New Approaches to Ultrasonic Characterization and NDT of Wood

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Introduction

Ultrasonic characterization and NDT of flaws in wood is aggravated by a high acoustic damping and sensitivity of the material to coupling media. However, wood has some peculiar properties beneficial for the development of new ultrasonic NDT methods.

In the present paper, we make use of its low acoustic impedance and high dynamic nonlinearity to develop new approaches to NDT of wood using air-coupled ultrasound and nonlinear vibrometry.

Focused Slanted Transmission Mode

The low acoustic impedance facilitates air-coupled ultrasound transmission in wood. The Focused Slanted Transmission (FST-) mode of air-coupled ultrasound was adopted for non-contact measurements of local elastic anisotropy of wood plates and veneer laminates.

Local Acoustic Anisotropy of Wood

Wood can be considered as an orthotropic material with the three main axes related to the annual rings: radial (R), longitudinal (L) and tangential (T). To characterize wood anisotropy we used the FST-mode which is based on flexural plate wave excitation and provides the highest transmission of air-coupled ultrasound through the plate. The angle of maximum transmission (θ_0) is given by the coincidence rule [1] which enables to determine the phase velocity of the plate wave:

$$V_p = V_{air} / \sin\theta_0 \qquad (1)$$

The results of the FST-methodology applied to characterization of wood anisotropy are shown in Fig. 1.

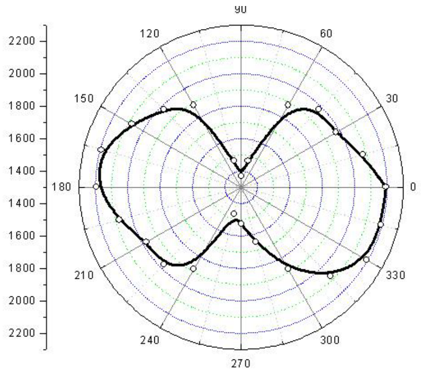


Figure 1: Anisotropy of flexural wave velocity (m/s) in a beech plate (thickness 4 mm, LT-plane).

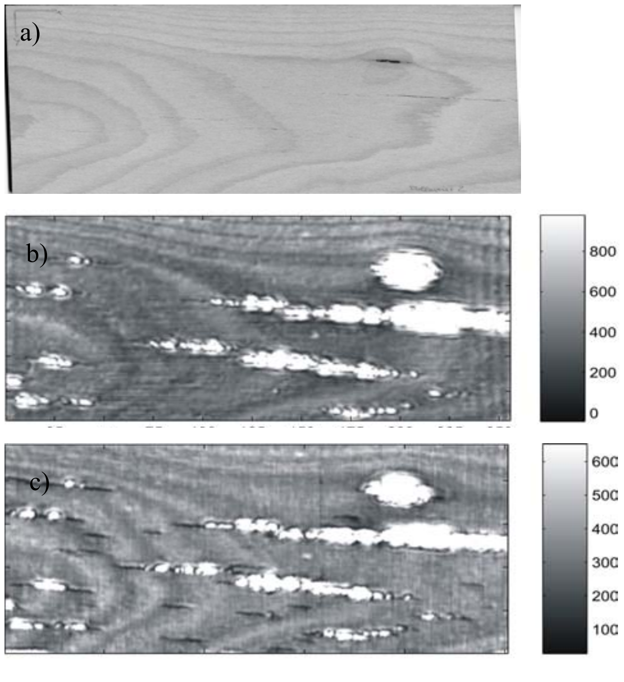
The phase velocity varies from about 2200 m/s in the L-direction to 1400 m/s in the T-direction. This leads to the anisotropy factor of about 1.6, which corresponds to its value for the R-polarized shear waves reported in [2].

FST-Mode-Imaging

The FST-mode can also be used for imaging of internal defects. First the angle of maximum transmission in clear wood is determined and set. Then the amplitude of the transmitted ultrasound is measured during the area scan of the sample.

The plate wave excited in the sample are scattered strongly when propagating normally to the crack. On the contrary, in the Normal Transmission (NT-) mode of air-coupled ultrasound these cracks will be hardly detectable.

Figure 2 shows a beech sample with surface cracks along the L-direction due to drying (checking). The C-scan was obtained by the plate waves generated normal to the checks (Fig. 2, c). White coloured areas in the images indicate open cracks in wood, which act like sound channels and provide a high ultrasonic transmission for both modes (b, c). Closed cracks are not visible in the NT-mode (Fig. 2, b) but they are clearly seen in the FST-Mode (black lines, Fig. 2, c).



Figures 2, a, b, c: Beech laminate sample (LT-plane, thickness 4mm): a) optical image; b) normal transmission mode c) FST-mode-image.

Nonlinear Vibrometry of Wood

We studied the opportunity for the higher harmonic modes of nonlinear vibrometry to be applied to nonlinear imaging of wood structure and NDT of flaws (delaminations, cracks, knots, poorly bonded areas, etc.) in wood-based materials.

