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The anisotropy of biological composites studied with ultrasonic technique

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Abstract

One of the most common biological composites is wood material. This natural orthotropic like material is characterized by a high anisotropy determined by the special disposition of the microstructure elements. The anisotropy of wood can be described in various ways using the values of ultrasonic velocities of bulk waves (longitudinal and shear) observed on the velocity surface deduced from the theoretical relationships given by the Christofel's equation. The simultaneous view into the three symmetry planes of the anisotropic behavior of wood is presented on the velocity surface. The spatial filtering action of wood structure is easily connected with longitudinal and shear velocities. The first step in examining the anisotropy of wood is to relate the velocities to the symmetry axes. The simplest way to describe the anisotropy of wood is to express the ratios of velocities. These ratios can be calculated separately for longitudinal or shear waves or for a combination of both. The birefringence of shear waves have a particular interest for the fine definition of anisotropy. A more global appreciation of wood anisotropy than the values of individual velocities is given with acoustic invariants. The stability of calculation of acoustic invariants versus different propagation angles confirms the validity of the chosen model for the tested material. Wood species having high density and any important organized structure in the millimeter scale exhibit a high ratio of invariants. The acoustic behavior of tropical wood species is less anisotropic than that of species from a temperate zone having low density.

Keywords: Anisotropy; Wood; Ultrasonics; Birefringence; Acoustic invariants

1. Introduction

In the study of materials, taking into account anisotropy is not just a matter of scientific pleasure, but is a mandatory task if the overwhelming part of the existing materials, which are mostly anisotropic, must be understood [1–6]. Anisotropic materials are therefore subject to major interest in the field of nondestructive testing (NDT) of materials [7–12] in our well developed economical society. The influence of anisotropy is most outspoken and must be taken into account in nondestructive characterization of anisotropic materials for NDT purposes, such as ultrasonic polar scans [13–16]. Highly sophisticated fiber reinforced composites are most often orthotropic. Nature on the other hand is responsible for even more complicated structures, such as wood. Timber [17–20], having dimensions that are significantly smaller than the radius of the originating tree, can generally be characterized, on a macroscopic scale, as homogeneous triclinic material, being characterized by 21 stiffness constants. Therefore timber wood is more anisotropic that orthotropic composites and is far from isotropic. Because the difference with orthotropic materials is relatively small, wood is called an 'orthotropic like' solid.

The anisotropy of materials is defined as the variation in the material physical response to the applied stress

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along different specimen axes. For biological materials, such as timber wood, the anisotropy results from the non-random distribution and orientation of the structural components. In the case of wood, the anisotropy results from the specific disposition of anatomical elements during the life of the tree. An accurate estimation of the mechanical behavior of wood requires a simultaneous view of its structure and its wave propagation phenomena. During propagation, wave parameters are affected by the wood structure which acts as a filter. This interaction sharply reveals the anisotropy of wood material. Hydrostatic pressure applied on wood specimens put in evidence very well the natural anisotropy of wood material. In this article some aspects related to the interaction between ultrasonic waves and wood anisotropy induced by its structure will be analyzed.

2. Theoretical considerations

The sound velocity in wood is commonly denoted by V_{PQ} where P stands for the sonic propagation direction and Q stands for the sonic polarization direction.

The relationship between the ultrasonic velocity and the material density is governed by Christoffel's equation. For an orthotropic like solid, such as wood, (with three axes of symmetry noted 1,2,3 or Longitudinal 'L', Radial 'R' and Tangential 'T' versus the annual rings) the solution of this equation requires three longitudinal velocities V_{ii} – commonly denoted for wood V_{LL}, V_{RR} and V_{TT} and three shear velocities V_{ij} denoted V_{LR}, V_{LT} and V_{RT} [17]. Experimentally, the shear waves can be measured as either V_{ij} or V_{ji} when the first index is the propagation direction and the second index is the polarization direction. For a perfect orthotropic solid $V_{ij} = V_{ji}$. If this condition does not hold, ultrasonic birefringence can be observed, induced by the elevated anisotropy of wood compared with orthotropy. The anisotropy of materials is represented by their stiffness tensor. For a general orientation of the material, there are 21 entries of the stiffness tensor. Nevertheless, these can be reduced to a smaller number of independent entries by means of linear operations resembling orienting the materials along its principle axes. Another way of revealing the number of independent entries is consideration of the solutions of Christoffel's equation. The solutions can be combined to form direction independent invariants, related to the sound velocities. This principle is also known as the invariants of tensors and has been a subject of interest in Refs. [17,21–23]. Considering that those quantities insensitive to the direction of propagation, they can act as references for anisotropy investigation. Combining the values of invariants in the three main symmetry planes, we obtain a single global value that characterizes each species [24]. This characteristic invariant is also called "I ratio" as it is formed as a ratio of the invariant in the transversal plane (RT or 23) and the invariants in planes containing the axis *L* (LR and LT or 12 and 13). It is well known [17] that the invariants ratio is equal to 1 for isotropic solids.

