# Non-destructive measurement of orthotropic elastic properties of wood samples by their modal impulse response

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## Context and objectives

Wood represents a major class of versatile materials in mechanics, comparable to metals on various criteria such as annual world production tonnage. Its density is 5 to 10 times lower than that of metals, due to its cellular structure, whose walls are essentially made up of layers of long-fibre nanocomposites. This makes wood highly efficient for applications, particularly for those requiring a high performance-to-mass ratio. However, contrary to the longitudinal elastic modulus ($E_L$), the knowledge of the transverse ($E_R$ and $E_T$) and shear ($G_{RT}$, $G_{LT}$ and $G_{LR}$) elastic properties of this orthotropic, heterogeneous, hygroscopic and variable material are still limited due to a lack of rapid and efficient characterization tools and methods. Currently, the existing technical data in databases are incomplete since, generally, only the longitudinal elastic modulus ($E_L$) is available, which is (more or less) satisfactory for long civil engineering beams, whereas the other elastic properties are essential for high-end and high-performance structural applications, such as parts for power generation, cars, planes, etc (Castanié et al 2024).

The aims of this study are: to quickly measure as much properties as possible of a single wood sample (to eliminate the effect of variability between samples) using the modal analysis of its vibrational impulse response (Al Fay et al 2023); to enrich the CIRAD wood database with orthotropic elastic constants on a wide range of wood species; and to analyse the correlations between macroscopic elastic behaviour and ultrastructural parameters, including density and microfibril angle (MFA), in order to improve prediction models.

## Material and methods

### *Wood samples*

Up to now, twenty-seven parallelepiped samples of wood from nineteen different species were tested. All samples had fixed dimensions of around 130×60×10 mm³, which cannot be modified as samples are valuable. They were taken from CIRAD "xylotheque" (Langbour et al 2019), a comprehensive library containing over 34.000 samples from 8.400 species from all around the world. These samples had different growth ring orientations on their transverse cross- section: some were quarter-sawn, with rings mainly parallel to the thickness or inclined at different angles, while others were flat-sawn, with rings mainly parallel to the width or also inclined at various angles. All samples had a straight grain, mainly oriented along the sample's length. It is important to note that there were samples of the same species with different orientations of growth rings. All measurements were performed under constant climatic conditions of 20°C and 40% RH.

*Experimental set-up*

The method used was a fast and non-destructive test by impulse modal analysis. Samples were mounted on soft elastic supports to achieve free-free-free-free boundary conditions and excited using either a small hammer or a steel ball. Vibrations were recorded by a high-sensitivity microphone (PCB - 130F20) and signals acquired with a digital oscilloscope (TDS 3032). Time-domain response data were processed using Fast Fourier Transform to obtain frequency-domain response. Finally, modal parameters were identified based on the least square complex frequency (LSCF) method (Peeters et al 2004) using MODAN, which is an integrated structural dynamic identification software developed by Femto-ST Institute (Besançon, France).

*Test configurations*

After trying three measurement configurations on several samples (flat, on edge and longitudinal orientations), only one configuration (flat) was finally retained for each sample. In this configuration, four different locations were considered to position the microphone and the impact. This was done to achieve two goals: exhaustively measure resonance frequencies, to ensure that no mode was missed within the considered frequency range, and accurately and rapidly associate each measured resonance frequency with its corresponding mode, based on the positions of impact and microphone relative to computed vibration nodes.

*Identification of elastic constants from frequencies*

Compliance elastic matrix C coefficients were initialized using Guitard and El Amri's (1987) empirical relationships based on sample density (only). As direct calculation, modal shapes and frequencies were computed using Cast3m FEA software[1], considering sample dimensions, wood's density, orthotropy, ring orientation and curvature (and even the grain angle) in a cylindrical coordinate system. A picture of each transverse cross section of the sample is used to determine the relative position of sample to the pith axis. Elastic constants were then optimized by minimizing squared differences between measured and computed frequencies, iteratively recalculated to achieve a given tolerance. The eigenmodes were tracked during the identification process by maximising the correlation function between the mode shapes computed at initialisation and those computed during the minimisation process.

*Sensitivity and identifiability analysis*

Before identifying elastic constants, a sensitivity analysis of each mode to different elastic constants was conducted by varying their initial values by 1%, thus obtaining a sensitivity matrix. This analysis was crucial for determining which elastic constants can be identified with which mode(s), particularly focusing on the lowest frequency modes to save measurement time and accuracy. Indeed, as the spectral density increases with the frequency, high-ranking modes are more difficult to separate from one another, especially as their amplitude is low. An identifiability analysis is conducted using a so-called I-index (Barick et al 2020). This analysis was essential to quantify the reliability of the identified elastic constants using various mode combinations. The I-index, based on the sensitivity function, assesses the conditioning and uniqueness of the solution in the inverse problem. A low I-index ensures robust and accurate identification of elastic constants with a unique solution (Barick et al 2020). To study the minimum modes required for identifying elastic constants, a numerical perfect wood sample with flat growth rings assumed parallel to the width (i.e., anatomical direction T is parallel to

[1] http://www-cast3m.cea.fr/

the width), with no grain angle, of "xylotheque" dimensions, a density of 700 kg/m³ and having elastic constants equal to those predicted by Guitard and El Amri's model (1987) were used. Its 'measured' natural frequencies were computed and the aim was to see whether the inverse identification algorithm could recover the correct elastic constants even if their initial values were multiplied by a coefficient of between 1.1 and 1.3. A sensitivity matrix was calculated, and two approaches were tested. The first one is a two-step approach: one by first identifying the three most sensitive constants ($E_L$, $E_R$, $G_{LR}$) and then reidentifying these three constants and the two less sensitive ones ($G_{RT}$, $G_{LT}$), using the updated compliance matrix C from the first step. The second one is a one-step approach with a simultaneous identification of the five elastic constants from the initial compliance matrix C.

