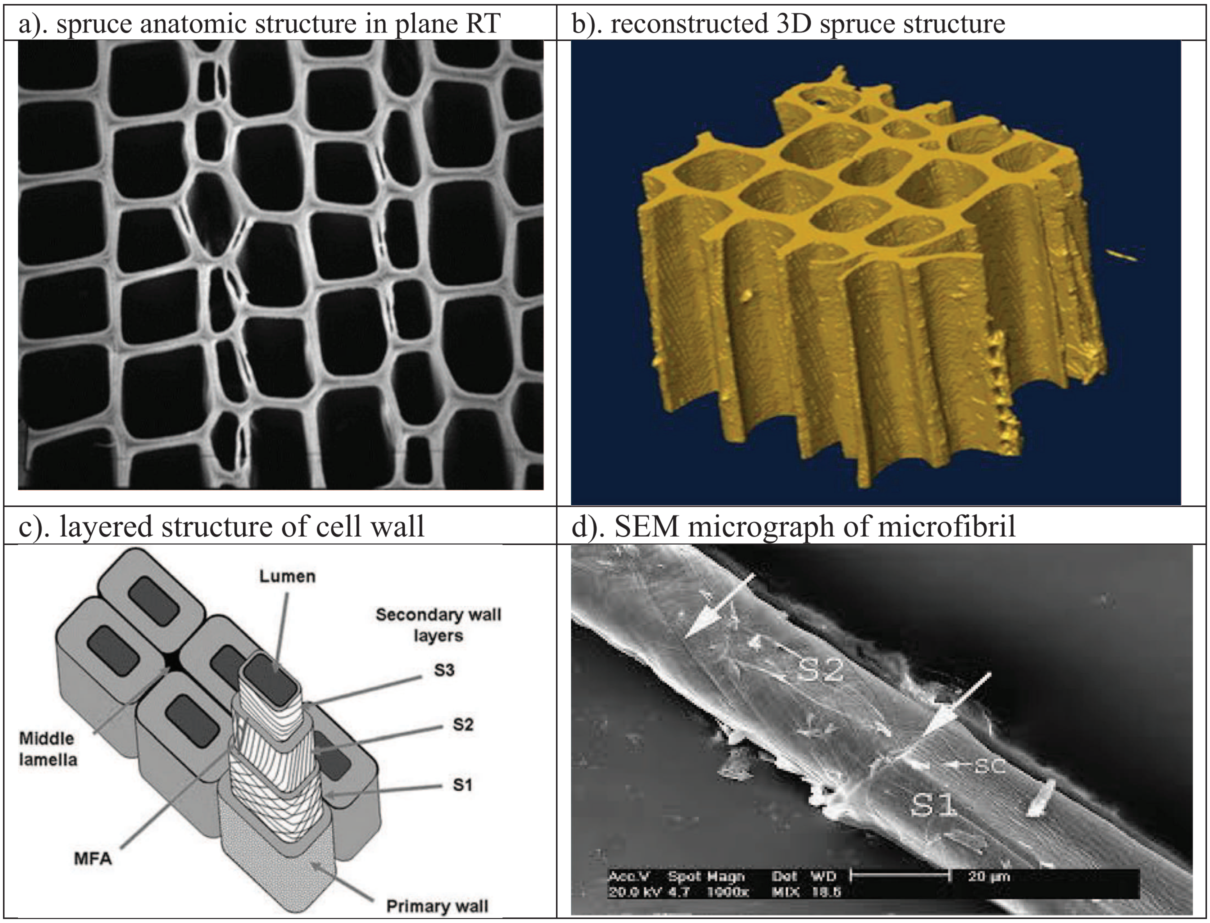
The sensitivity of velocities measured in the L direction to anatomical wood structure in the high frequency range can be attributed to the continuity of wood fibres or tracheids of about 3…4 mm length, running parallel with the tree axis. The wavelength matched the size of the anatomic wood structure composed of cylindrical cells (like tubes) with walls made of cellulosic microfibrils embedded in a lignin matrix. Figure 2 illustrates some aspects of the anatomic structure of spruce.

The angle of microfibrils has a determining role for the mechanical properties of wood [16]. It can be mentioned that ultrasonic waves propagating in wood reveal some anatomical particularities of the microscopic structure, if an appropriate frequency is used.

2.2 Stiffness moduli determined on an increment core

On an increment core specimen it was possible to measure the six diagonal terms of the stiffness matrix, using P waves-compressional waves and S waves – shear waves (Tab. 2). The values of velocity V_{LL}, as well as V_{LR} and V_{RT} were strongly affected by the size of the increment core.

The validity of the method I presented could be assessed only by comparing the results of the elastic diagonal stiffnesses C_{ii} on the increment cores with those on cubes tested with bulk ultrasonic waves and with those for standard specimens loaded in static bending for which the static Young modulus E_{L} was measured. In static bending tests on standard specimens the following values


a). spruce anatomic structure in plane RT

b). reconstructed 3D spruce structure

c). layered structure of cell wall

d). SEM micrograph of microfibril

Figure 2. Anatomic structure of wood. Legend: (a) Spruce anatomic structure with scanning electron microscopy (SEM) in the RT plane. The width of the image corresponds to approximately 240 μm ([13], Fig. 14, p. 54); (b) 3D reconstruction of approximately 200 μm high section of the microsample ([13], Fig. 6, p. 54); (c) Microfibril angle (MFA) defined as the angle of the microfibril bundles with respect to the cell axis in the S2 wall layer ([14], Fig. 3, p. 183); (d) SEM micrograph of spruce tracheid. The fracture between layers S1 and layer S2 is oriented perpendicular to the tracheid axis (lower right large arrow). Surface corrugations (SC) running approximately parallel to the tracheid axis are present on the S1 surface. Cracks (upper left arrow) originate from helical striations present in the S2 layer ([15], Fig. 2, p. 419).

Table 2. P wave velocity and S shear waves velocity and stiffness on increment core (5 mm diameter and 2 cm length) and standard specimen (2 cm × 2 cm × 30 cm) on beech (*Fagus Sylvatica*) Average values. Wood moisture content 10% [4].

Specimen type	Density	Velocity of P waves (m/s)			Stiffness moduli (N/mm^2)		
P waves	(kg/m^3)	V_{LL}	V_{RR}	V_{TT}	C_{LL}	C_{RR}	C_{TT}
Increment cores	696	4150	1949	1452	12 071	2663	1493
Standard specimens	578	4980	2137	1492	17 245	3160	1547
Difference (%)		20.0	4.6	2.7	43	18.6	3.6
		Velocity of S waves (m/s)			Shear moduli (N/mm^2)		
Shear waves		V_{LR}	V_{LT}	V_{RT}	G_{LR}	G_{LT}	G_{RT}
Increment cores	696	1000	1151	493	1050	1081	163
Cubic specimens	578	1368	1361	650	1302	1303	290
Difference (%)		36.8	18.2	31.8	24.0	20.5	43.7

Table 3. Correlation coefficients between stiffnesses on cores and standard specimens and in static bending test modulus E_{L} and modulus of rupture in bending (*Fagus Sylvatica*) [4].

Parameters for statistical analysis	Correlation coefficients					
	Ultrasonic test			Static test		
	Cubes			Standard specimens		
Increment cores	C_{LL}	C_{TT}	C_{RR}	Density	E_{L}	Rupture
C_{LL}	0.673^{***}	–	–		0.704^{***}	0.701^{***}
C_{TT}	0.766^{***}	0.452^{**}	–		0.697^{***}	0.561^{***}
C_{RR}	0.456^{**}	NS	0.440^{**}	–	0.\$%***	0.380^{*}
Density	0.877^{***}	0.601^{***}	0.670^{***}	0.980^{***}	0.829^{***}	0.639^{***}

were measured: $E_{\mathrm{L}} = 10992\,\mathrm{N/mm^2}$; modulus of rupture noted σ rupture or MOR $= 108\,\mathrm{N/mm^2}$.

Again, using the tools of statistics, significant simple regression correlations (Tab. 3) were found between the stiffnesses of the increment cores and the standard specimens for E_{L} and the modulus of rupture submitted to bending tests. Therefore, it was noted that the regression equations between the modulus E_{L} and modulus of rupture and C_{LL} is able to predict the strength of living tree wood through a simple ultrasonic test in the L anisotropic direction on an increment core of 5 mm diameter.

We have seen that the theoretical approach for characterising an orthotropic material required the computation of 9 elastic constants. The technique of ultrasonic velocity measurement by immersion was only partially appropriate to measure all terms of the stiffness matrix. Shear waves do not propagate in water. Therefore, it was necessary to search for an ultrasonic transmission technique having direct contact with the specimens, using a dry coupling medium (a cellophane sheet) for wood specimens excited with a transducer of higher frequency in the 0.5 MHz…1 MHz range.

In the ‘80s. direct contact through transmission ultrasonic methodology had been used for the characterisation of composite materials using a viscous coupling medium. At that time, the Institute Supérieur de Mécanique de Paris, the laboratory of Professor Jean T Vinh, was an academic establishment in France, where this ultrasonic technique for the characterisation of composite materials was well established [10, 11]. Working in this laboratory, I had the opportunity to develop an appropriate ultrasonic technique for the characterisation of wood material using the advanced equipment produced by Panametrics with transducers in the 0.5 MHz…1 MHz frequency range.

I was faced again with the problem of selecting appropriate specimens. My first choice was to use 1.5 cm cubes on which the velocities V_{LL}, V_{RR}, V_{TT} as well as V_{RT}, V_{LT} and V_{LR}, can be measured on the same specimen. Wood being a very heterogeneous natural material it was evident that the number of specimens should be reduced to a minimum. This approach using one cube was to avoid interference caused by the high heterogeneity of wood in axial measurements. For out of axes measurements cubes oriented at different angles were used.

2.3 Stiffnesses, compliances and moduli of elasticity of wood

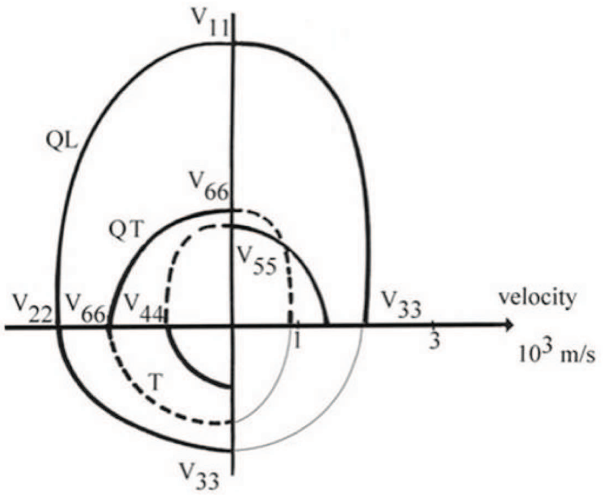
We know theoretically, from the Christoffel equations, that for the characterisation of orthotropic materials we need to determine six diagonal stiffnesses and three non-diagonal stiffnesses. In other words, we have to determine 9 stiffnesses for each wood species studied. The measurements of velocities for calculating the six diagonal stiffnesses were straightforward and were calculated from the square of the velocity multiplied by the density. Figure 3a shows these velocities on a velocity surface for the particular case of wood. Determination of the three off-diagonal terms of the stiffness matrix was really complicated because of the coupled vibrational effect between the compressional (longitudinal) wave, commonly noted as the P wave and the shear wave, noted as the S wave [17, 19]. Figure 3b illustrates the anisotropic symmetry axes and the complexity of the structural anatomic elements of softwood and hardwoods.

For calculation of the off diagonal terms of the stiffness matrix it was necessary to have specimens cut out of symmetry axes. The first experimental strategy was to produce cubic specimens oriented at different angles (15°, 30°, 45° and 60°) to the reference axes in each anisotropic plane and to measure the corresponding velocities with longitudinal and shear transducers. In this way I collected many values for the same off diagonal constants. To select only one value, an optimisation technique based on the definition of admissible error, was required [17, 20].

Finally, for each wood species studied, I was able to determine nine stiffness constants which combined with an appropriate calculation technique allowed determination of three Young’s moduli, three shear moduli and six Poisson’s ratios. This approach required a very large number of specimens (15 for each wood species) for the calculation of the off diagonal stiffnesses and much experimental work (Tab. 4).

It is interesting to compare the values of technical constants, for the moduli E_{L}, E_{R} and E_{T} and the Poisson ratios in the LT and LR planes determined in static tests and ultrasonic tests (Tab. 5).

The differences between the ultrasonic and static moduli of elasticity could be understood within some limits. The values of the Young moduli were higher with a). Velocity surface of wood and orthotropic and natural axes: axis 1 is L, axis 2 is R, axis 3 is T



b). Wood symmetry axes L R T and anatomic elements of softwoods and hardwoods

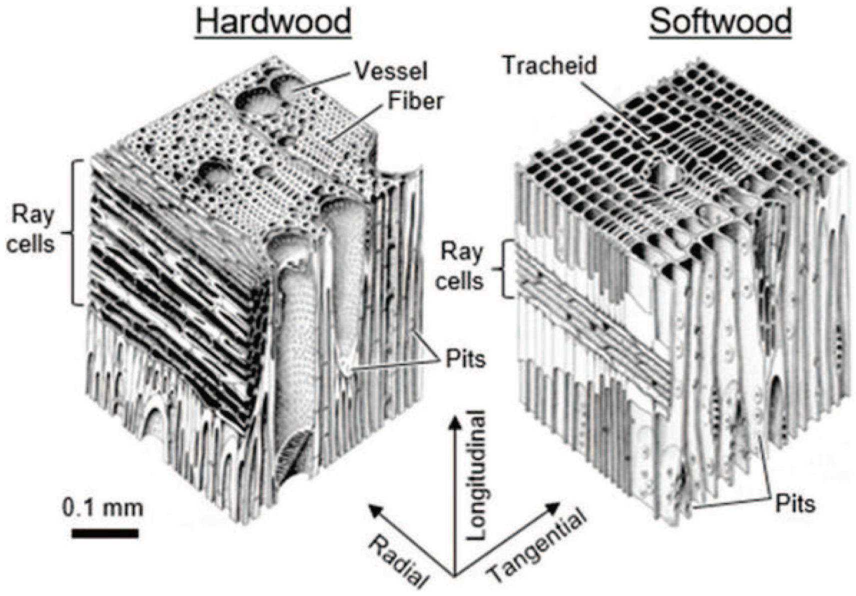


Figure 3. Ultrasonic velocities propagating in wood as an orthotropic solid and the velocity surface in wood [17]. Legend: (a) Velocity surface of curly maple wood deduced from experimental values measured using broadband transducers that have a central frequency of 1 MHz for *P* waves and *S* waves in the through transmission technique ([17], Fig. 5.4, p. 67). Ultrasonic velocities in an orthotropic solid and in wood: $V_{11} = V_{\mathrm{LL}}$, $V_{22} = V_{\mathrm{RR}}$, $V_{33} = V_{\mathrm{TT}}$, for *P* waves and $V_{44} = V_{\mathrm{RT}}$, $V_{55} = V_{\mathrm{LT}}$, $V_{66} = V_{\mathrm{LR}}$, for *S* shear waves ([17], Fig. 2.1, p. 21); (b) Anisotropic symmetry axes and structural anatomic elements of softwood and hardwoods ([18], Fig. 4).

the ultrasonic test than with the static bending test. It is worth mentioning that the thermodynamic regime of the dynamic tests with ultrasound (adiabatic) is different from the static test regime (isotherm). For E_{L} the difference is 6.7%. Higher differences were for E_{R} and E_{T}. In terms of wood structure, it can be noted that the static test deformed the anatomic structure in the R and T axes. Poisson ratios in the LT Plane illustrate better the effect of wood structure, if we compare the ratio ν_{LT} and ν_{TL}. for the static test which is 1.96 and for the ultrasonic test which is 0.91. The most important effect is on axis T for which the difference between ν_{TL} in static and

Table 4. Young moduli and shear moduli on cubic specimens of beech (*Fagus Sylvatica*) at 1 MHz frequency and the corresponding static values [17].

