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Vibro-acoustic characterization of wood floors and influence of the constructive principle

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ABSTRACT

This work aims to study the vibro-acoustic behavior of wood floors. The ultimate goal is to be able to better take into account the low frequencies (20 Hz-100 Hz) in the acoustic global indices used in building acoustics and thus, to better adapt them to light wood constructions sensitive to this range of frequencies. By modifying the arrangement of wooden joists, two constructive principles were considered in order to observe the effect of rigidity. The natural frequencies and the modal deformations of these wood floors were then estimated from the frequency response functions resulting from hammer impact measurements. A finite element modeling of these floors was then carried out by having previously estimated the input parameters (Young's modulus) from the measurements made on each of the structural elements of these floors (joists, plates) in condition free movement. A parametric study was then carried out in order to better understand the influence of these constructive principles.

Keywords: Wooden buildings, natural frequencies
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1. INTRODUCTION

This work deals with the study of the natural frequencies of wood floors. More particularly, the influence of the geometrical and mechanical characteristics on the values of these natural frequencies is here considered. Ultimately, the goal is to better understand the acoustic transmission of low frequency signals such as footsteps often considered troublesome [1]. To date, most acoustic indicators do not take into account these low frequencies [2]. Two constructive floor principles have been studied. First, the natural frequencies of the wood floors are estimated from the frequency responses from the measurements. As a result, a finite element model is proposed in order to find these natural frequencies. The input parameters of this model are either derived from the literature or estimated from the study of the vibratory behavior of structural elements alone (wood joists and OSB panels) assumed in free conditions. Three types of tensors of elasticity have been studied: the isotropic tensor, the isotropic-transverse tensor and the orthotropic tensor. After retaining one of these tensors of elasticity, this model is used in order to realize a parametric study allowing to study the influence of the properties and characteristics of the wooden floors such as the dimensions of the joists, the thickness of the wood panels, density and Young's modulus.

2. MEASUREMENT CAMPAIGNS AND ESTIMATION OF THE NATURAL FREQUENCIES

Two floors made of spruce wood joists and OSB panels, of dimensions $[L : l : h] = [391 : 225 : 19.3]$ are studied here (see Figure 1). The first floor is called "transversal floor" because its wooden joists are arranged parallel to the width l of the floor (see Figure 2 (a)) The second floor is called "longitudinal floor", its joists being arranged parallel to the L length of the floor (see Figure 2 (b)). For future comparisons, these floors are close to those considered by D. Blon in his thesis work [3]. They are both placed on studs at their corners (see Figure 1). OSB panels are screwed onto wood joists.

Alongside the measurements made on these wooden floors, measurements are also made on the elements alone. The joist wood is of dimensions in centimeters $[L_b : l_b : h_b] = [400 : 6.3 : 17.5]$ and density $\rho_b = 496\ kg.m^{-3}$ (see Figure 3). The Oriented Strand Board (OSB) is of dimensions in centimeters $[L_p : l_p : h_p] = [250 : 40 : 1.8]$ and density $\rho_p = 603\ kg.m^{-3}$. The measurements are made by suspending these elements using elastic tensioners.

These structures are excited by means of an impact hammer (*Brüel & Kjær 8202*) associated with a force sensor (*Brüel & Kjær 8200*). The acceleration is estimated at different reception positions using an accelerometer (*Brüel & Kjær 4370*). The position of the excitation point, denoted "E" is chosen in order to excite a large number of natural modes. For each receiving position, the measurement is repeated three times to ensure the reliability of the results. An accelerometer is also placed near the point of excitation so as to control the impact force given by the impact hammer. Its position, denoted R_1, is on the side parallel to the one with the excitation and reception points. A total of 15 measurements were estimated for the wood joist, 36 for the OSB panel, 90 for the longitudinal floor and 75 for the transversal floor.