Theoretical Background of Dynamic Acoustic Nonlinearity in Wood

An acoustic nonlinearity is manifested in stiffness modulation. The first mechanism of wood nonlinearity is concerned with a dynamic hysteresis of the material. For cyclic loading, the inelastic response of polymer composites (and wood, in particular, [3]) leads to a stress-strain ($\sigma - \varepsilon$) hysteresis. The hysteresis mechanism results in the specific higher harmonic spectrum: for a hysteresis loop, the frequency of the stiffness ($C(t) = \partial\sigma / \partial\varepsilon$) modulation is twice as high as the driving frequency, hence the nonlinear output $\sigma(t) = C(t)\varepsilon(t)$ contains odd harmonics only:

$$\omega_{out} = (2n+1)\omega_{in} \,. \tag{2}$$

The second mechanism of nonlinearity is associated with "clapping" of non- or weakly-bonded internal surfaces while activated by elastic waves. Defects in wood like cracks, delaminations or knots, obviously, provide such interfaces. Unlike the hystreresis, the nonlinear mechanism of "clapping" was shown to be a source of highly efficient harmonic generation of both odd and even orders [4].

Experimental Results

The obvious domination of the odd harmonics in a typical single-point spectrum (Figure 3) measured for softwood (spruce) specimen confirms the hysteresis mechanism of the dynamic nonlinearity in clear wood.

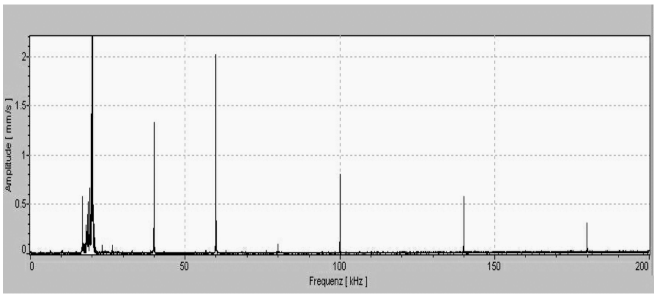


Figure 3: Single-point nonlinear spectrum of the LR-plate of spruce. Excitation frequency (left) is 20 kHz.

Since wood is strongly inhomogeneous material, its local nonlinear response will also vary substantially from point to point. This is confirmed by a typical higher harmonic C-scan of the LR-plane of spruce specimen (Fig. 4).

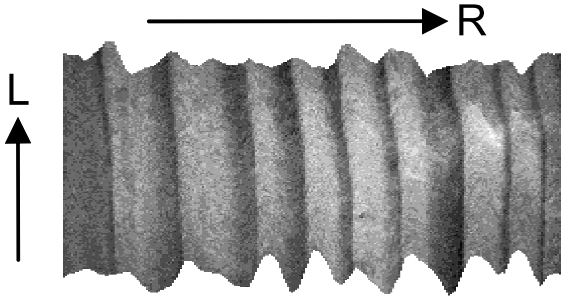


Figure 4: Third harmonic C-scan of the LR-plate of spruce. Crests positions coincide with latewood/earlywood interface.

Since maximum nonlinearity corresponds to the most compliant area of material, from Fig. 4 one can see that such an area is a few-cell thick layer of the transition interface between latewood and earlywood. This most load-vulnerable part of clear wood is formed early in the growing season and is concerned with the thinnest-walled wood cells.

Defects like cracks could have a strong impact on the reliability of a product. Figure 5 demonstrates the presence of a few "clapping" points within a knot that produces even higher harmonics and can be critical for load-carrying capacity of a product.

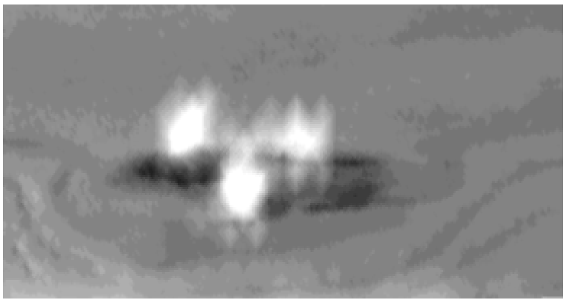


Figure 5: Eighth-harmonic image of a "faulty" spike knot in softwood

Conclusions

The elastic anisotropy of wood can be determined remotely by using plate waves generated by using the FST-mode of air-coupled ultrasound.

Both the NT- and FST-modes are applicable to acoustic imaging of cracked defects in wood. The benefit of the FST-methodology is that it is capable of detecting closed cracks.

The dynamic nonlinearity of clear wood is concerned with the hysteresis in stress-strain relation and enables to discern compliant areas in wood structure. "Clapping" mechanism is responsible for dynamic nonlinearity of defects and can be used for detecting and imaging of flaws in wood and wood composites.

References

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