Species	Frequency	Young moduli (MPa)			Shear moduli (MPa)		
Beech	MHz	E_{L}	E_{R}	E_{T}	G_{RT}	G_{LT}	G_{LR}
	1.0	89.63	18.0	16.41	3.56	9.78	13.96
	Static * [21]	140.0	22.8	11.60	4.70	10.8	16.40

Table 5. Comparation between the technical constants for Sitka spruce wood at 12% moisture content using ultrasonic (1 MHz) and static tests [22].

Test	Technical constants (10^8 N/m^2)						Poisson ratios		
	Young's moduli			Shear moduli			Plane LT		Plane LR
	E_{L}	E_{R}	E_{T}	G_{RT}	G_{LT}	G_{LR}	ν_{LT}	ν_{TL}	ν_{LR}
Static	90.5	8.17	4.03	–	–	–	0.057	0.029	0.438
Ultrasonic	96.64	10.37	4.87	0.91	10.95	11.96	0.045	0.049	0.430
Differences %	+6.7	+26.9	+20.8				−21.0	+68.9	−1.8

Table 6. Poisson ratios in each anisotropic plane, on cubic specimens at 1 MHz frequency on cubic specimens of spruce and corresponding static values [22].

Species	Frequency	Poisson ratios in three anisotropic planes								
		Plane LT			Plane LR			Plane RT		
	MHz	ν_{LT}	ν_{TL}	Ratio	ν_{LR}	ν_{RL}	Ratio	ν_{RT}	ν_{TR}	Ratio
Spruce	1.0	0.863	0.100	8.63	1.281	0.257	28.53	0.555	0.147	3.77
	Static *	0.518	0.043	11.04	0.449	0.070	6.41	0.707	0.359	1.96

ultrasonic test is 68.9%. Ultrasonic testing does not affect wood anatomic structure.

To illustrate the effect of wood anisotropy, a more detailed analysis related to the Poisson ratios values in each anisotropic plane is given in Table 6. In the LR plane the Poisson ratio with the ultrasonic technique is 28 and with a static test it is only 6. In the RT plane the Poisson ratio with the ultrasonic technique is 3.77 and with the static test is 1.96. The important differences observed in the LR plane with the ultrasonic test can be attributed to the presence of medullary rays. The static test is less sensitive to the anatomic structure of wood.

The validity of the Poisson ratio values with the ultrasonic test was determined with the following equations:

$$1 - \nu_{ij} \cdot \nu_{ji} > 0. \tag{7}$$

Due to the anatomic structure of some softwood species of honeycomb type, some Poisson ratios can have negative values or have values > 1 [23].

The next step in my methodological research was to reduce the number of cube type specimens (15 by wood species) by introducing another type of specimen, namely three disks with 3.5 cm diameter faces, having one disk for each anisotropic plane. The faces were cut at angles of 15, 30, 45, 60 degrees (Fig. 4). This was a big step in advancing the methodology for the determination of the off-diagonal terms of the stiffness matrix of wood. With this type of specimen, the experimental work was less fastidious, but the complex optimisation procedure was still required for calculation of minimum error [25].

2.4 Off diagonal terms of stiffness matrix and surface wave mode conversion

Mode conversion of surface wave propagation in orthotropic solids allows the detection of various types of waves propagating simultaneously. The specimen required for this was a wood material block measuring 600 mm × 180 mm × 90 mm (L × R × T) with an edge of 45° in each anisotropic plane. With this specimen it was possible to measure the velocity of surface waves and to deduce the univocal value of the off diagonal term of the stiffness matrix. This approach was inspired by the article published by Deresiewicz and Mindlin [26].

The properties of surface waves enable us to deduce the off-diagonal terms of the stiffness matrix, when the surface wave velocity is known, using the general equation:

$$C_{ij} = f\left(\rho V_{\mathrm{surface}} C_{ii}, n_i\right). \tag{8}$$

As an example, Table 7 gives data for the calculation of the off diagonal term C_{13} of wood.

The methodology for the determination of off diagonal terms of the stiffness matrix with surface wave mode conversion was mentioned in [28–30].

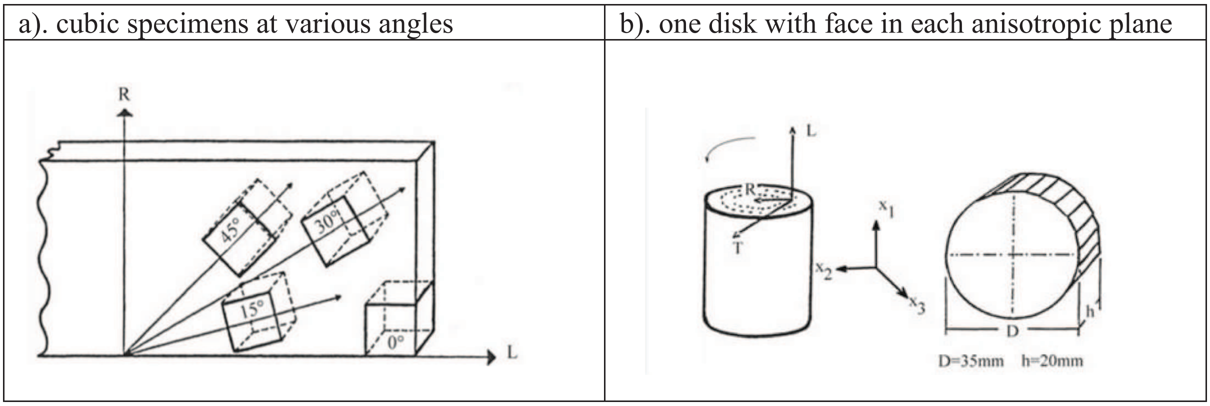


Figure 4. Types of wood specimens for off axes ultrasonic velocity measurements for each anisotropic plane. Legend: (a) Cubic specimens at various angles ([24], Fig. 4.18, p. 78); (b) One disk in each anisotropic plane ([24], Fig. 4.19, p. 79).

Table 7. Velocity of surface wave and off diagonal term of stiffness matrix [27].

Characteristics	Parameters
Wood density	$.\rho$
Free surface orientation	Plane 12
Propagation direction	Axis 1
Polarisation direction	Axis 3
Off-diagonal term to calculate	C_{13}
Velocity of surface waves measured	V
Equation	
$M \cdot C_{ij}^4 + N \cdot C_{ij}^2 + P = 0$	
Coefficients of the equation for the calculation of C_{13}	M, N, P
$M = \dfrac{(\rho V^2 - C_{55})}{C_{33} \cdot C_{55}}$	
$N = 2\left[\dfrac{(\rho V^2)^2}{C_{55}} - \rho V^2 \left(1 + \dfrac{C_{11}}{C_{55}}\right) + C_{11}\right]$	
$P = (\rho V^2)^3 \dfrac{(C_{33} - C_{55})}{C_{55}} + (\rho V^2)^2 \left(C_{33} - C_{11} + \dfrac{2C_{11} \cdot C_{33}}{C_{55}}\right) + \rho V^2 \dfrac{2C_{11}C_{55}}{C_{11}C_{33} - C_{11} \cdot C_{55}}$	

Table 8. Comparison between the C_{ij} terms of the stiffness matrix calculated with bulk and surface waves [31].

Types of waves	Off diagonal of stiffness matrix (10^8 N/m^2) axis 1 – L, axis 2 – R, axis 3 – T					
	Beech			Spruce		
	C_{12}	C_{13}	C_{23}	C_{12}	C_{13}	C_{23}
Bulk	30.36	16.89	7.42	2.84	2.31	7.60
Surface	34.42	16.16	10.67	3.78	3.58	7.88
Difference %	+11.8	−4.3	+30.3	+24.8	+35.4	+3.7

For comparison, the values of the terms Cij calculated with data from bulk wave velocities and the optimisation procedure with the terms determined by surface wave mode conversion are given in Table 8. It can be mentioned that for spruce the values of the off diagonal terms are significantly higher with mode conversion than those with the optimisation procedure based on error calculation. For beech the range of variation is within the limits of the experimental error for the C_{12} and C_{13} terms. However, for beech, for C_{23} the difference is 30%. Here again we can analyse the wood behaviour in terms of anatomic structure. Spruce has a relatively simple structure with long tracheids and small medullary rays while beech has a complex structure of short fibres and numerous vessels and large medullary rays. The presence of rays in the RT plane could be related to C_{23}.

2.5 Various elastic symmetries of wood for global characterisation

The most general elastic symmetry of a solid is the triclinic symmetry. This case is only of academic interest. If

Table 9. Comparison of wood elastic symmetry and deviation (%) of high symmetries of the stiffness tensor from monoclinic symmetry of several wood species on sphere specimens [32].

Wood species	Simplest symmetry	Stiffness tensor deviation (%) from monoclinic symmetry					
		Algorithm Arts [32, 33]			Algorithm Francois [34]		
	Isotropic	Transverse isotropic	Orthotropic	Triclinic	Transverse isotropic	Orthotropic	Triclinic
Pine	74.2	19.5	14.8	8.0	–	–	–
Beech	–				26.3	19.2	–
Oak	72.9	10.9	5.2	2.8	16.6	13.2	8.6
Sapele	69.5	23.3	13.4	6.4	–	–	–

triclinic symmetry is applied to wood. the stiffness matrix has 21 terms. The most appropriate specimen for this purpose is a sphere, of 4 cm diameter [32].

The general anisotropic characterization of a solid depends on the procedure of inversion of the general elastic tensor, calculated from physical measurements and the level of symmetry deduced from the complete stiffness tensor in an arbitrary coordinate system. This approach needs the introduction of the Voigt stiffness tensor and dilatational stiffness tensor and the corresponding eigenvector directions for the determination of the "best reference frame" [33].

François [34] refined this method and used pole figures to illustrate the correlation between the measured stiffness tensor and the theoretic one, corresponding to symmetry by every plane of the space. He mentioned that "The discrepancy between the two tensors and the order of the symmetry levels allow to choose the best symmetry for the studied material." Table 9 gives the deviation (%) of high symmetries of the stiffness tensor from monoclinic symmetry for the following species: three European species – pine, beech, oak and one tropical species – sapele. The orthotropic symmetry seems to be appropriate for the case of wood.

For a more effective approach in producing specimens for systematic research on wood elastic constants, a polyhedron with 28 faces can replace the sphere [35]. However, due to technological progress in the first decade of the XXI st century, the most effective technique for determining all terms of the elastic tensor of wood is utilising resonant ultrasound spectroscopy using only one sample, a cube [36–38].

2.6 Acoustic invariants and wood anisotropy

The invariants of tensors are parameters used for characterization of the elastic or viscoelastic behaviour of anisotropic solids, as described by Betten [39]. The stability of calculated invariants versus different angles of propagation confirms the validity of the structural model (orthotropic or other) chosen for the tested material. The invariants express synthetically the anisotropy of the material [40]. Acoustic invariants of wood species have been introduced in the literature of wood science since 1988 by Bucur [41].

The acoustic invariants are quantities insensitive to the direction of wave propagation. Therefore, the acoustic invariants can act as reference parameter for wood anisotropy investigation. The acoustic invariants can be calculated starting with Christoffel's equations.

In the particular case of wave propagation taking place in plane 12, we have:

$$\left(\Gamma_{11}-\rho V^2\right)\left(\Gamma_{22}-\rho V^2\right)-\Gamma_{12}^2=0. \tag{9}$$

And

$$\left(\Gamma_{33}-\rho V^2\right)=0. \tag{10}$$

Equation (9) can be written

$$\left(\rho V^2\right)^2-\rho V^2\left(\Gamma_{11}+\Gamma_{22}\right)+\Gamma_{11}\Gamma_{22}-\Gamma_{11}^2=0. \tag{11}$$

This equation of second degree in ρV^2 has two roots, V_{QL} and V_{QT}, corresponding to the quasi-longitudinal and quasi-shear waves, which propagate in plane 12. Both waves have the polarization vector in plane 12 for any propagation angle α. The roots can be deduced as:

$$2\rho V_{\mathrm{QL}}^2=\left(\Gamma_{11}+\Gamma_{22}\right)+\left[\left(\Gamma_{11}-\Gamma_{22}\right)^2+4\Gamma_{12}\right]^{1/2} \tag{12}$$

$$2\rho V_{\mathrm{QT}}^2=\left(\Gamma_{11}+\Gamma_{22}\right)-\left[\left(\Gamma_{11}-\Gamma_{22}\right)^2+4\Gamma_{12}\right]^{1/2}. \tag{13}$$

The equation (13) corresponds to a pure shear wave V_{T} propagating in plane 12 whose polarization vector is entirely along axis 3. The value of this velocity is calculated as:

$$\rho V_{\mathrm{T}}^2=\Gamma_{33}=C_{55}n_1^2+C_{44}n_2^2. \tag{14}$$

From an analytical point of view this equation is that of an ellipse. This means that the propagation path of V_{T} is elliptical.

On the other hand, the velocity curves corresponding to the QL and QT waves lie respectively exterior and interior to the curve defined by equation (16) which is also an ellipse:

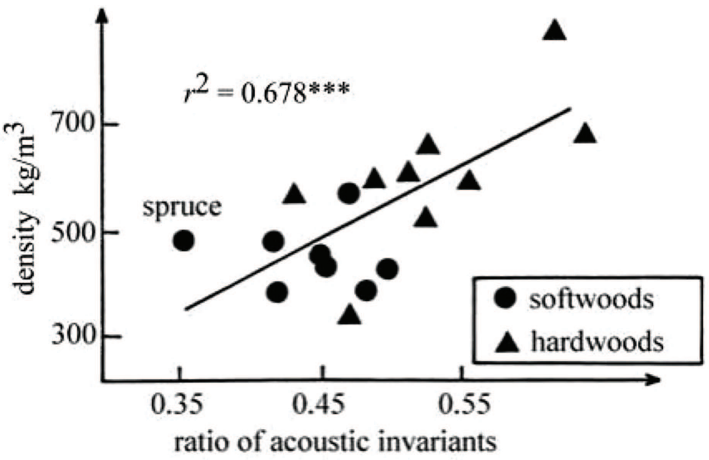
$$\Gamma_{11}+\Gamma_{22}=\left(C_{11}+C_{66}\right)n_1^2+\left(C_{22}+C_{66}\right)n_2^2=2\rho V^2. \tag{15}$$

where, after expressing the stiffnesses as a function of velocities and density, we have:

$$V^2=V_{\mathrm{ellipse}}^2=\frac{1}{2}\left(V_{\mathrm{QL}}^2+V_{\mathrm{QL}}^2\right). \tag{16}$$

Table 10. Ratio of acoustic invariants for several wood species [41].