The acquisition of the temporal signals is carried out *via* the software "Samurai" (https://acsoft.co.uk/product/samurai/) whose post-processing makes it possible to obtain the frequency signals by Fourier transform. A code, developed under Matlab for the

purpose of estimating the frequency responses "Acceleration / Force" (denoted FRF) and extracting the natural frequencies, is then used. The FRF are smoothed *via* the Savitzky-Golay algorithm [4] (function "sgolayfilt" in Matlab) .The peaks of these FRF are then detected from the function "findpeaks". In order to avoid small peaks that probably do not correspond to a specific mode, a criterion imposing the minimum height of the peaks to be considered is associated with this function. The probability densities of the frequencies associated with these detected peaks are then calculated ("histogram" function in Matlab with a bandwidth set at 2 Hz). The natural frequencies are then supposed to be those having the highest densities of probability.

Figure 1: Photograph of the study floors.

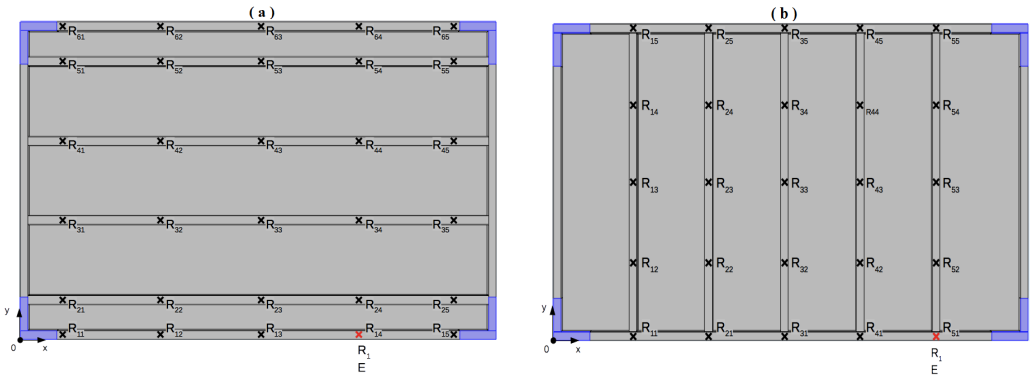

Figure 2: Schematic representation (a) of the "longitudinal" floor and (b) of the "transversal" floor with dimensions in centimeters $[L : l : h] = [391 : 225 : 19.3]$, *as well as emission and reception positions.*

The figure 4 (a) respectively shows the FRF obtained for the case of the transversal floor placed on studs at its corners (see Figure 2 (b)). A good repeatability is observed which reinforces us on the measurement methodology. The circles on the curves show the peaks detected by our approach. All the frequencies associated with the peaks detected are of course not necessarily natural frequencies. However, the estimation method based on the probability density seems to be able to extract the natural frequencies as shown in the figure and 4 (b)for the case of the transverse floor. This is also true for the suspended beam, the suspended OSB panel and the longitudinal floor.

