Study of the relationship between attenuation of elastic waves and physical mechanical properties of wood for the non-destructive evaluation of wooden infrastructures

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Introduction

Wood is a privileged building material in the context of sustainable development (Skog et al. 2015). The evaluation of the quality of this material for the surveillance of wooden structures is the subject of advanced research. Among the control/diagnostic protocols, acoustic and ultrasonic methods are in a privileged position but further research is required to improve their reliability (Arciniegas et al. 2014). The wood material is complex to characterize due to its biological origin. It can be considered as an anisotropic, heterogeneous and hygroscopic material (Bodig and Jayne 1982, Espinosa et al. 2018). It is therefore necessary to study the relationships between the mechanical and physical characteristics of wood, and the corresponding acoustic properties. Here we are particularly interested in the viscoelastic behavior of wood and the attenuation of elastic waves under acoustic and ultrasonic testing.

The objective of this study is to evaluate the effect of the variation of physical-mechanical properties of wood associated with structural deterioration, such as the modulus of elasticity (MOE), and density, on the attenuation of acoustic waves propagating in wood. A large variety of wood samples were tested using two methods based on either acoustic or ultrasonic excitation, and relationships between different physical and mechanical parameters were stablished.

Materials and methods

Samples from 58 tropical wood species from CIRAD's wood collection were tested to cover a broad range of densities, ranging from 205 kg/m^3 to 1287 kg/m^3. Samples were stabilized in a climate-controlled room with 65% relative humidity and a temperature of 20°C, with a theoretical moisture content at equilibrium of 12%. The samples geometry corresponded to bars of 2.5-by-2.5 cm cross section for two different lengths along the longitudinal axis: 39 cm for the acoustic tests and 15 cm for the ultrasonic tests.

For acoustic tests, BING® device was used (Brancheriau et al. 2010), relying on a free-vibration analysis to estimate the MOE and the loss tangent ($\tan \delta$) associated to internal friction. For the MOE, depending on the impact orientation, the test was either in bending (transversal test) or in compression (longitudinal test, Fig. 1 and 2).

For ultrasonic tests, a through-transmission configuration was used (Fig. 3), with sensors at a resonant frequency of 500 kHz (Fig. 4), allowing to estimate MOE using the wave velocity information and the attenuation measurements, $\tan \delta$ and attenuation coefficient α, from the amplitude information.

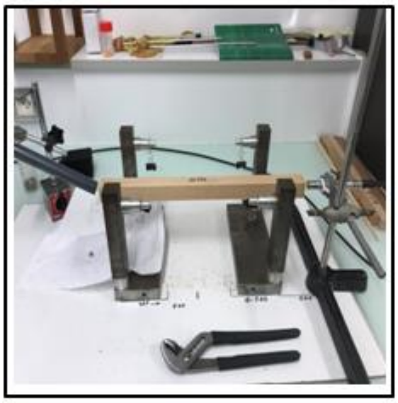

Fig. 1: Experimental setup for the acoustic measurements in compression (longitudinal test)

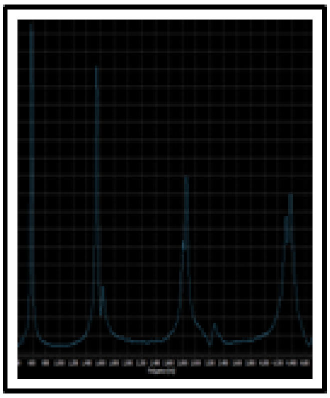

Fig. 2: Frequency response of the output signal after processing

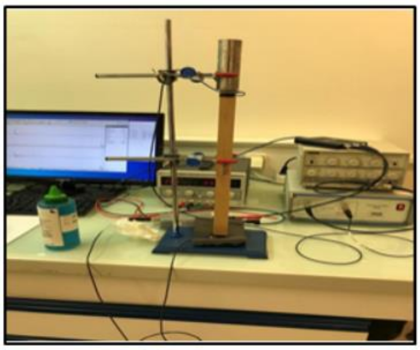

Fig. 3: Experimental setup for the ultrasonic measurements

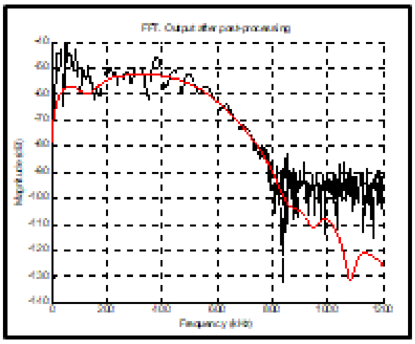

Fig. 4: Frequency response of the output signal after processing

Results

Considering the MOE measurements, a first comparison was made between the values obtained in compression and bending for the acoustic tests (Fig. 5), showing a good agreement from the two configurations. Values ranged from 6152 MPa to 27663 MPa in bending and from 5225 MPa to 29322 MPa in compression. MOE measurements from ultrasonic tests ranged between 5271 MPa to 33532 MPa. Fig. 6 presents the comparison between the MOE measurements obtained from the ultrasonic and acoustic (bending) tests, showing also good agreement, presenting slightly higher values for the ultrasonic case.