Harwood species	Ratio of acoustic invariants	Softwood species	Ratio of acoustic invariants
Poplar	0.47	Spruce-resonance wood	0.42
Tulip tree	0.43	Red spruce	0.42
Beech	0.52	Pine	0.47
Pernambuco	0.61	Sitka spruce	0.50
Correlation between the ratio of acoustic invariants and wood density $R^2 = 0.678$ *** [37]			



Similar expressions can be deduced for the propagation in planes 13 or LT and 23 or RT.

A complete analysis of propagation phenomena in orthotropic solids involves simultaneous plotting of the velocity curves corresponding to the three planes of elastic symmetry. The respective position of each curve is governed by the ratios between the diagonal stiffness terms. Analysis of possible intersections between the three curves in each plane and of discontinuities that may appear at the junction between two planes provides information on the departure of the tested material from the truly orthotropic model. In the specific case of propagation taking place in plane 12, this arises from the following theoretical considerations:

- at angle α:

$$\Gamma_{11} + \Gamma_{22} = C_{11}n_1^2 + C_{22}n_2^2 + C_{66}\left(n_1^2 + n_2^2\right) \quad (17)$$

- at angle $\beta = \pi - \alpha$:

$$\Gamma_{11} + \Gamma_{22} = C_{11}n_2^2 + C_{22}n_1^2 + C_{66}\left(n_1^2 + n_2^2\right). \quad (18)$$

Consequently, adding equations (17) and (18) leads to an expression of an invariant ($I = \Sigma\Gamma$) with the angle α as follows:

$$\Sigma\Gamma = C_{11} + C_{22} + 2C_{66} = V_{11}^2\rho + V_{22}^2\rho + 2V_{66}^2\rho. \quad (19)$$

Expressed in terms of velocities, in plane 12, the invariant I_{12}, related to the velocities propagating in the axes, of the considered plane of elastic symmetry is as follows:

$$I_{12(0)} = V_{11}^2 + V_{22}^2 + 2V_{66}^2. \quad (20)$$

Similar expressions can be written for propagation in plane 13 and 23

$$I_{13(0)} = V_{11}^2 + V_{33}^2 + 2V_{55}^2. \quad (21)$$

And

$$I_{23(0)} = V_{22}^2 + V_{33}^2 + 2V_{44}^2. \quad (22)$$

Combining the values of invariants as a ratio between the invariant in the transversal plane (23) and the average invariant in planes containing the 1 axis (planes 12 and 13) we obtain a unique value called the I_{ratio}:

$$I_{\text{ratio}} = \frac{I_{23}}{\frac{I_{12}+I_{13}}{2}} = \frac{2I_{23}}{I_{12}+I_{13}}. \quad (23)$$

This synthetic treatment of invariants allows the definition of a global parameter representative of the overall acoustical properties of a wood species.

Table 10 gives the ratio of acoustic invariants for several wood species and the variation of the ratio of acoustic invariants with density (correlation coefficient $R^2 = 0.678$). The weight of evidence suggests that wood species having high density and any important organized structure at the millimetre length scale in the transverse anisotropic plane exhibit high values for the ratio

Table 11. Effect of frequency on attenuation coefficients $\alpha_{ij} = -\frac{1}{d}\ln \mathrm{A/Ao}$ (in Nepers/cm) and velocities (in m/s) in curly maple and common spruce, measured in wood anisotropic axes with the sinusoidal burst transmission technique and longitudinal and transverse waves. Velocity in m/s. (Note: $1\,\mathrm{dB}/10^{2}\,\mathrm{m} = 8.69\,\mathrm{Np}/10^{-2}\,\mathrm{m}$). d – the size of the specimen for path wave measurement [43].

Wood species	Wave type	Parameters	Frequency of excitation				
			0.10 MHz	0.25 MHz	0.50 MHz	1.0 MHz	1.5 MHz
Curly maple	P wave	$\alpha11$	1.55	1.62	1.62	1.75	1.90
		V_{11}	4332	4409	4540	4706	4559
		$\alpha22$	2.30	2.25	2.29	2.47	2.63
		V_{22}	2285	2270	2279	2325	2340
		$\alpha33$	2.82	2.82	3.03	3.22	3.22
		V_{33}	1254	1291	1321	1316	1345
	S wave	$\alpha44$	1.64	1.85	1.85	2.32	2.47
		V_{44}	869	966	918	918	–
		$\alpha55$	1.68	1.77	2.10	2.47	2.39
		V_{55}	1214	1350	1394	1428	1399
		$\alpha66$	1.77	1.94	2.05	2.27	2.34
		V_{66}	1342	1552	1566	1602	1580
Spruce	P wave	$\alpha11$	2.17	2.07	2.10	2.29	2.47
		V_{11}	4458	4847	5343	5327	5401
		$\alpha22$	2.83	3.02	3.22	3.22	–
		V_{22}	1612	1741	1832	1832	–
		$\alpha33$	2.71	3.02	3.02	3.02	3.22
		V_{33}	1283	1400	1321	1325	1346
	S wave	$\alpha44$	No signal				
		V_{44}	No signal				
		$\alpha55$	1.62	1.62	1,85	2.06	2.17
		V_{55}	1310	1320	1356	1383	1372
		$\alpha66$	1.64	1.71	1.71	2.17	2.36
		V_{66}	1250	1372	1383	1822	1839

Notes. $1\,\mathrm{dB}/10^{-2}\,\mathrm{m} = 8.69\,\mathrm{Np}/10^{-2}\,\mathrm{m}$.

of invariants. The variation in density has a corresponding variation in the associated ultrasonic velocity. Consequently, the acoustic behaviour of a species of high density is less anisotropic than that of a species having low density.

2.7 Attenuation of ultrasonic waves in wood

The viscoelastic behaviour of wood can be identified from the interaction of mechanical waves (ultrasonic or acoustic) with the material structure. The decrease of the amplitude of waves propagating in wood and the fluctuation in the phase of the signal have many causes, but most of the decrease is due to the energy losses induced by scattering produced by the structural inhomogeneities.

2.7.1 Theoretical considerations

The basis of the ultrasonic evaluation of the viscoelastic behaviour of wood is associated with measurements of velocities and of the attenuation coefficients of waves. The numerical significance of attenuation depends on the specific measurement situation [42]. In what follows the method of attenuation measurement in wood with the through – transmission ultrasonic technique is considered.

The dispersion equation [11, 12] relating all the parameters of propagation phenomena in anisotropic solids is:

$$\left|\Gamma^{*}_{kl}(\omega) - \lambda^{*}\delta_{kl}\right| = 0 \tag{24}$$

$$\left|C^{*}_{ijkl}(\omega)\, n_j n_l - \lambda^{*}\delta_{kl}\right| = 0. \tag{25}$$

The eigen value λ^{*} of dispersion equation is

$$\lambda^{*} = \frac{\rho V^{2}}{\left(1 - i\alpha V\omega^{-1}\right)^{2}}. \tag{26}$$

For the case of the off-axis propagation in plane 12 the dispersion equation can be written as:

$$\left[\left(\Gamma^{*}_{11} - \lambda^{*}\right)\left(\Gamma^{*}_{22} - \lambda^{*}\right) - \Gamma^{*2}_{12}\right]\left[\Gamma^{*}_{33} - \lambda^{*}\right] = 0. \tag{27}$$

From this equation λ^{*} as well as α – the attenuation coefficient – can be determined.

The attenuation measurements on specimens can be performed either with broadband pulses, containing a wide range of frequencies using ultrasonic spectroscopy, or with narrow band pulses, using burst excitation at a fixed frequency.

In what follows the adopted calculation relationship of attenuation coefficients of ultrasonic waves propagating

Table 12. Statistical analysis of the influence of natural variability of spruce wood on attenuation expressed by measured velocity, signal amplitude and frequency in the L axis. Specimens – cubes-in air dried conditions [47].

Statistical parameters	Density	Parameters of the ultrasonic P wave on spruce		
		Velocity V_{LL}	Amplitude	Frequency
	.kg/m^3	(m/s)	(dB)	(kHz)
Minimum	345	5512	22.5	628
Maximum	600	6694	59.7	980
Average	493	6209	47.0	854
Coeff. of variation (%)	11	4	19	8

in wood is

$$\alpha_{ij} = -\frac{1}{d}\ln \mathrm{A}/\mathrm{Ao}. \tag{28}$$

where d is the distance of wave propagation and A – the amplitude of waves and Ao – the reference amplitude of the signal with transducers in contact.

Determination of the attenuation coefficients of the ultrasound propagating in wood is of major interest for understanding of the visco-elastic behaviour of this material. The role of wood anatomic structure was commented on by [43–46].

2.7.2 Factors affecting ultrasonic wave attenuation

The attenuation of ultrasonic waves propagating in wood is affected by the frequency of waves and by the anisotropy and the anatomic structure of wood [43].

Table 11 gives the attenuation coefficients for all the anisotropic axes and planes. The coefficients were calculated for excitation by both longitudinal and shear waves for two wood species – spruce and curly maple. This shows that:

- The attenuation coefficients increase with frequency for both longitudinal and transverse waves.
- For longitudinal waves, the T direction exhibits the highest attenuation.
- For transverse waves, generally, there were no significant differences between the attenuation coefficients of waves propagating in different anisotropic directions.
- The attenuation coefficients of the longitudinal wave in the L and R directions are higher in spruce than in maple. This is probably due to important differences in densities in annual ring zones (i.e., in spruce in earlywood the density is 300 kg/m^3 and in latewood the density is 900 kg/m^3). In spruce the proportion of the latewood is 15–20% of the annual ring width. In maple the latewood zone is very narrow, about 5%. The propagation phenomena on the scale of the structure of ultrasonic waves in wood can be understood using a simplified acoustical model [7]. Wood cells may be treated as "tubes" of cellulosic crystalline substance embedded in an amorphous matrix – lignin. Solid wood is then a rectangular array of tubes embedded in a matrix. The longitudinal orientation of the tubes is slightly disturbed by horizontal elements, the medullary rays. In the longitudinal direction the dissipation of acoustical energy takes place at the edges of the tubes. Accordingly, the longitudinal axes which are constructed from long elements provide high values of velocities and relatively small values of attenuation. The highest attenuation is expected in the T direction in which no continuous wood structure exists.

Some data related to the statistical analysis of the values of the amplitude of the ultrasonic signal for the measurements of the attenuation coefficient in axis L and on the influence of the natural variability of wood material are given in Table 12. The statistical coefficient of variation was 19% for the amplitude of the signal of P waves. The coefficient of variation of the velocity V_{LL} is only 4%. This means that the attenuation of ultrasonic waves in L direction is more sensitive to the structure of the material than the velocity V_{LL}.

Anisotropy and dispersion of ultrasonic waves in wood are clearly expressed by the attenuation coefficients. Taking into consideration the case of horse chestnut (a wood species having a relatively homogeneous structure, with very low proportion of latewood in the annual ring) and the attenuation expressed by the ratio of values of velocities of P waves and of shear waves for the range of frequency 0.1 MHz to 1.5 MHz, it was observed that the maximum dispersion was 37% (Tab. 13).

In general, the increasing frequency of P waves illustrates better wood anisotropy expressed by the ratio of velocities or attenuation coefficients, especially related to the L axis. However, the ratio of invariants of velocities decreased with frequency from 0.624 at 0.1 MHz to 0.472 for 1.5 MHz, by about 24%. Moreover, the ratios of ultrasonic velocities of P waves or Shear waves related to the L axis clearly express the dispersion phenomenon in wood (Tab. 13). As regards the ratio of attenuation coefficients, the dispersion of P waves is well illustrated by the variation of the ratio of attenuation coefficients by up to −73% and of shear waves by up to −62% (Tab. 14). Attenuation coefficients are very sensitive to wood structure.

The system used by Bucur and Feeney [42] operated at a fixed frequency in order to produce a pure single frequency. This approach proved a very useful way for the development of an appropriate methodology for measurement of attenuation coefficients and for understanding internal loss mechanisms typical for each wood species. Attention should now be paid to the development

Table 13. Wood anisotropy expressed by the ratio of ultrasonic velocities as a function of frequency for air dried specimens of horse chestnut [42].

Waves type	Anisotropy	Frequency (MHz)					Dispersion
		0.1	0.25	0.50	1.0	1.5	Δ from 0.1 to 1.5 MHz
		Ratio of velocities					%
P wave	V_{11}/V_{22}	1.551	1.994	2.024	2.166	2.291	+32.3
	V_{22}/V_{33}	1.560	1.648	1.673	1.691	1.691	+7.7
	V_{11}/V_{33}	2.420	3.188	3.387	2.578	3.874	+37.5
S waves	V_{66}/V_{44}	2.609	2.681	2.555	2.553	2.560	−1.9
	V_{55}/V_{44}	2.387	2.258	2.079	2.037	2.040	−14.5
	V_{66}/V_{55}	1.093	1.188	1.229	1.253	1.255	+17.9
Invariants	Ratio	0.624	0.533	0.519	0.501	0.472	−24.3

Table 14. Wood anisotropy expressed by the ratio of ultrasonic attenuation coefficients as a function of frequency for air dried specimens of horse chestnut [42].

Waves type	Anisotropy	Frequency (MHz)					Dispersion
		0.1	0.25	0.50	1.0	1.5	Δ from 0.1 to 1.5 MHz
		Ratio of attenuation coefficients					%
P waves	α_{11}/α_{22}	0.137	0.169	0.260	0.067	0.380	+63.3
	α_{22}/α_{33}	0.417	0.444	0.089	0.249	0.110	−73.6
	α_{11}/α_{33}	0.087	0.088	0.022	0.017	0.042	−51.7
S waves	α_{66}/α_{44} at 90°	0.037	0.039	0.026	0.022	0.014	−62.1
	α_{66}/α_{55} at 0°	0.679	0.333	0.418	0.333	0.375	−44.7
	α_{66}/α_{55} at 90°	0.249	0.452	0.222	0.249	0.283	+3.4

of transfer function measurements using ultrasonic spectroscopy for the gradual improvement of non-destructive evaluation methods for solid wood and wood-based materials. Such experiments combined with data from pure frequency experiments as outlined above offer the possibility of deducing wood microstructure parameters from ultrasonic measurements as well as obtaining an improved understanding of the nature of different wood species.

2.8 Local characterisation of wood with acoustic microscopy

The main interest in acoustic microscopy arises from the direct interaction between the wave and the elastic properties of the material through which it propagates. The resolution is at the millimetre or micron scale for ultrasonic frequencies in the megahertz or gigahertz ranges. The spatial resolution is dependent on the characteristics of the material tested, transducer frequency, and working distance. At a frequency higher than 1 GHz the wavelength in water is 0.8 μm, which means that this submicrometre resolution is approaching that of an optical microscope. In this case, a dominant role in image contrast is played by the Rayleigh waves, which are excited at the surface of the sample. Evidently, the ultrasonic signal depends on the value of the surface wave velocity in the sample. Another interesting point is the fact that this wave contains longitudinal and shear components, each of which decays exponentially with depth. The sensitivity to the structural elements becomes much higher because of the differences between the anisotropic elastic properties of the anatomical elements of wood, which can be seen with different contrast. The intrinsic contrast in wood acoustic micrographs is quite good [48–50]. Mercury was used as the coupling liquid. The anatomical elements such as the annual rings, the latewood and the earlywood zones, fibres, and rays were observed at different scales ranging from 1000 to 250 μm.