3. Materials and Method

Spruce (*Picea abies*) is a softwood and has a very regular structure and the transition between early wood and late wood is gradually. Spruce is very popular in the manufacturing of musical instruments. The ultrasonic direct transmission method was used, as described in [17], to measure the sonic bulk velocities along the principle axes, on cubic specimens of 16 mm size. Panametrix equipment was used at 1 MHz. The uncertainty in velocity measurements is 1%.

4. Results

The wood anisotropy is expressed by the measured ultrasonic velocities of Spruce, in Table 1. As expected, the highest anisotropy expressed by the ratios of longitudinal velocities ($A_2 = 4.65$) was observed with V_{LL}/V_{TT}, corresponding to the propagation phenomena along the fibers and perpendicular to them. The birefringence has been well described with shear waves. Again in the LT plane the highest value was observed ($A_{20} = 0.518$).

Table 1
Anisotropy expressed by the ratios of ultrasonic velocities for spruce [18]

Parameters	Anisotropy calculated with	Coefficients	
		Equations	Values for spruce
A_1	Longitudinal waves	V_{LL}/V_{RR}	2.95
A_2	Longitudinal waves	V_{LL}/V_{TT}	4.65
A_3	Longitudinal waves	V_{RR}/V_{TT}	1.57
A_4	Shear waves	V_{LR}/V_{RL}	1.15
A_5	Shear waves	V_{LT}/V_{TL}	2.08
A_6	Shear waves	V_{RT}/V_{TR}	1.29
A_7	Longitudinal and shear waves, related to one axis	V_{LL}/V_{LR}	4.08
A_8	Longitudinal and shear waves, related to one axis	V_{LL}/V_{LT}	4.64
A_9	Longitudinal and shear waves, related to one axis	V_{RR}/V_{RT}	4.33
A_{10}	Longitudinal and shear waves, related to one axis	V_{RR}/V_{RL}	1.59
A_{11}	Longitudinal and shear waves, related to one axis	V_{TT}/V_{TR}	3.56
A_{12}	Longitudinal and shear waves, related to one axis	V_{TT}/V_{TL}	2.07
A_{13}	Longitudinal waves in LR plane	$\frac{V_{LL}-V_{RR}}{V_{LL}}$	0.661
A_{14}	Longitudinal waves in LR plane	$\frac{V_{LL}-V_{RR}}{V_{RR}}$	1.95
A_{15}	Longitudinal waves in LT plane	$\frac{V_{LL}-V_{TT}}{V_{LLk}}$	0.784
A_{16}	Longitudinal waves in LT plane	$\frac{V_{LL}-V_{TT}}{V_{TT}}$	3.65
A_{17}	Longitudinal waves in RT plane	$\frac{V_{RR}-V_{TT}}{V_{RR}}$	0.364
A_{18}	Longitudinal waves in LT plane	$\frac{V_{RR}-V_{TT}}{V_{TT}}$	0.573
A_{19}	Shear waves, birefringence in LR plane	$\frac{V_{LR}-V_{LR}}{V_{LR}}$	0.134
A_{20}	Shear waves, birefringence in LT plane	$\frac{V_{LT}-V_{TL}}{V_{LT}}$	0.518
A_{21}	Shear waves, birefringence in RT plane	$\frac{V_{RT}-V_{TR}}{V_{RT}}$	0.509
A_{22}	Acoustic invariants ratio	I ratio	0.15

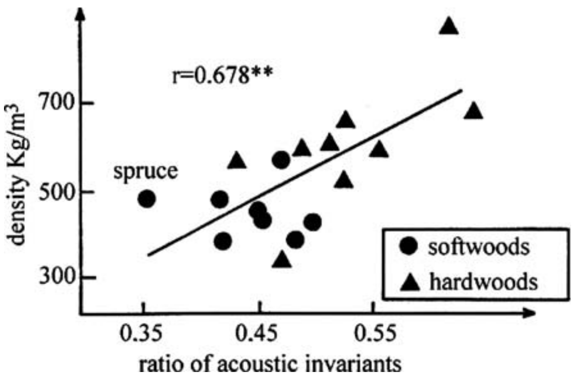

Fig. 1. Correlation between the ratio of acoustic invariants and wood density [17].

The maximum of anisotropy was deduced with the anisotropic coefficient corresponding to the ratio of the difference between the longitudinal velocities expressed by $A_{15} = \frac{V_{LL}-V_{TT}}{V_{LL}} = 0.784$.

Fig. 1 illustrates the experimental relations between the ratio of acoustic invariants and the mass density. Note that for isotropic solids the ratio of invariants must be 1. Wood species having high density and any important organized structure on millimeter scale in the RT plane exhibit high values for the ratio of invariants. The acoustic behavior of those species is less anisotropic than that of species having low density (ex spruce) and typical softwood structure. The acoustic behavior of tropical wood species having high density is less anisotropic than that of species from a temperate zone having low density.

5. Conclusions

Compared to modern composites wood is a relatively highly anisotropic material. This is one of the most eye catching "defects" of this natural composite. The elevated anisotropy of wood is highly appreciated and exploited only in the field of the manufacturing of various fine musical instruments.

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