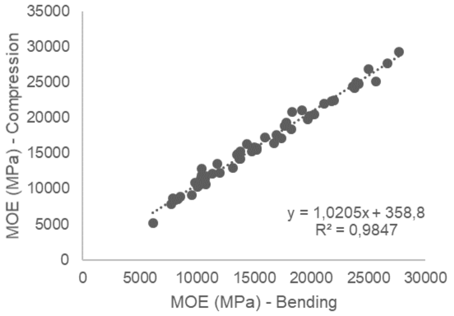

Fig. 5: Comparison between MOE from acoustic measurements for bending and compression

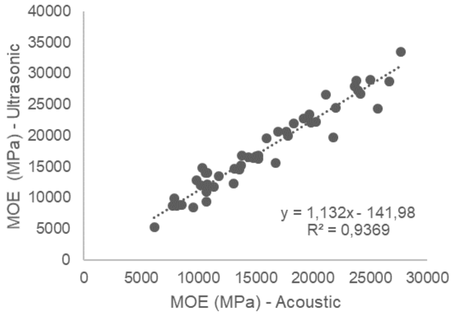

Fig. 6: Comparison between MOE from ultrasonic and acoustic (bending) measurements

With respect to the attenuation measurements, again a first comparison was made between the tan δ values obtained from acoustic tests in compression and bending (Fig. 7), leading to a R^2 of 0.89 and therefore a good agreement as for the MOE measurements. In the case of ultrasonic tests, tan δ values were larger (by a factor close to 9) compared to the acoustic ones considering that the attenuation increases with frequency, as shown in Fig 8.

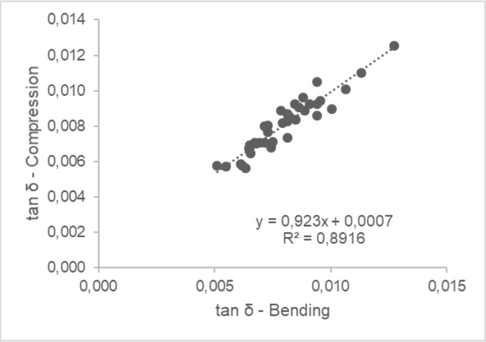

Fig. 7: Comparison between tan δ from acoustic measurements for bending and compression

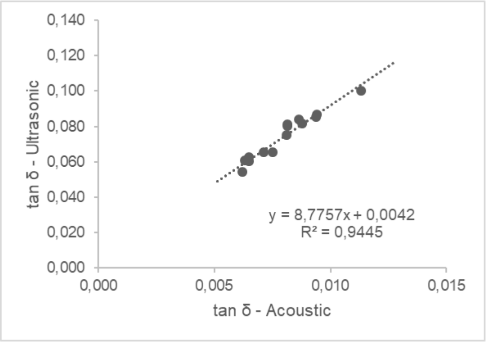

Fig. 8: Comparison between tan δ from ultrasonic and acoustic (bending) measurements

Also, MOE and the attenuation coefficient α from the ultrasonic measurements were compared to the density of the samples. In the case of the MOE (Fig. 9), larger values were found for species with higher density. For the attenuation coefficient α the relationship was the opposite (Fig. 10), with decreasing values as the density of the sample increased.

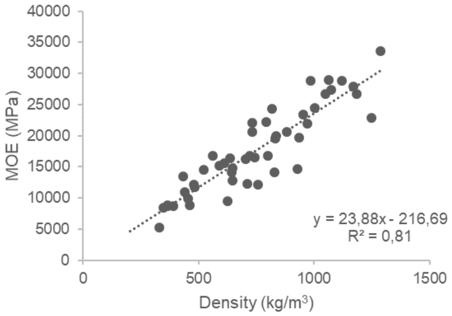

Fig. 9: Comparison between MOE from ultrasonic measurements and density

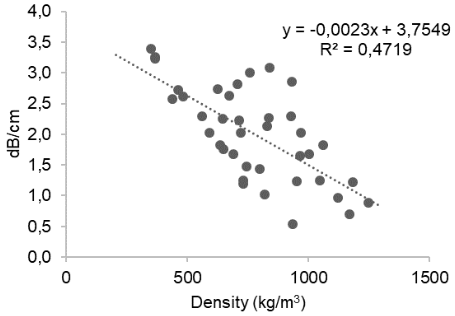

Fig. 10: Comparison between the attenuation coefficient α from ultrasonic measurements and density

Conclusions

The viscoelastic behavior of wood was studied through a set of experiments using acoustic and ultrasonic methods. Good agreement was observed for the MOE and tan δ obtained either by comparing compression and bending in the acoustic case, or by comparing ultrasonic and acoustic measurements. Density is a key parameter affecting MOE and attenuation. Numerical modeling techniques could help to study the effect of the wood anatomy in the propagation of elastic waves.

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