The very fact that an acoustic microscope can directly visualize the anatomic structure and to determine some of the acoustic and elastic properties of wood specimens may be a very important attribute in the development of a new non-destructive procedure for very fine quantitative anatomical studies. We refer here to the possibility of measurements of the elastic constants of all anatomical elements (fibers, vessels, tracheids, rays, cellular walls, microfibrils, etc.)

3 Comments of Professor F. Beall on the ultrasonic methodology developed by V. Bucur

Below are given the comments of Professor Frank C Beall from the University of California, Forest Products Laboratory, College of Natural Resources in his letter of

Table 15. Velocity measured with the ultrasonic technique on specimens of spruce and maple for violins 16×16×16 mm with broad-band transducers at 1 MHz frequency [57].

Wood Species	Density (kg/m^3)	Violin sample	Velocities of ultrasonic waves (m/s)					
			P – compressional waves			S – shear waves		
			$V_{11} = V_{\mathrm{LL}}$	$V_{22} = V_{\mathrm{RR}}$	$V_{33} = V_{\mathrm{TT}}$	$V_{44} = V_{\mathrm{RT}}$	$V_{55} = V_{\mathrm{LT}}$	$V_{66} = V_{\mathrm{LR}}$
Resonance spruce (*Picea spp.*)								
P. abies	400	P1	5050	2000	1500	300	1425	1375
P. rubens	485	P3	6000	2150	1600	330	1240	1320
P. sitchensis	370	P6	5600	2150	1450	300	1340	1400
P. sitchensis	437	P4	5481	2178	1530	340	1300	1487
P. engelmany	352	P5	5500	2225	1850	325	1386	1361
Fiddle back maple (*Acer spp.*)								
A. pseudoplatanus	670	A7	4600	2500	1870	925	1529	1835
A. platanoides	740	A3	4940	2491	1942	937	1350	1698
A. macrophylum	600	A6	4500	2340	1550	900	1340	1720
A. saccharinum	700	A1	4785	2376	1786	653	1352	1738
A. rubrum	560	A2	3800	2510	1850	740	1450	1750

the 11 June 2003 addressed to Professor Xavier Deglise – Université Henri Poincaré in Nancy, France related to the ultrasonic approach for mechanical characterisation of wood. developed by V. Bucur:

"to my knowledge she was the first person to consider the propagation of bulk elastic waves in wood, taking into account the complete set of nine elastic constants describing the orthotropic elastic behaviour of the material. Her research revolved around the determination of three notoriously difficult to measure, off – diagonal constants. She also investigated the attenuation of elastic waves for various species and propagation directions, as well as earlywood – latewood differences in sound propagation properties. Her approach in describing the relationship of wave propagation as related to macroscopic and microscopic characteristics of wood is a unique contribution in the field and should help promote the more scientific use of acoustic wave propagation in non-destructive evaluation techniques. Her book 'Acoustics of Wood' is a popular reference for researcher in the field of elastic wave propagation in wood. Her forthcoming book 'Nondestructive characterisation and imaging of wood' will be the first concise overview of imaging methods used for wood characterisation. I am very familiar with both books which are now standard references in most forest products libraries. Since I served as a reviewer of the later book, I can attest to its scientific usefulness".

Part II Acoustic parameters and elastic constants of wood and wood – based materials

4 Acoustical characteristics of woods for musical instruments

Two wood species, namely spruce and curly maple have been used since the Baroque period for the construction of violins and other string musical instruments of this family. Spruce known as tone wood or spruce resonance wood (*Picea abies*) used for violin and other string instruments is extremely anisotropic from an acoustical point of view, and is characterized by high values of sound velocity in the longitudinal direction (6000 m/s) and relatively low density (400 kg/m^3). At the same time, shear velocities in the transversal plane are very low (300 m/s). The most important characteristic of spruce for musical instruments is the high acoustic and elastic anisotropy, produced by a very regular macroscopic anatomic structure. The relationship between elastic properties and the typical structural characteristics (growth ring pattern and the corresponding microdensitometric pattern, the microfibril angle, the cellulose crystallinity and the mineral constituents in the cell wall) and long-term loading has been discussed [7, 51–54]. Curly maple is a wood species having a very complex and irregular anatomic structure [55]. Curly maple has a high density of about 700 kg/m^3. The maximum velocity of P waves is 4300 m/s and the lowest shear velocity is 812 m/s.

To address core questions about the role of wood in the construction of string musical instruments in general, and in particular its role for instruments from the violin family it is necessary to know all the elastic constants of this material. With this data and by using finite element analysis it is possible to study the modes of vibrations of the plates of the violin or of the body of the instrument. The ultrasonic velocity method can be used to determine three Young's moduli, three shear moduli and the corresponding Poisson ratios. Specimens were cubes of 16 mm and transducers of 1 MHz frequency were employed. Specimens were cut from the blanks of violins and violas which were employed for making the instruments by the world recognised scientist and luthier C.M. Hutchin, for violins numbered from 261 to 271 [56].

The velocities and the elastic constants are given in Tables 15–19. Very old wood specimens have very low values of density and of E moduli, and therefore are not

Table 16. Diagonal terms of the stiffness matrix deduced from previous velocities for spruce and maple for violins [57].

Species	Density (kg/m^3)	Diagonal terms of stiffness matrix (10^8 N/m^2) C_{11}	C_{22}	C_{33}	C_{44}	C_{55}	C_{66}
		Resonance spruce (*Picea spp.*)					
P. abies	400	102.01	16.00	10.24	0.36	8.12	7.56
P. rubens	485	174.60	22.44	12.42	0.53	7.45	8.46
P. ssitchensis	370	116.03	17.10	7.78	0.33	6.64	7.25
P. sitchensis	437	131.30	20.70	10.23	0.51	7.38	9.65
P. engelmani	352	106.48	17.41	12.04	0.37	6.76	6.52
		Fiddle back maple (*Acer spp.*)					
A. pseudoplatanus	670	141.34	41.87	23.43	5.73	15.68	22.56
A.platanoides	740	180.59	46.91	27.90	7.20	13.68	21.34
A macrophylum	600	121.50	32.85	14.42	4.86	10.77	17.75
A. saccharinum	700	160.27	29.52	22.33	2.82	12.79	21.09
A.rubrum	560	80.86	35.28	19.16	3.06	11.77	17.15

Table 17. Off diagonal terms of stiffnesses and compliance of wood for violins [57].

Wood Species	Density	Off-diagonal terms of stiffness matrix and compliance matrix					
		Plane 12	Plane 13	Plane 23	Plane 12	Plane 13	Plane 23
		Stiffnesses (10^8 N/m^2)			Compliances (10^{-11} N/m^2)		
	(kg/m^3)	C_{12}	C_{13}	C_{23}	$-S_{12}$	$-S_{13}$	$-S_{23}$
		Spruce (*Picea spp.*)					
P. abies	400	17.53	13.20	12.14	14.13	1.18	−738.81
P. rubens	485	22.98	16.43	15.46	5.29	−2.19	390.18
P. sitchensis	370	14.97	10.20	7.57	5.13	8.21	95.75
P. sitchensis	437	27.25	22.25	13.39	−5.26	13.30	425.70
P. engelmani	352	26.91	20.79	14.11	−3.79	35.24	139.00
		Fiddle back maple (*Acer spp.*)					
A. Pseudoplatanus	670	32.49	30.72	18.53	3.06	10.88	25.78
A. platanoides	740	54.17	43.70	16.26	8.79	12.37	18.25
A. macrophylum	600	43.47	32.19	20.38	1.94	5.97	19.48
A. saccharinum	700	43.47	32.19	20.38	4.45	7.92	35.29
A. rubrum	560	11.50	14.19	12.78	2.81	15.26	39.06

Table 18. Technical terms calculated with previous data for spruce and maple for violins [57].

Species	Density	Technical terms (10^8 N/m^2)					
		Young moduli			Shear moduli		
	(kg/m^3)	$E_1 = E_L$	$E_2 = E_R$	$E_3 = E_T$	$G_{44} = G_{RT}$	$G_{55} = G_{LT}$	$G_{66} = G_{LR}$
		Spruce (*Picea spp.*)					
P. abies	400	82.79	1.56	1.03	0.36	8.12	7.56
P. rubens	485	150.89	3.13	1.75	0.53	7.45	8.46
P. sitchensis	370	99.95	9.49	4.30	0.33	6.64	7.25
P. sitchensis	437	82.31	3.15	1.57	0.51	7.38	9.86
P. engelmani	357	62.11	0.85	0.56	0.37	6.52	6.76
		Fiddle back maple (*Acer spp.*)					
A. pseudoplatanus	670	98.59	26.55	12.93	5.73	15.68	22.56
A. platanoides	740	89.53	29.08	16.99	7.20	13.86	21.34
A. macrophylum	600	111.20	27.66	11.71	4.86	10.77	17.75
A. saccharinum	700	104.37	19.17	10.97	2.82	12.79	21.09
A. rubrum	560	69.77	19.17	10.97	3.06	11.77	17.15

Table 19. Poisson ratios calculated with data from ultrasonic measurements at 1 MHz [57].

Species	Density	Violin	Poisson ratios			Specimens' origin and age	
	(kg/m^3)	Sample	ν LR	ν LT	ν RT	Years	Origin
			Spruce (*Picea spp.*)				
P. abies	400	P1	0.022	0.001	0.761	7	Switzerland
P. rubens	485	P3	0.006	0.004	0.681	85	Vermont US
P. sitchensis	370	P6	0.048	0.035	0.411	15	Alaska US
P. sitchensis	437	P4	−0.018	0.052	0.670	15	Alska US
P. engelmani	357	P5	−0.003	0.019	0.770	Very old	Colorado US
			Fiddle back maple (*Acer spp.*)				
A. Pseudoplatanus	670	A7	0.081	0.140	0.333	1	Vermont US
A. platanoides	740	A3	0.055	0.260	0.106	35	New Hamp.
A. macrophylum	600	A6	0.057	0.069	0.228	15	Oregano US
A. saccharinum	700	A1	0.123	0.087	0.228	25	Germany
A. rubrum	560	A2	0.188	0.111	0.226	35	Vermont US

recommended to be used by violin makers. The negative values of Poisson ratios could be explained by the interaction of wood microstructure (sizes of tracheid in 3D) with the wavelength of ultrasonic waves. This is the case for softwoods, for which the model of wood microstructure is that of a honey comb structure. NB: The relationships between the Poisson ratios should satisfy the condition $1 - \nu_{ij} \cdot \nu_{ji} > 0$.

5 Ultrasonic velocity and wood fracture mechanics

Ultrasonic velocity variation can express the evolution of the fracture process in wood in relationship with the generation of cracks under static stress [58]. This was my first original contribution to the fracture mechanics of wood combined with ultrasonic non-destructive testing.

Bending static tests on wood specimens conducted from zero stress until fracture and concomitantly ultrasonic velocity measurements performed with increasing stress allowed the determination of the four phases of wood fracture mechanics. These phases are:

- phase I, below $0.2\,\sigma_{\text{rupture}}$, – corresponding to submicroscopic deformation,
- phase II between $0.2\,\sigma_{\text{rupture}}$ and $0.7\,\sigma_{\text{rupture}}$ corresponding to macroscopic deformation,
- phase 1II between $0.7\,\sigma_{\text{rupture}}$ and $0.9\,\sigma_{\text{rupture}}$, generating cracks (fissures) and
- phase IV over $0.9\,\sigma_{\text{rupture}}$, corresponding to crack propagation and rupture.

In the first zone increasing velocity is observed. In the second zone the velocity is constant, while in the third and fourth zone the velocity decreases dramatically with increasing stress. In this way I determined the contribution of wood structure to the behaviour of this material under stress which can be observed even at a very low level of $0.1\ \sigma_{\text{rupture}}$.

6 Detection of biological agents degrading wood structure

Wood degradation by ligninolytic fungi causes considerable losses in sylviculture, arboriculture, and in the wood and construction industry. They degrade wood cell wall components acting specifically on cellulose, hemicellulose or lignin [59, 60].

The ultrasonic velocity method combined with X-ray microdensitometric analysis were employed for the detection of fungi attack in wood of pine and beech. Two species of fungi were selected: *Gloeophyllum trabeum* (Pers.:Fr. MurrilI) and *Trametes versicolor* (L.:Fr. Pilat). These fungi species induce typical decay attack mainly on cellulose in pine (brown rot) and mainly on lignin in beech (white rot). The attack was conducted for 1, 2, 3, 4 and 5 months in sterile laboratory conditions.

Fungi attack was detected with ultrasonic velocities (Tab. 20). After 5 months of attack on beech specimens a decrease of all velocities in various proportions was observed. Shear wave velocity V_{44} decreased by 48% for beech on which the lignin was attacked in the RT plane. On pine specimens in which the cellulose was attacked, the velocity V_{22} decreased by 56% in the R axis, and V_{55} in the LT plane decreased by 37%. Acoustic invariants (Tab. 21) illustrate the global destruction of the wood structure. In the RT transverse plane in which the anatomical elements were dislocated by fungal attack, a difference of 24% for beech and of 51% for pine was observed. X-ray microdensitometric analysis shows that after 5 months of fungal attack all the values of density components decreased. In beech the loss was about 25% for all components (Tab. 21). In pine the earlywood density component decrease was about 20% and in latewood about 40%.

It can be concluded that the ultrasonic velocity method as well as the X ray micro densitometry are two complementary non-destructive techniques, able to detect fungal attack of different intensity on wood specimens (Tab. 22).

Table 20. Effect of fungi decay on ultrasonic velocities at 1 MHz frequency [61].

Wood species	Treatment	Ultrasonic velocities (m/s)					
		P compressional waves			*S* shear waves		
		V_{11}	V_{22}	V_{33}	V_{44}	V_{55}	V_{66}
Beech	Initial	4909	2210	1590	865	1562	1649
Lignin attack	After 5 months white rot	4580	1759	1280	450	1391	1438
	Difference (%)	−7	−20	−19	−48	−11	−13
Pine	Initial	5565	2162	1823	617	1681	1860
Cellulose attack	After 5 months brown rot	3715	952	947	390	961	1232
	Difference (%)	−33	−56	−48	−37	−43	−34

Table 21. Acoustic invariants and the fungi attack in each anisotropic plane of wood [61].

Wood species	Treatment	Acoustic invariants				
		I_{12}	I_{13}	I_{23}	*I* average axis 1	*I* ratio
Beech	Initial	2933	2807	1492	2876	0.52
	After 5 months white rot	2634	2551	1133	2582	0.44
	Difference (%)	10	9	24	9	16
Pine	Initial	3262	3160	1480	3211	0.46
	After 5 months brown rot	2106	2034	726	2070	0.33
	Difference (%)	35	37	51	35	24

Notes. *I* average is calculated for I_{12} and I_{13} containing the axis 1 or axis L of wood.

Table 22. X ray micro densitometric components of specimens attacked by fungi [59].