## Results and discussion

*Minimum modes required for identifying elastic constants of a perfect wood sample*

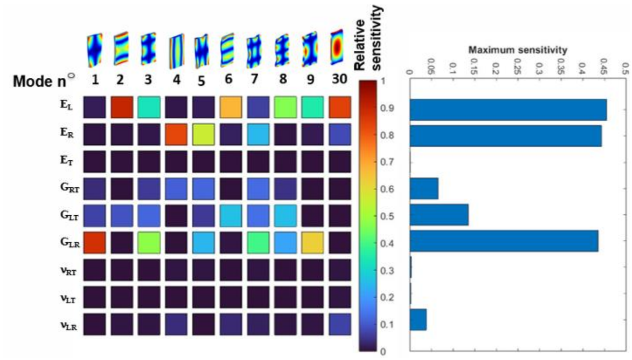


Fig. 1: (left) relative sensitivity $\frac{\Delta f_m/f_m}{\Delta X_i/X_i}$ of the computed mode of rank n°m to the elastic coefficients $X_i$(e.g., $X_i$ = $E_i$ or $G_{ij}$ or $\nu_{ij}$), normalised by the sum of the sensitivity for a given mode, with the maximum sensitivity of the modes to each elastic constant (right). The colours of the mode shapes above the rank of modes indicate the normalised intensity of the out-of-plane displacements, with blue corresponding to the vibration nodes.

The relative sensitivity matrix of each mode, which is usually measurable but given here for the numerical perfect wood sample, is given in Figure 1. It shows that the modes are mainly sensitive to $E_L$, $E_R$ and $G_{LR}$ and, to a lesser extent, to $G_{LT}$, $G_{RT}$ and a little to $\nu_{LR}$, the latter not being taken into account in the identification. Calculating the I-index, using this sensitivity matrix, shows that a good combination of five modes (i.e., modes n°1, 2, 4, 6 and 7) was sufficient to robustly identify the five elastic constants in our case. In addition, by comparing one-step and the two-step identification methods shows that a one-step process achieved similar accuracy (relative error <1% for four elastic constants and 1.14% for $G_{LT}$, the constant with the lowest sensitivities), indicating it is both sufficient and time-saving compared to the two-step.

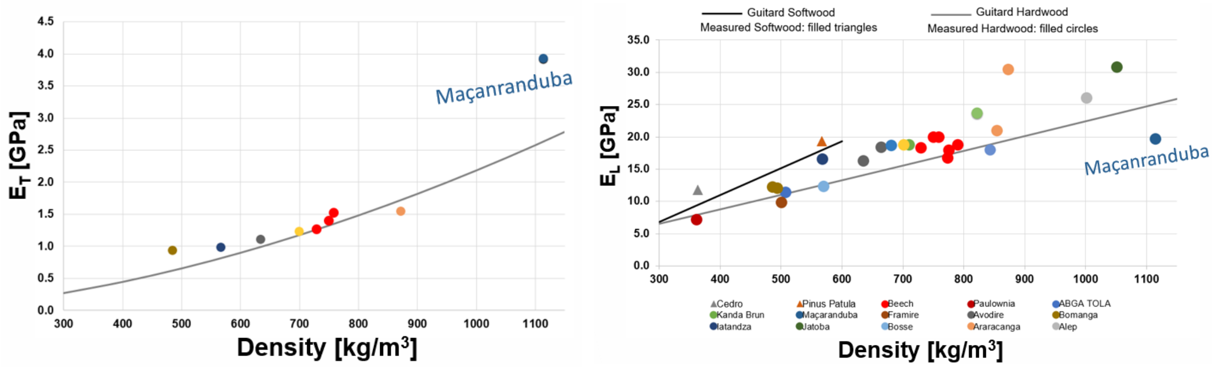


Fig. 2: Measured samples: hardwood (circles), softwood (triangles).
Guitard and El Amri's regression laws: softwood (black), hardwood (grey).

*Identification of elastic constants of real wood samples across a wide density range*

The identification process described above was applied to various wood samples (hardwood and softwood) with a wide range of densities, from 360 to 1115 kg/m³. The elastic constants identified are generally close to those given by the Guitard's models, as shown in Figure 2, except for densities over 900 kg/m³, where significant deviations were observed. We expect this discrepancy arises because the Guitard's models have been adjusted mainly on wood with low or intermediate density. Moreover, they only consider the density as a parameter and no other anatomical properties. For example, Maçaranduba (*Manilkara bidentata*) flat-sawn sample, exhibited lower longitudinal modulus $E_L$ and higher transverse modulus $E_T$ compared to the predictions from Guitard's models, potentially due to a high MFA.

## Conclusion and perspectives

This study used modal impulse response analysis to efficiently identify some orthotropic elastic properties of wood samples, focusing on key modes by using identifiability criteria based on a sensitivity analysis. The I-index showed that not all modes are needed to determine the elastic constants, and a one-step method is sufficiently accurate. While the results validated the method over a wide range of wood densities, discrepancies are observed at high densities or could be linked to anatomical parameters like a high microfibril angle. Future and ongoing work will extend the study to other wood samples, compare results with ultrasound time-of-flight (Toulgoat et al 2024) and quasi-static testing (torsion and bending) methods, measure the average MFA of all samples using XRD measurements and investigate the relationship between the macroscopic elastic properties of woods and anatomical parameters (mainly density and microfibril angle) in order to improve prediction models.

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