Wood species	Specimens	X ray micro density components (kg/m^3)				
		Earlywood	Average	Latewood	*D* min	*D* Max
		White rot – Lignin attack				
Beech	Control	660	697	789	591	853
	Five months	490	524	583	439	638
	Difference %	25.7	24.8	26.1	25.7	25.2
		Brown rot – Cellulose attack				
Pine	Control	455	602	920	377	1012
	Five months	360	420	546	324	607
	Difference %	20.8	30.2	40.6	16.3	40.0

Currently in sawmills, logs can be stored in water for various periods of time when several type of bacteria can develop. On the other hand, bacterial activity can be used to improve the permeability of wood for better impregnation. The impact of five months of water storage together with a bacterial treatment, on the mechanical properties of spruce is analysed by ultrasonic waves. The *Bacillus subtilis* is used to improve the permeability of spruce sapwood. This bacillus attacks the sub microscopic structure of wood distorting the torus of aspirated pit. This physical modification of the wood structure was expected to lead to better transport of preservative liquids for better wood preservation.

The elastic constants were calculated through ultrasonic velocities which were measured for different types of specimens. The results were compared with the constant E_L as determined by a static bending test. The calculated loss of strength seems to be negligible but variations in the elastic properties of anatomical planes in the radial axes, can be predicted well.

The ultrasonic velocity method was used to study the modification of wood structure in spruce specimens (Tab. 23). The most important degradation by bacillus attack was observed with shear waves in V_{44} on the RT plane for a significant difference of about 15%.

Using ultrasonic data, the Young's modulus and the shear modulus of spruce attacked by *Bacillus subtilis* were calculated. It was noted that the value of E_L decreased by 10% but the value of E_T increased by 20%. The most important degradation of spruce structure was in the transverse anisotropic plane and was illustrated by the decrease of shear modulus G_{RT} by 31% (Tabs. 24 and 25).

Static bending tests confirmed the decrease in the modulus E_L by 5% as well as in the σ rupture by 17% and in the shock test by 12% (Tab. 26).

Table 23. Impact of water storage and *Bacillus subtilis* attack on ultrasonic velocities [62].

Wood	Ultrasonic velocity (m/s)						
	Density	*P* compressional waves			*S* shear waves		
Picea abies	(kg/m^3)	V_{LL}	V_{RR}	V_{TT}	V_{RT}	V_{LT}	V_{LR}
Sound	407	4619	1994	1251	665	1276	1395
Attacked	383	4740	2115	1309	567	1222	1480
Difference %	−6	+3	+2	+4	−15	−4	+1
Test *T*	NS	NS	NS	NS	**	NS	NS

Table 24. Impact of water storage and *Bacillus subtilis* attack on ultrasonic velocities [62].

	Density	Acoustic invariants in planes (m/s)			Ratio
Wood	(kg/m^3)	I_{LR}	I_{LT}	I_{RT}	*I* ratio
Sound	407	5025	5114	2535	0.50
Attacked	383	5596	5212	2613	0.48
Difference %	−6	+10	+1	+8	−4
Test *T*	NS	NS	NS	NS	NS

In conclusion it can be noted that the mechanical parameters of wood species after five months of *Bacillus subtilis* attack varied in a range acceptable to the wood industry. The ultrasonic technique offers a comprehensive approach to structural modifications of wood after a *Bacillus subtilis* attack of five months. Acoustic invariants show structural modification of wood induced by *Bacillus subtilis* attack. For practical applications, it can be mentioned that the *Bacillus subtilis* attack for a limited time of 5 months is not destructive for logs and can be used in a preliminary phase for improving wood impregnation process.

7 Mechanical characterisation of wood-based composites

Wood based composites include a wide range of products, and their properties depend on wood species, type of bonding, composition, finishing, etc. The bonding between wood elements can be by thermosetting with resins or using adhesive mixtures or binders like cement. The economic impact of using these composites is of worldwide significance. Wood based composites of numerous types are available on the market because they are relatively easy to process. Wood species play a relevant role in defining the properties of wood -based composites. The main technical characteristics of these composites are their mechanical strength, their good thermal and phonic insulation, good durability and flame retardancy.

The ultrasonic velocity method was developed for mechanical characterisation of laminated veneer lumber [63], ageing monitoring of flakeboards [64] and characterisation of wood cement composites with wood particles in different proportions [65].

The aim of this section is to discuss the ultrasonic velocity method for detection of the anisotropy of structural flakeboards and to explore the microstructure of 3 types of composites namely: medium – density fiberboard (MDF), oriented strandboard (OSB) and chipboard (CB) by using the ultrasonic method combined with X ray micro-densitometry.

7.1 Anisotropy of structural flakeboards

The anisotropy of the flakeboards is a mechanical characteristic which has an important impact on the product's quality. The ultrasonic velocity method and acoustic emission method were used for the determination of the anisotropy of structural flakeboards of 19 mm thickness manufactured from a mixture of softwood and hardwood slabs bonded with urea formaldehyde resin. Geometric characteristics of the boards were noted such as: axis 1 along the technologic flux, axis 2 perpendicular to the technologic flux, axis 3 – along the thickness. The elastic symmetry of the board was hypothesised as orthotropic [66].

The anisotropy of the structural flakeboard specimens were studied with the ultrasonic equipment being a Panametrics AU5052 analyser and transducers of 1 MHz frequency. The surface waves were measured with the Satec 80 mobile equipment (made in France), of 80 kHz frequency transducers. Acoustic emission equipment was Dunagan – Locan with a frequency response of 1.2 kHz to 1.2 MHz and the transducer was R15 with a frequency response of 150 kHz. The reference at the transducer was set at 1 μV for 0 dB. On the specimen the transducer was located successively at 5, 10, 15 and 20 cm from the source. Breaking a 0.5 mm pencil lead on the surface of the specimen was the source for acoustic emission.

Ultrasonic velocity values with *P* waves and *S* shear waves are given in Table 27. The values of the velocity V_{11} is in the same range as the velocity V_{22} and of the surface velocity, at around 2300 m/s. The velocity of *P* waves in the thickness direction of the board is on average 700 m/s. The values of the dynamic modulus E_L calculated with the ultrasonic velocity method (27.69×10^8 N/m^2) is slightly higher than that determined in static tests (25.5×10^8 N/m^2) (Tab. 28). The ultrasonic velocity method allows the measurement of three shear moduli (Tab. 29).

Table 25. Impact of water storage and *Bacillus subtilis* attack on technical constants calculated from experimental data with ultrasonic velocity method [62].

Wood specimens	Density	Technical constants calculated with ultrasonic velocity method					
		Young moduli (10^8 N/m^2)			Shear moduli (10^8 N/m^2)		
Picea abies	(kg/m^3)	E_L	E_R	E_T	G_RT	G_LT	G_LR
Sound	407	86	13	3	1.80	6.63	7.92
Attacked	383	78	11	4	1.24	5.75	8.40
Difference %	−6	−10	−13	+20	−31	−13	+6

Table 26. Strength characteristics of sound and attacked wood by static tests [62].

Wood specimens	Density	Three point static bending		Shock test
		E_L	σ rupture	Shock energy
	(kg/m^3)	(10^8 N/m^2)	(daN/cm^2)	(kg.m/cm^2)
Sound	407	82	638	430
Attacked	383	78	529	380
Difference	−6	−5	−17	−12

Table 27. Ultrasonic velocities on flakeboards of 19 mm thickness with bulk waves and surface waves [67].

	Density	Bulk waves frequency 1 MHz						Surface wave
	(kg/m^3)	P waves (m/s)			S waves (m/s)			(m/s)
		V_{11}	V_{22}	V_{33}	V_{44}	V_{55}	V_{66}	v_surface
Average	634	2379	2155	704	564	618	1129	2345
Minim	602	2198	1966	652	528	574	1070	2172
Maximum	665	2613	2310	841	622	648	1239	2612
Coef variation %	3	4	4	6	3	3	3	4

Table 28. Technical constants calculated from ultrasonic data and static bending test measurements (average values) of flakeboard specimens [67].

Ultrasonic testing						Static bending test	
Density	Modulus E_1	Modulus E_3	Poisson ratios			Modulus E_1	Rupture $\sigma 1$ axis 1
(kg/m^3)	10^8 N/m^2	10^8 N/m^2	ν 12	ν 13	ν 31	10^8 N/m^2	10^6 N/m^2
612	27.69	Very small	0.145	0.076	0.007	25.50	14.30

Table 29. Shear moduli with the ultrasonic velocity method. Average values of data for flakeboard specimens [67].

Density	Ultrasonic shear moduli expressed in N/m^2			Anisotropy ratio	
(kg/m^3)	G_{44}	G_{55}	G_{66}	G_{66}/G_{44}	G_{55}/G_{44}
612	14.46×10^6	23.37×10^6	7.8×10^8	16.5	1.61

At the first glance, the values V_{11} and V_{22} as well as the values V_{44} and V_{55} suggest a transverse isotropic symmetry in the flakeboard. However, the differences between the values of shear moduli G_{44} and G_{55} are important. Therefore, it was reported that orthotropic symmetry was appropriate for elastic characterisation of the flakeboard specimens.

Table 30 synthetises the anisotropy of flakeboards. Flake alignment can be observed with the ultrasonic velocity method – P waves by comparing the velocities V_{11} and V_{22}. Skin damage of the external layer of the board can be detected with the acoustic emission technique and with velocities of surface waves. The interlaminar heterogeneity between the surface layers and the core of the flakeboard can be detected with shear waves by comparing the ratios of velocities V_{66}/V_{55} which was 1.86 … 1.97 and V_{66}/V_{44} which was 1.91 … 1.99. It can be pointed out that the quality of the

Table 30. Manufacturing characteristics of flakeboard (19 mm thickness) and anisotropy expressed by acoustic parameters [67]. Legend: Macroscopic aspect of the flake board (`https://furniture.mu/wp-content/uploads/2018/08/oriental-strand-board-osb-500x500-1-300x300.jpg` Accessed 4 April 2023).

Flakeboard characteristics	Acoustic parameters	Anisotropy		
		Definition	Values	
			Minimum	Maximum
Flake alignment with ultrasonic velocity method – P waves				
	Longitudinal velocities	V_{11}/V_{22}	1.11	1.13
	Surface velocity	Axis 1 / Axis 2	1.03	1.10
	Acoustic invariants	I_{12}/I_{13}	1.32	1.46
Skin damage with acoustic emission at 5 cm				
	Peak amplitude	Reference signal	1.04	1.08
	Events duration ratio	Axis 1/Axis 2	1.18	0.80
	Count number ratio	Axis 1/Axis 2	0.15	0.11
	Energy ratio	Axis 1/Axis 2	1.72	1.68
Interlaminar heterogeneity with shear waves velocity method				
	Plane 12/Plane 13	V_{66}/V_{55}	1.86	1.91
	Plane 12/Plane 23	V_{66}/V_{44}	1.87	1.99
Global board anisotropy	Acoustic invariants	I ratio global	0.72	0.82
Macroscopic aspect of the flakeboard with the random alignment of flakes				
				

flakeboards from which the specimens were cut was very good.

In conclusion it can be observed that the anisotropy of structural flakeboard anisotropy can be expressed by the ratio of the acoustic invariants in plane 12 and 13. Flake alignment, damage on skin layers and interlaminar heterogeneity can be detected by the ultrasonic velocity method combined with the acoustic emission method.

7.2 Microstructure of wood-based composites with the ultrasonic velocity method and with X ray microdensitometry

Combined nondestructive methods have been used to compare the mechanical properties of wood – based panel products in relation to their microstructure. Three types of composites were considered: medium – density fibreboard (MDF), oriented strandboard (OSB) and

Table 31. Analysis of variance to study the effect of tree and of increment core position in tree along the L or T axes. Parameters used: ultrasonic velocities of various frequencies. Specimens: increment cores of 5 mm diameter of beech (*Fagus Sylvatica*) [4].

Variation source	Wave	Frequency	Test F for the following characteristics					
			V_{LL}	V_{RR}	V_{TT}	V_{LR}	V_{LT}	V_{TR}
Tree								
	P wave	80 kHz	NS	**	NS			
		2 MHz	**	**	**			
	S wave	1 MHz				*	NS	*
Position in tree								
	P wave	80 kHz	NS	**	*			
		2 MHz	**	NS	**			
	S wave	! MHz				NS	*	**
Interaction								
	P wave	80 kHz	NS	NS	NS			
		2 MHz						
	S wave	1 MHz				NS	**	NS

Notes. NS – not significant. Symbols: ** significant at 1% significant at 5%.

chipboard (CB). The overall elastic properties of panels were assumed to be orthotropic [68].

The diagonal terms of the stiffness matrix were determined with the ultrasonic velocity method. The properties of the skin and the core of the panel were characterized using X-ray microdensitometry, ultrasonic velocity measurements, dynamic thermo – mechanical analysis and low voltage scanning electron microscopy.

Clear differences have been established in the physical properties of the three panel products. Average mechanical properties have shown that the highest anisotropy is in OSB and the lowest in CB. Always the mechanical characteristics of the skin are higher than average characteristics of the panels while that of the core are inferior to average characteristics. E, the Young's elastic modulus is much higher (2 to 5 times) in the skin than in the core. The X-ray microdensitometric technique has shown that heterogeneity in the skin and core is highest in OSB.

Part III Ultrasonic methodology in forestry

8 Practical applications of the ultrasonic velocity method in forestry

Applications of ultrasonic velocity methods in forestry have been developed for four main purposes:

- the determination of wood mechanical parameters in increment cores bored from living trees;
- the determination of the slope of the grain on standing trees;
- the effect of pruning treatment on wood quality of standing trees;
- the determination of the viability of acorns as an important group of forest seed products.

8.1 Increment cores and characterisation of standing trees wood quality

We have seen in Section 2.2 that for each increment core bored at a height of 1.30 m from the ground, it was possible to determine the gravimetric density of wood, to measure the velocities of P waves and S waves and to calculate the corresponding stiffnesses. These parameters can characterise the mechanical properties of wood for each tree.

Furthermore, it was necessary to study the effect on the values of velocities of the position of the specimen in a tree, at different heights. The analysis of variance (Tab. 31) demonstrated that the velocities V_{LL}, V_{RR}, V_{TT} and V_{LR} and V_{TR} on increment cores at frequencies of 1 MHz or 2 MHz are able to detect the effect of individual "tree" and of the "position" in tree of the increment in a tree along axis L or T.

The F test at the highly significant 0.01 level showing the effect due to the position of the core in the tree, illustrated by V_{LL} of 2 MHz frequency and by V_{LT} of 1 MHz, can be understood as the response of the anatomic structure of wood in the L direction to the propagation of ultrasonic waves.

The sensitivity of velocities, measured in the L direction, to anatomical wood structure in the high frequency range can be attributed to the continuity of wood fibres of about 3 . . . 4 mm length, running parallel with the tree growth axis. At the 1 . . . 2 MHz wave frequency, the wavelength matched the size of the anatomic wood structure composed of tracheids and fibres. It can be mentioned that the ultrasonic waves propagating in wood reveal some particularities of microscopic structure, if an appropriate frequency is used.

Two regression equations have an important practical meaning for using increment cores of 5 mm diameter to express wood mechanical characteristics of a tree, namely the correlations of modulus of rupture on standard specimens in bending with velocity V_{LL} and with the stiffness C_{LL}

$$\mathrm{MOR} = 0.02996V_{\mathrm{LL}}^{\mathrm{core}} - 15.65 \quad \text{and correlation coefficient } r = 0.701^{***} \tag{29}$$

$$\mathrm{MOR} = 0.01178C_{\mathrm{LL}}^{\mathrm{core}} - 33.56 \quad \text{and correlation coefficient } r = 0.511^{**}. \tag{30}$$

Based on results presented here it was concluded that the ultrasonic velocity method on increment cores of 5 mm diameter is capable of rapidly detecting the differences between individual mechanical characteristics of living trees [4].

8.2 Slope of grain on standing trees

Relationships between the grain angle of wood specimens and ultrasonic velocity of P waves in three anisotropic planes were thoroughly studied [69]. Deviation of fibres from the axial growing direction of a tree is a defect for wood quality and is called the slope of grain. Deviation of several degrees can be observed visually on standing trees. The deviation of fibres for some species can be limited to a superficial zone or can be profound, affecting the entire tree wood (Fig. 5a). For other species the deviation can be included in all the wood of the tree (Fig. 5b). The ultrasonic technique proposed by Bucur and Perrin [70] can detect this defect in wood. The proposed technique was possible starting from the theoretical assessment that the path of ultrasonic waves at the surface of a standing trees is elliptical and the maximum velocity corresponds to the value measured along the axis, for the slope of grain 0°. By comparing the velocities at different angles, it is possible to calculate the slope of the grain of wood on standing trees. The array of sensors on a tree are arranged as shown in Figure 5c.

Ultrasonic velocity was measured with a mobile pulse receiver equipment SATTEC AU 80 with the following main characteristics: maximum pulser voltage 250 V, band width 3–300 kHz; band filter receiver 80 kHz, sensitivity 1–100 $\mathrm{mV.cm^{-1}}$; time base 30–10 000 μs; repetition rate 20 Hz. The measurements were performed on living trees and on air dried lumber. The emitter was put at a well-defined point and the receiver at three arbitrary points on an arch of a radius of several centimetres. To validate the experiment, the grain angle was visually measured previously. Knowing the equation of wave propagation, and the elliptical pattern of ultrasonic waves in wood it was possible to calculate the angle between the anisotropic direction L and the wood fibres' deviation which expressed the slope of the grain. The grain angle accuracy prediction depends on the accuracy of velocity measurements. The regression equation between the angle determined with the ultrasonic velocity method and with the visual method is:

$$\mathrm{Y}\,(^\circ\text{ultrasound}) = 0.646 + 0.916X\,(^\circ\text{visual}) \quad r = 0.949^{***}, n = 22 \text{ spruce trees.} \tag{31}$$

The same methodology can be applied to lumber.

8.3 Effect of pruning treatment on wood quality of trees

Some exceptional trees like spruce resonance trees known as tone wood trees have the trunk of a perfect cylindrical shape due to natural pruning. Consequently, wood tissue has very few knots and large zones without knots. Figure 6a illustrates a natural population of deodar trees (*Cedrus deodara*) which can live up to 1000 years old. A tree can reach 60 m tall with a trunk up to 3 m diameter, the stem is cylindrical and has a conic crown with level branches and drooping branches, due to natural pruning.

Pruning trees by foresters is a current sylvicultural practice with the aim of improving wood quality. Pruning requires trimming of branches at several heights of the tree (Fig. 6b). The integration of the pruned branch into wood tissue is shown in Figure 6c. The pruned branch generated a knot in lumber.

A considerable body of knowledge has been amassed over time on the influence of pruning on wood quality. While it is important to increase this body of knowledge, it is also important to use it properly for the detection of the effect of this silvicultural treatment on standing trees' wood quality. The principal effects of pruning on wood quality are related to the disappearance of knots, to the improvement of the cylindrical shape of the stem of the tree, to the reduction of the proportion of juvenile wood, and to the improvement of some physical properties such as density and shrinkage [72, 73].

The effect of pruning on wood stiffnesses studied with surface ultrasonic waves on trees and with bulk waves on increment cores of 5 mm diameter was reported by Bucur [71]. Two codominant trees of Douglas fir (*Psadotsuga mennziesii* Mirb.) from the forest of Amance in eastern France have been selected. The first was pruned half of its height (9 m) and the second was a control tree. The diameter of these trees was around 30 cm at 1.30 m from the ground. The trees were fallen and sectioned in logs. Ultrasonic tests were run on logs and increment cores. Each log was measured at 18 zones at different heights from the ground, from 0.20 m to 8.50 m. On four generating lines. Inside every zone the points of measurement were selected from wood without defects. At each point an increment core of 5 mm in diameter and 0.10 m long was bored. The ultrasonic measurements on logs weress performed along the diameter in the R direction with bulk waves and in the L direction with surface waves (distance between the emitter and receiver 1 m) using the AU 80 SATTEC apparatus (France), with a frequency of 80 kHz.

a). slope of grain on *Abies concolor* tree b). slope of grain in a log

c). elliptical path of ultrasonic d). array of sensors on a tree

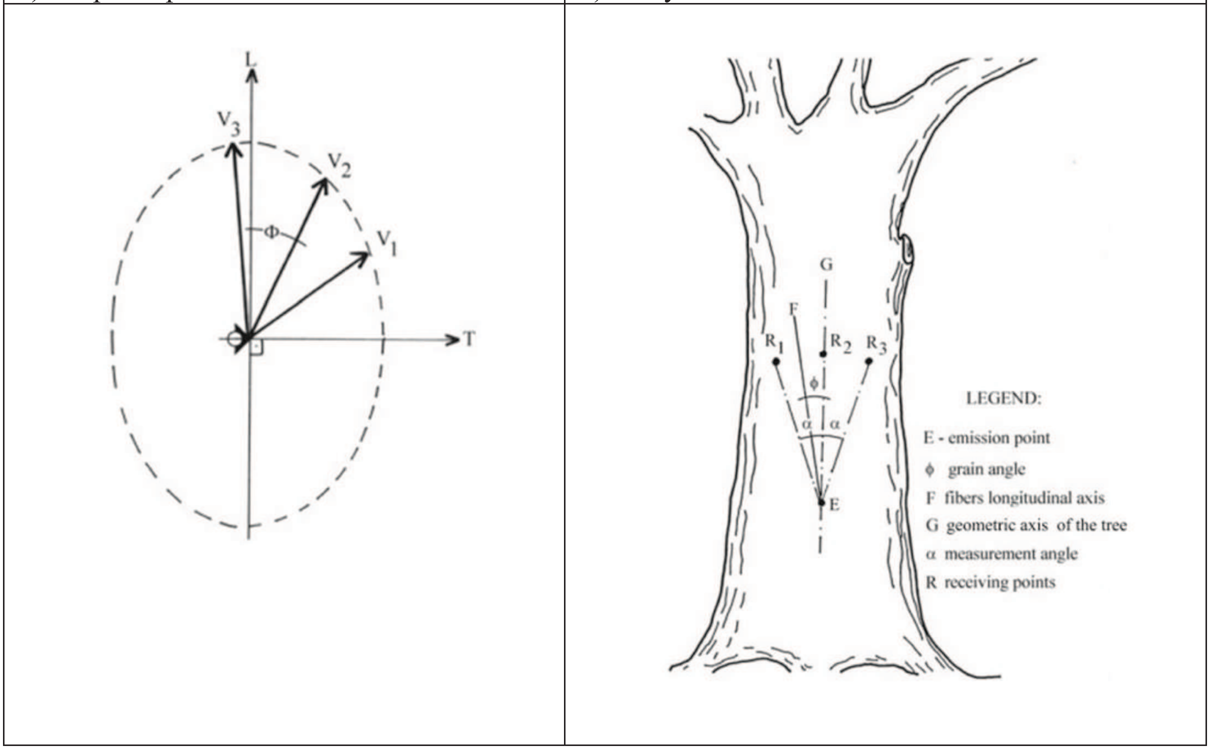


Figure 5. Detection of the slope of the grain on standing trees [70]. Legend: (a) Slope of the grain at several angles in *Abies concolor* (`http://tchester.org/sj/analysis/pix/Abies_concolor_3_1_crop_40.jpg` accessed 17 January 2023); (b) Spiral grain in a log of (*Pinus longaeva*) ([76], Fig. 1); (c) Elliptical path of ultrasonic wave propagation in a standing tree, determined with three measurements of longitudinal velocities V_1, V_2, and V_3 which can precisely determine the slope of the grain (angle φ), bearing in mind that along the fibres in the L axis, the velocity value is at a maximum; (d) The array of transducers for grain angle measurements on a tree at breast height. ϕ the angle of the slope of grain [70].

For measurements on increment cores ultrasonic transducers were used with longitudinal and transverse waves (frequency *I* MHz). Ultrasonic waves were generated by the ultrasonic analyser 5052 UA Panametrics. In what follows are presented the results on trees and on increment cores.

On trees, at 1.30 height the average value of velocity in the R direction was 1589 m/s in a pruned tree compared with 1272 m/s in a control tree which gives a difference of 20% (Tab. 32). The average value of velocity in the L direction was 6006 m/s in a pruned tree compared with 5528 m/s in a control tree which gives a difference

a). natural pruning of *Cedrus deodara*

b). tree stem after pruning of branches

c) development of branch colar

d) knots in lummber

e). surface velocity in L direction versus the height of the tree in pruned and not pruned Douglas fir

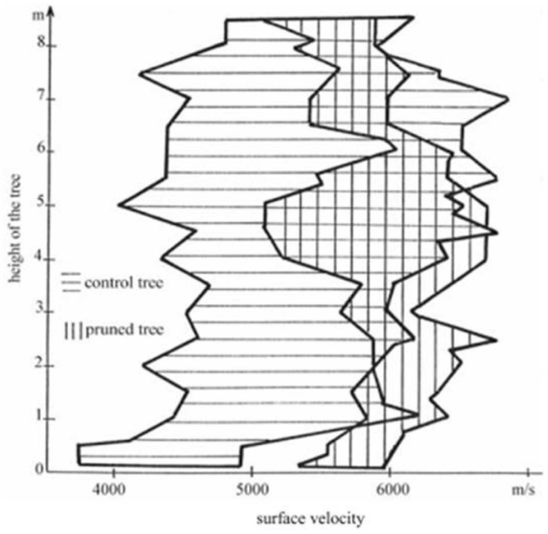


Figure 6. Pruning of forest trees to improve wood quality. Legend: (a) Natural pruned trees Deodar Tree (*Cedrus deodara*): (`https://cdn.shopify.com/s/files/1/0579/7924/0580/files/cd_480x480.jpg?v=1699253666` accessed 29 August 2024); (b) Stem aspect after pruning the branches (Photo Brett R. McLeod 2015); (c) Section in the LR plane around the pruning zone showing the development of a branch collar (`https://texastreeteam.com/wp-content/uploads/2018/05/IMG_9477-175x300.jpg` accessed 29 August 2024); (d) Knots on lumber generated by a pruned branch (`https://em2ys5fu2fg.exactdn.com/wp-content/uploads/2020/02/Picture1.jpg?strip=all&lossy=1&ssl=1` accessed 29 August 2024); (e) Variation of surface velocity versus the height of the tree in pruned and controlled Douglas fir grown in the Eastern part of France ([71], Fig. 3, p. 272).

Table 32. Characteristics of a pruned Douglas tree compared with a Douglas control tree grown in the same area, in the Eastern part of France. Trees diameter at 1.30 m height was 30 cm. Measurements in green conditions on logs from fallen trees. Ultrasonic frequency 80 kHz [71].

Tree type	Velocity along R axis (m/s) (bulk waves)		Velocity along L axis (m/s) (surface waves)	
	Mean	Range	Mean	Range
Pruned tree at 1.30 m, – density 547 kg/m^3	1589	1545–1607	6006	5720–6424
Pruned tree from 0.2 to 8.5 m	1491	1259–1852	5916	5526–6523
Control tree at 1.30 m – density 548 kg/m^3	1272	1240–1304	5528	4515–5699
Control tree from 0.2 m to 8.50 m	1480	1273–1789 n	5448	4040–6785

of 8%. The effect of pruning was more visible in the R direction.

Figure 5e illustrates the variation of surface velocity versus the height of the tree in pruned and controlled Douglas fir. Note the reduced dispersion of velocity V_{LL} on a pruned tree compared to the control tree. The quality of pruned tree wood is less heterogeneous than that of the control tree. The increasing velocities measured in pruned trees could be interpreted as a result of the improvement in the wood quality. It is also interesting to observe the variation in surface velocity related to the height of the tree. The dispersion of values of surface velocity is higher in control trees than in pruned trees. This means that the variability in the wood quality of pruned trees is smaller than that in control trees. Surface waves have a very small penetration on a tree and therefore the effect of the pruning treatment was less visible (differences observed were only of 7.9%). The effect of pruning studied with bulk waves measured at 1.30 m is observed on V_{RR} which increased by 19.94% on the pruned tree compared with the control tree.

It is worth mentioning that the ultrasonic velocity method on trees in the R direction was a pioneering approach which leaded to the development of ultrasonic tomography on trees and logs.

On increment cores, the following constants: C_{LL}, C_{TT}, G_{LR}, G_{LT} and G_{TR} were calculated (Tab. 33). When comparing the elastic constants measured on increment cores for pruned and control trees the following differences were observed:

- C_{LL} increased in pruned tree with about 7%;
- C_{TT} was not affected;
- G_{TR} increased in pruned tree with about 13%;
- G_{LR} and G_{LT} decreased in pruned tree with about maximum 5 %.

This means that, in general, the mechanical properties of wood of pruned trees were improved in the L direction and the most important benefit was for G_{TR}, and shear stress in the TR plane. It can be supposed the pruned tree will be more resistant to winds than the control tree.

A possible explanation of the benefit of pruning on wood structure is based on the increase in length of sapwood tracheids, the increase in width of the annual ring and of the corresponding latewood zone and increase in thickness of the cell wall.

Effects of pruning on some characteristics of wood properties (density, modulus of elasticity E_{L}, stress wave velocity V_{LL} and microfibril angle) of young radiata pine grown at a dry-land site in New Zealand, was reported by Moore et al. [74].

8.4 Germinability of acorns detected with the ultrasonic velocity method

During the last decades of the XX th century there has been a great deal of interest in developing nondestructive techniques to characterize the germinability of forest seeds. In the Scandinavian countries and elsewhere in the world, various aspects of the application of X-ray analysis to coniferous tree seeds have been considered. It was impossible to distinguish between nonviable seeds or seeds having a conspicuous delay in germination, by means of X-ray photography alone.

A novel application of the ultrasonic velocity method was proposed by Bucur and Muller [75] to separate germinated and non-viable acorns produced by oaks (*Quercus robur*) and in this way to predict their germinability. The physical parameters under consideration have been morphological (dimensions of two axes) and physical criteria (density, ultrasonic velocity, impedance and acoustic stiffness). For the experiments all specimens were 6 months old, of an average trading quality (about 50% non-viable acorns).

The investigation was divided into two parts: research and possible industrial application. Research aspects were related to the determination of relationships between morphological and physical characteristics (ultrasonic velocity, impedance, stiffness, density) of acorns. Industrial applications required determining if the physical parameters under consideration were sufficiently subtle in their measurement capability to form the basis of a quality control system in the production processes of acorns.

Acorns are oblong, about 25 mm long and 15 mm wide (Fig. 7a). The shape of acorns is very nearly an ellipsoid. For this reason, we defined the morphological characteristics of every acorn by two dimensions D and d

Table 33. Elastic constants of wood ($10^8\,\mathrm{N/m^2}$) measured on increment cores of 5 mm diameter of a pruned Douglas tree compared with a Douglas control tree grown in the same area. Measurements were at 12% wood moisture content [71].

Elastic constants	Wave type	Elastic constants of wood ($10^8\,\mathrm{N/m^2}$)		
		Pruned tree	Control tree	Difference (%)
C_{LL}	P waves			
Average		121.7	112.8	7.3
Range of variation		32.4–292.6	25.2–261.3	
C_{TT}	P waves			
Average		16.47	16.40	0.4
Range of variation		11.3–27.4	10.1–29.1	
G_{LR}	S waves			
Average		11.58	12.21	−5.4
Range of variation		5.4–17.9	7.29–20.3	
G_{LT}	S waves			
Average		10.58	10.98	−3.7
Range of variation		6.5–15.9	6.4–16.5	
G_{TR}	S waves			
Average		1.51	1.31	13.2
Range of variation		0.6–4.6	0.67–2.8	

(Fig. 7b). The ratio D/d was defined as the shape coefficient. The average value of this coefficient was 1.6. The ultrasonic velocity was determined using the classical through transmission method for solids using SATTEC AU 80 (France) mobile equipment, transducers with an ultrasonic frequency of 80 kHz for bulk P waves.

The experimental relationship between physical and morphological parameters of acorns detected a significant correlation between velocity and density of non-viable acorns ($r = 0.319^{***}$), and between density and shape coefficient for non-viable acorns ($r = 0.346^{***}$). With Principal component analysis (Fig. 7c) it was possible to detect the viable and the nonviable acorns (explained variability = 71% in plane $1, 2$). The main vectors were the density and the velocity Vd along the small axis of the acorn. From this statistical analysis we note that an acceptable basis for estimating the germinability of acorns in a batch is provided by two physical characteristics of acorns, the small diameter and the density. The parameter measured is the ultrasonic velocity along the small diameter of the acorn.

9 Expertise

I acted as technical expert for the development of the ultrasonic velocity technique for quality control of wood products with American Weyerhaeuser Company, Isoroy Company Lisieux, France, and for the characterisation of wood for concert harps for the company Salvi Harps Italy. Collaboration with Panametrics–Sartrouville, France and Schlumberger–Nancy, France was required to select the types of transducers for wood testing with ultrasonic waves of various frequencies. Technical reports have been transmitted to the companies mentioned.

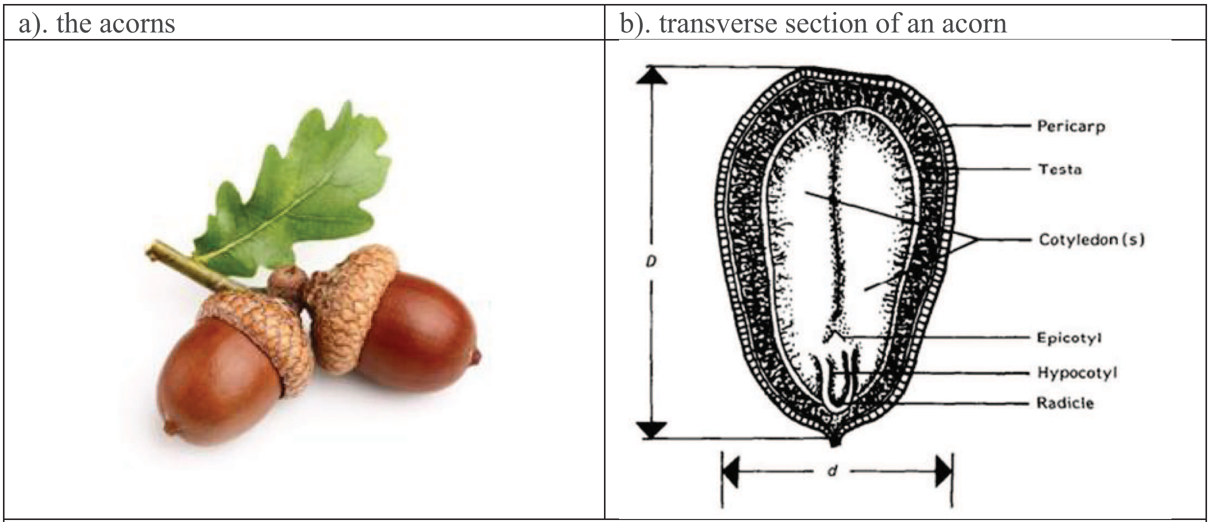
I acted as reviewer for Acta Acustica united with Acustica, Journal of Acoustical Society of America, Ultrasonics, Journal of Catgut Acoustical Society, Wood Science and Technology, Holzforschung, Holz als Roh und Werkstoff, Annales des Sciences Forestières, Annales of Forest Science, Revue Forestière Française.

I acted as co-supervisor for Master of Science reports – DEA Science du bois – Henry Poincare University, Nancy, France from 1983 to 1999. I co-supervised PhD theses from 1986 to 1999 with Henry Poincare University, Nancy and Blaise Pascal University Clermont Ferand, and academic institutions like Ecole de Mines de Saint Etienne and Ecole des Eaux et Forêts de Nancy. I was invited by Shizuoka University Japan for 3 months September, October November 1995, to give lectures on ultrasonic techniques and wood quality.

10 Concluding remarks

The advances presented in previous pages in the field of ultrasound for wood science and technology, and for forestry and the wood industry during the last two decades of the XX th century concerned the development of the non-destructive ultrasonic velocity method, through the direct transmission technique. Theoretical considerations were presented for the determination of elastic constants of wood as an orthotropic material. Based on these considerations the elastic constants of numerous wood species were calculated. The anisotropy a). the acorns

b). transverse section of an acorn



c).acorns: non- viable (o) mostly in quadrant II and III ,viable ●; vectors: velocity Vd and density ρ

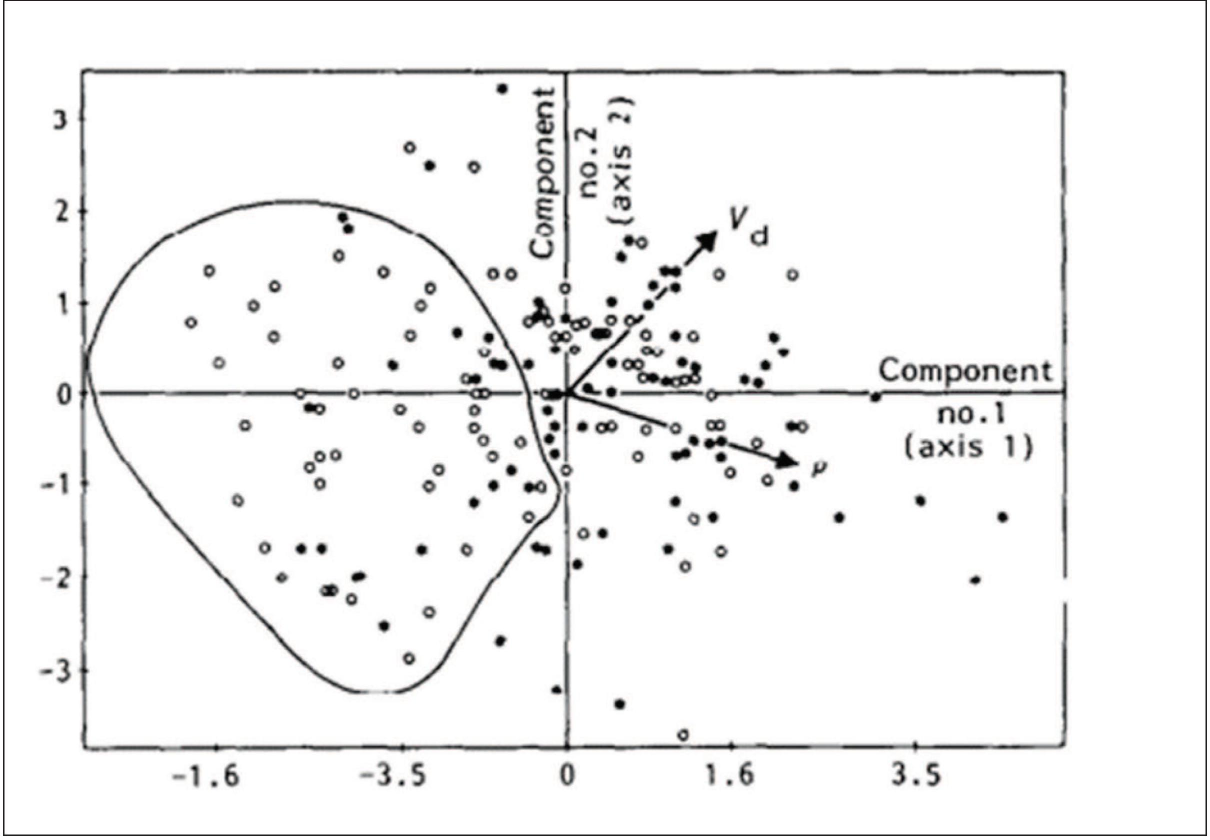


Figure 7. Ultrasonic characterization of acorns [75]. Legend: (a) The acorn `https://imengine.prod.srp.navigacloud.com/?uuid=B491E74D-505B-43B6-8C0A-1E491FDA0290&type=primary&q=72&width=1024`; (b) Longitudinal section of acorn. $D = 25$ and $d = 15$ mm ([75], Fig. 1, p. 225); (c) The swarm of experimental points in principal component plane 1, 2. principal component analysis. Plane 12 – explained variance 71%. The germinated acorns are mostly around their inertia centre in the first quadrant. The non-viable acorns are structured around another centre in the third quadrant ([75], Fig. 4, p. 228).

of wood species was characterised by new parameters introduced in wood science, the acoustics invariants. Wave propagation phenomena were related to macroscopic and microscopic particularities of wood structure. Acoustic microscopy for wood structure was explored and was a pioneering activity.

A special interest was directed towards the mechanical characterisation of wood species for musical instruments. The complete set of elastic constants for resonance spruce and for fiddleback maple (wood species of excellent quality) were determined. Some negative Poisson ratios were calculated and were explained by the interaction between the wavelength and the honey comb like structure of coniferous wood species. Possible relationships of wave propagation with macroscopic and microscopic characteristics of wood were considered.

Attention was also directed to the detection of wood degradation by biological agents producing decay (fungi, bacteria), by using the ultrasonic velocity method combined with X ray densitometry. The ultrasonic velocity method was also applied for quality assessment of some wood-based composites.

For applications in Forestry, it was demonstrated that increment cores of 5 mm diameter bored from standing trees, in a forest, produced a specimen on which it was possible to determine three stiffnesses and three shear moduli of wood. The ultrasonic velocity method developed for this type of specimen, allowed the determination of wood mechanical quality of standing trees. Other factors (the slope of grain, pruning) affecting the quality of wood of standing trees were detected. In Forestry, seeds are important resources. The capacity of the germinability of acorns was detected with the ultrasonic velocity method.

It is worth mentioning that the advances described before in the field of ultrasound for wood science and technology and forestry during the last two decades of the XX th century at Forestry Research Centre in Nancy, France, have been achieved due to national and international cooperative actions which were very beneficial for the exchange of ideas between numerous academics, scientists, technicians and students involved in wood science, in material science and ultrasound.

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Conflicts of interest

The author declares no conflict of interest.

Data availability statement

The research data associated with this article are included within the article.

References

1. H. Polge: Fifteen years of wood radiation densitometry. Wood Science and Technology 12 (1978) 187–196.
2. I. Facaoaru, V. Bucur: Moisture content influence on pulse velocity and natural frequency of black polar wood (Populus nigra), in: Proceedings of Second International RILEM Symposium, 6–7 September, Constanta, Romania, Vol I, 1974, pp. 48–56.
3. I. Facaoaru, V. Bucur: Ultrasonic method for investigation of wood anisotropy, in: Proceedings of Second International RILEM Symposium, 6–7 September, Constanta, Romania, Vol I, 1974, 66–75.
4. V. Bucur: An ultrasonic method for measuring the elastic constants of wood increment cores bored from living trees. Ultrasonics 83, 3 (1983) 116–126.
5. H. Polge, F. Thiercelin: Growth stress appraisal through increment core measurements. Wood Science 12, 2 (1979) 86–92.
6. V. Bucur: Relations entre le diamètre tangentiel des carottes de sondage et la vitesse de propagation des ultrasons. Holzforschung 36, 3 (1982) 137–141.
7. V. Bucur: Anatomical structure and some acoustical properties of resonance wood. Catgut Acoustical Society Newsletter 33 (1980) 24–29.
8. R.F.S. Hearmon: The assessment of wood properties by vibration and high frequency acoustic waves, in: Proceedings of 2nd Symposium Nondestructive testing of wood. Washington State University, Pullman, 1965, pp. 49–66.
9. R.F.S. Hearmon: An Introduction to Applied Anisotropic Elasticity. Oxford University Press, Oxford, UK, 1961.
10. T. Vinh, Y. Chevalier, D. Le Nizerhy: Mécanique des matériaux composites. Caractérisation mécanique, Etudes dynamiques. Institut Supérieur des Matériaux et de la Construction Mécanique, Paris-St Ouen, 1979.
11. Y. Chevalier, J.T. Vinh: Mechanical Characterization of Materials and Wave Dispersion. Wiley, 2010.
12. J. Achenbach: Wave Propagation in Elastic Solids. Elsevier, 2012.
13. P. Trtik, J. Dual, D. Keunecke, D. Mannes, P. Niemz, P. Stähli, A. Kaestner, A. Groso, M. Stampanoni: 3D imaging of microstructure of spruce wood. Journal of Structural Biology 159, 1 (2007) 46–55.
14. T.M. Gorman, D.E. Kretschmann, D.W. Green, M.C. Wiemann: Effect of site characteristics on juvenile wood transition in lodgepole pine in the inland northwest. Wood and Fiber Science 50, 2 (2018) 180–192.
15. J. Brändström: Microfibril angle of the S1 cell wall layer of Norway spruce compression wood tracheids. IAWA Journal 25, 3 (2004) 415–423.
16. V. Bucur: L'angle des microfibrilles. Méthodes de mesure. Etude Bibliographique. Document à distribution limitée, Station de Recherches sur la Qualité des Bois, INRA-CRF, Nancy – Champenoux, n° 1, 1982, 95pp.
17. V. Bucur: Ondes ultrasonores dans le bois. Caractérisation mécanique et qualité de certaines essences de bois. Thèse de Docteur Ingénieur, Option Génie Mécanique, I.S.M.C.M. St Ouen, Paris – Institut de Mécanique de Paris, 20 Décembre, 1984, 128pp.
18. J.E. Jakes, C.G. Hunt, S.L. Zelinka, P.N. Ciesielski, N.Z. Plaza: Effects of moisture on diffusion in unmodified wood cell walls: a phenomenological polymer science approach. Forests 10, 8 (2019) 1084.
19. V. Bucur, La vitesse des ultrasons et la qualité du bois. Communication présentée au 19e Colloque du Groupe Français de Rhéologie, Paris, 28–30 Novembre, 1984, 15pp.
20. V. Bucur: Off diagonal termes of stiffens matrix (Les termes non diagonaux de la matrice des rigidités du bois). Holzforschung 40, 5 (1986) 315–324.
21. R. Keylwerth: Die anisotrope Elastizitat des Holzes und der Lagenholzer. VDI Forschung-sheft 430 Ausgabe B, Band 17, Deutcher Ingenieur, Dusseldorf, 1951.
22. V. Bucur, M. Carminati, J.R. Perrin, A. Perrin: La variabilité du bois d'Epicéa de Sitka et sa réponse acousto-élastique. Document à distribution limitée, Station de Recherches sur la Qualité du Bois, INRA-CRF, Nancy – Champenoux, n° 1987/1, 1987, 22pp.

23. V. Bucur: Wood characterisation through ultrasonic waves, in: A. Alippi, W.G. Mayer, Eds. Ultrasonic Method in Evaluation of Inhomogeneous Materials. NATO ASI Series E, Applied Sci. No 126. Nijhoff, Dordrecht, 1987, pp. 323–342.
24. V. Bucur: Chapter 4.3.2 Specimens for ultrasonic testing, in: Acoustics of wood, 2nd edn. Springer, 2006, pp. 74–80.
25. V. Bucur, J.R. Perrin: Ultrasonic waves – Wood structure interaction, in: 1988 Spring Conference "Acoustics 88", University of Cambridge, 5–8 Avril. Proceeding Institute of Acoustics, Vol. 10, Part. 2. Edinburgh (G.B.), 1988, 199–206.
26. H. Deresiewicz, R.D. Mindlin: Waves of the surface of a crystal. Journal of Applied Physics 28 (1957) 669–671.
27. V. Bucur, F. Rocaboy: Surface wave propagation in wood: prospective method for the determination of wood off-diagonal terms of stiffness matrix. Ultrasonics 26 (1988) 344–347.
28. V. Bucur, F. Rocaboy: Mechanical wave propagation in media of various complexities, in: Surface Waves – Guides Waves. Ultrasonics International 1987. Pathway of Ultrasound, 6/7/1987, Kensington Town Hall, London. Document à distribution limitée, Station de Recherches sur la Qualité des Bois, INRACRF, Nancy – Champenoux, n° 1987/3, 1987, 46pp.
29. V. Bucur, J.R. Perrin, F. Rocaboy: On bulk and surface waves propagation in wood, in: Paper A6 8th Symp. Ultrasonic Electronics, organisé par IEEE-UFFC Society, Tokyo, 1987, 2pp.
30. V. Bucur: Mode conversion ultrasonic testing on wood, in: Advanced Research Lecture on International School on Physical Acoustics, 3rd Course Ultrasonic signal Processing, Ettore Majorana Centre for Scientific Culture, Erice (Trapani), Italie, 20–30/10/1988. Document à distribution limitée, Station de Recherches sur la Qualité des Bois, INRA-CRF, Nancy – Champenoux, n° 1988/4, 27pp. and also in A. Alippi, Ed. Ultrasonic Signal Processing. World Scientific, Singapore, 1988, pp. 463–473.
31. V. Bucur, F. Rocaboy, J.F. Perrin: On surface acoustic waves propagation in wood, in: Actes du Colloque "Comportement Mécanique du Bois", G.S. Rhéologie du Bois, Bordeaux, 8-9/06, 1988, pp. 61–68.
32. V. Bucur, P. Rasolofosaon: Dynamic elastic anisotropy and nonlinearity in wood and rock. Ultrasonics 36, 7 (1998) 813–824.
33. R. Arts: A study of general anisotropic elasticity in rocks by wave propagation. Theoretical and experimental aspects. PhD thesis University Paris 6, France, 1993.
34. M. François: Identification des symétries matérielle de matériaux anisotropes PhD thésis. University Paris 6 France, 1995.
35. R. Gonçalves, A.J. Trinca, B.P. Pellis: Elastic constants of wood determined by ultrasound using three geometries of specimens. Wood Science and Technology 48 (2014) 269–287.
36. S. Schubert, D. Gsell, J. Dual, M. Motavalli, P. Niemz: Resonant ultrasound spectroscopy applied to wood: comparison of the shear modulus of wood before and after exposure to fungal pathogens, in: The 14th International Symposium of NDT of Wood, 2005.
37. M. El Mouridi, T. Laurent, L. Brancheriau, O. Arnould, A. Famiri, A. Hakam, J. Gril: Searching for material symmetries in the burr wood of thuja by a direct contact ultrasonic method on spherical samples. Maderas. Ciencia y tecnología 13, 3 (2011) 285–296.
38. R. Longo, D. Laux, S. Pagano, T. Delaunay, E. Le Clézio, O. Arnould: Elastic characterization of wood by Resonant Ultrasound Spectroscopy (RUS): a comprehensive study. Wood Science and Technology 52 (2018) 383–402.
39. J. Betten: Theory of invariants in creep mechanics of anisotropic materials, in: Mechanical Behavior of Anisotropic Solids/Comportment Méchanique des Solides Anisotropes: Proceedings of the Euromech. Colloquium 115. Villard-de-Lans, June 19–22, 1979. Springer Netherlands, Dordrecht, 1982, pp. 65–80.
40. M.J.P. Musgrave: Personal Communications about the anisotropy, 1985.
41. V. Bucur: Wood structural anisotropy estimated by acoustic invariants. International Association Wood Anatomists IAWA Bulletin 9, 1 (1988) 67–74.
42. V. Bucur, F. Feeney: Attenuation of ultrasound in solid wood. Ultrasonics 30, 2 (1992) 76–81.
43. V. Bucur, I. Böhnke: Factors affecting ultrasonic measurements in solid wood. Ultrasonics 32, 5 (1994) 385–390.
44. V. Bucur: Viscoelastic behaviour of resonance wood expressed by ultrasonic measurements, in: Proceedings of Internationl Symposium on Musical Acoustics, ISMA'92, Tokyo, Japan, August 28 September 1, 1992, 13pp.
45. V. Bucur: Viscoelastic behaviour of wood with ultrasound, in: Mechanics of Micro Structured Materials. Proceedings of Euromech Colloquium 304. University of Cambridge, England, 28–30 June, 1993, 19pp.
46. F. Feeney: Ultrasonic characterisation of the structure and properties of wood. PhD thesis, University of Surrey, United Kingdom, 1999.
47. I. Böhnke: Etude expérimentale et théorique des traitements thermiques du bois. PhD thesis, Ecole de Mines, St. Etienne France, 1993.
48. V. Bucur, A. Saied, J. Attal: Identification of wood anatomic elements by acoustic microscopy. Catgut Acoustical Society Journal – Series II 2 (1992) 803.
49. V. Bucur, A. Saied, J. Attal: Identification of wood anatomical elements by acoustic microscopy, in: 22nd International Symposium on Acoustical Imaging, Florence, Italy, 1995.
50. V. Bucur: Imaging of microscopic wood structure with the ultrasonic acoustic microscope Sonoscan C SAM D 9000. Document Laboratoire d'études et recherches sur le matériau bois. LERMAB, Nancy, 1999.
51. D. Thomas, A. Clément, V. Bucur: Le bois de résonance: ses propriétés acoustiques et sa composition minérale. 2ème édition des "Journées Scientifiques Forêt Bois", Epinal 23–25 Septembre, 1998.
52. V. Bucur, A. Clement, M. Bitsch, C. Houssement: Acoustic properties of resonance wood and distribution of inorganic components of the cell wall. Holz als Roh-Werkstoff 57 (1999) 103–104.
53. F. Rocaboy, V. Bucur: About the physical properties of wood of twentieth century violins. Catgut Acoustical Society of Journal 1, 6 (1990) 21–28.
54. V. Bucur: Modifications des propriétés acoustiques du bois de résonance sous l'effet de sollicitations de longue durée. Annales des Sciences Forestières 37, 3 (1980) 249–264.

55. V. Bucur: La structure anatomique du bois d'érable ondé. Revue Forestière Française 44 (1992) 150–155.
56. V. Bucur: About the anisotropy of resonance wood for violins, in: Proceedings of Fortschritte der Akustik, DAGA'90, Technische Universität Wien, Austria, 9–12 April, Teil A, 1990, pp. 553–557.
57. V. Bucur: Varieties of resonance wood and their elastic constants. Catgut Acoustical Society Newsletters 47 (1987) 42–48.
58. V. Bucur: Wood failure testing with ultrasonic method, in: Proceedings of 4th Symposium on Nondestuctive Testing of Wood, Vancouver, 28–30 August, 1979, pp. 223–226.
59. V. Bucur, S. Garros, A. Navarrete, M.T. De Troya, R. Guyonnet: Kinetics of wood degradation by fungi with microdensitometric technique. Wood Science and Technology 31 (1997) 383–389.
60. C. Bauer, G. Kilbertus, V. Bucur: Technique ultrasonore de caractérisation du degré d'altération des bois de Hêtre et de Pin soumis à l'attaque de différents champignons. Holzforschung 45, 1 (1991) 41–46.
61. V. Bucur, A. Navarrete, M.T. de Troya, E. Sanchez, S. Garros, R. Diez: Fungi decay in wood by combined nondestructive techniques, in: Ultrasonics International'93, 6–8 Julv, Technical University of Vienne, Austria, 1993, pp. 287–290.
62. F. Efransjah, G. Kilbertus, V. Bucur: Impact of water storage on mechanical properties of spruce as detected by ultrasound. Wood Science and Technology 23 (1989) 35–42.
63. F. Mothe, R. Marchal, V. Bucur: Mechanical characterisation of laminated veneer lumber (LVL) from European oak wood by acoustical methods, in: Proceedings of First European Symposium on Nondestructive Evaluation of Wood, University of Sopron, 21–23 September. Vol. 1, 1994, 197–206.
64. M.H. Petit, V. Bucur, C. Viriot: Ageing monitoring of structural flakeboards by ultrasound, in: Proceedings of 6th International Symposium on Nondestructive Testing of Wood. Washington State University, Pullman, 1991, pp. 23–25.
65. A.L. Beraldo, A. Zoulalian, V. Bucur: Application des ultrasons à un composite bois-ciment et mise en évidence du rôle inhibiteur des sucres sur la prise et le durcissement du ciment. Rapport présenté au Séminaire Annuel de l'Ecole Doctorale "PROMEN" "La Matière Divisée" le 26–27 Mai 1994, Faculté de Médecine de Brabois, Université Henry Poincaré Vandoeuvre-lès-Nancy, 1994, 6pp.
66. V. Bucur: Anisotropy characterization of structural flakeboards with ultrasonic methods. Wood and Fiber Science 24, 3 (1992) 337–346.
67. V. Bucur: Wood composites anisotropy with two ultrasonic techniques, in: Ultrasonics International 91, Le Touquet, 1–4 July, Conference Proc., 1991, 531–534.
68. V. Bucur, M.P. Ansell, C.Y. Barlow, J. Pritchard, S. Garros, X. Deglise: Physical methods for characterizing wood composite panel products. Holzforschung 52 (1998) 553–561.
69. V. Bucur: Relationships between grain angle of wood specimens and ultrasonic velocity. Catgut Acoustical Society Inc. Newsletter 41 (1984) 30–35.
70. V. Bucur, J.R. Perrin: Procédé ultrasonore pour l'estimation de l'angle du fil du bois Brevet français no 90 06589 INRA Paris, France, 1990.
71. V. Bucur: Ultrasonic, hardness and X ray densitometric analysis of wood Ultrasonics 23, 6 (1985) 269–275.
72. H. Polge, R. Keller: Influence de l'élagage de branches vivantes sur la structure des accroissements annuels et sur quelques caractéristiques du bois de douglas et de grandis. Annales des Sciences Forestieres 30, 2 (1973) 127–140.
73. V. Bucur: Que peuvent apporter les mesures acoustiques à l'estimation de la texture des produits forestiers? Conférence aux Premières Rencontres Technologiques et Scientifiques des Industries Alimentaires, AGORAL, Nancy, 26–28 Avril, 1988, 4pp.
74. J.R. Moore, D.J. Cown, R.B. McKinley, C.O. Sabatia: Effects of stand density and seedlot on three wood properties of young radiata pine grown at a dry-land site in New Zealand. New Zealand Journal of Forestry Science 45 (2015) 1–15.
75. V. Bucur, C. Muller: Non-destructive approach for analysing the germinability of acorns. Ultrasonics 26, 3 (1988) 224–228.
76. M.R. Wing, A.J. Knowles, S.R. Melbostad, A.K. Hones: Spiral grain in bristlecone pine (Pinus longaeva) exhibits no correlation with environmental factors. Trees 28 (2014) 487–491.

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Appendix

Students	**Research staff**	
	Technical staff	**Scientists and academics**
PhD Thesis	**INRA Nancy staff**	**(a) Staff in France**
BAUER C., France	Research engineers	INRA – Forest Research Centre – Nancy
BARTHOLOMEU A., Brazil	GARROS, S.	BOUVAREL, P. Deputy Officer
BERALDO A.L., Brazil;	PERRIN, J. R.	POLGE, H. Qualité Bois Laboratory – Director
BOHNKE Isabelle, France	**Secretary**	THIERCELIN, F.
BONFIELDP.W., UK	JAQUEMOT J	JANIN, G.,
CHAZELAS J.L., France	**Technicians**	MOTHE, F.
DAKAK, J.E., – Maroc	AUBER D	INRA Laboratories and other
EFRANSJAH F, Indonesia	BITSCH, M.	CLEMENT, A.
FEENEY F., – Irland	HOUSSEMENT, C	MARCHAL, R.
HAPCA A., – Romania	GELHAYE, P.	MULLER, C.
ONIC Ludivine, – France	GERARDET, B.	PETIT, M.H.
PRITCHARD J., – UK	HERBE, C.	ROCABOY, F.
Master Thesis	HURPEAU, T.	Institut Français du Pétrole
CARMINATI M., France	MICHEL, P.	RASOLOFOSAON P.N.J.
CHIESA V., Italy	PERRIN, A.	ZINSZNER B
DIEZ R., Spain	PERRIN, J.	Institut de Mécanique de Paris
EL RAZI., Maroc		CHEVALIER, Y
MUNTEANU C., France		VINH, T
NOSEI G., Venezuela		French Universités
SAREM M., Iran		ATTAL, J. – Montpellier
THOMAS D., France		DEGLISE, X. – Nancy
		GUITARD D. – Nancy
		GUYONNET R – Saint Etienne
		KELLER, R – Nancy
		KIILBERTUS, G – Nancy
		LAUNAY, J – Orleans
		MERLIN, A – Nancy
		ORY, J M – Nancy
		SAIED, A. – Montpellier
		PIZZI, A – Nancy
		VERGNE, A – Clermont Ferrand
		ZOULALIAN, A – Nancy
		(b) International staff
		Academic staff
		ALIPPI, A. – ITALY – Roma University
		ANSELL, M.P – UK – Bath University
		ARCHER R.R. – USA – AMHERST Boston
		BARLOW, C. – UK – Cambridge University
		CHIVERS, R.C. – UK – Surrey University
		GONÇALVES, R – BRAZIL Campinas University
		LEWARK, S – GERMANY – Gottingen University
		MUSGRAVE, MP – UK – Imperial College London
		PELLERIN, R – USA Washington State University
		ROSS, R – USA Forest Research Lab., Madison
		SOBUE, N – JAPAN Shizuoka University
		STEPHENS, RWB UK – Imperial College London
		UZIELLI, L – ITALY – Florence University
		Scientists – Research staff
		de TROYA, M.T. – SPAIN – INIA Madrid
		NAVARRETE, A. – SPAIN – INIA Madrid
		SANCHEZ, E. – SPAIN – INIA Madrid
		Editors of books and journals
		MAYER W G – USA – American Acoust. Soc.
		HUTCHINS C H M – USA Catgut Acoust. Soc.
		HAINES D – USA Catgut Acoust. Soc. Journal