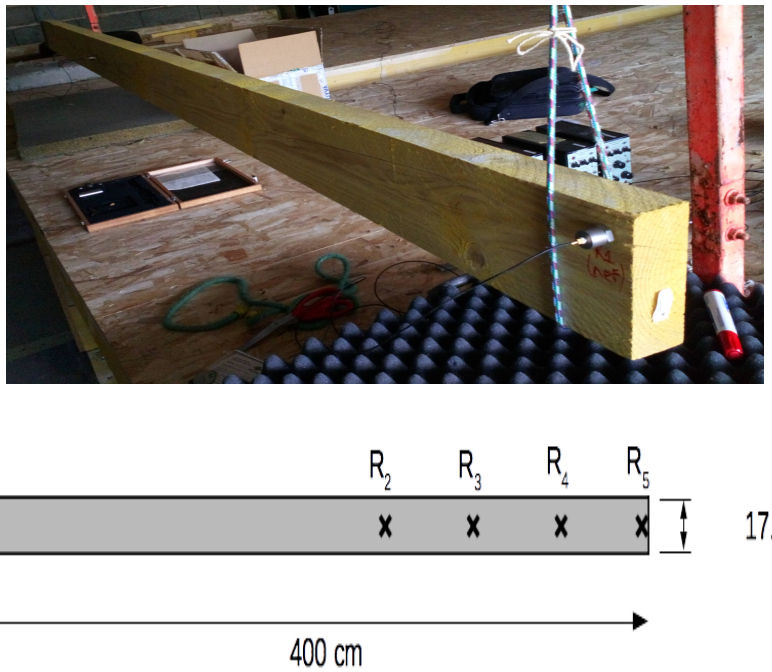

Figure 3: Photograph and schematic representation of the tested wood joist with dimensions in centimeters $[L_b : l_b : h_b] = [400 : 6.3 : 17.5]$ *and density* $\rho_b = 496\ kg.m^{-3}$*, as well as emission and reception positions.*

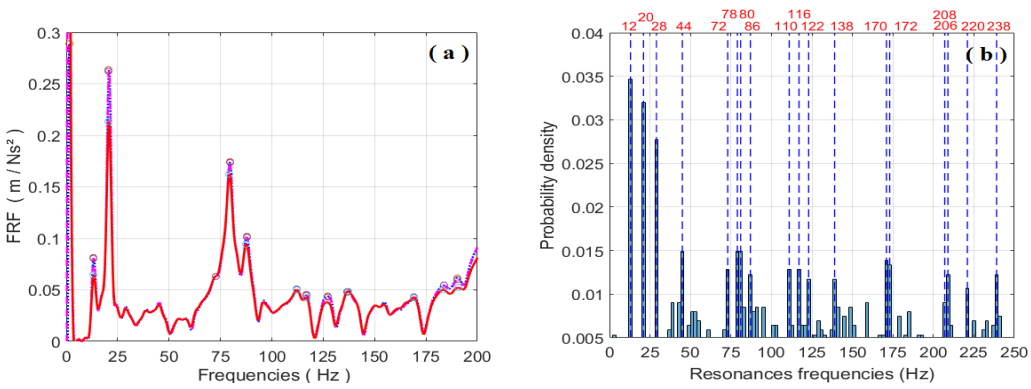

Figure 4: Transversal floor: (a) FRF estimated at the reception position R_{35}*, "-", "- -", ":": measurements 1, 2 and 3; "o": detected peaks; (b) probability density of frequencies related to FRF peaks (histrogram) and "- -" estimate first natural frequencies.*

3. FINITE ELEMENT MODEL

3.3.1. Presentation of the model

The chosen model is based on the well-known equation governing the motion of a structure (fundamental law of dynamics) [5, 6]:

$$\rho \frac{\partial^2 \mathbf{u}(\mathbf{x}, t)}{\partial t^2} = \nabla . \sigma(\mathbf{u}(\mathbf{x}, t)), \tag{1}$$

and for a harmonic solution $u = U \sin(\omega t)$:

$$-\rho \omega^2 U = div(\sigma(U)), \tag{2}$$

with $\mathbf{x} = (x_1, x_2, x3)$ the position vector in the base $(\vec{e_1}, \vec{e_2}, \vec{e_3})$, $\mathbf{u} = (u_1, u_2, u_3)$ the displacement vector of the structure, ρ the density, and $\sigma(\mathbf{u}(\mathbf{x}, t))$ the stress tensor. If the material is considered to have linear elastic behavior, Hooke's Law allows writing :

$$\sigma(\mathbf{u}(\mathbf{x}, t)) = C\epsilon(\mathbf{u}(\mathbf{x}, t)); \tag{3}$$

where C is the tensor of elasticity, and $\epsilon(\mathbf{u}(\mathbf{x}, t))$ the linearized strain tensor defined from the spatial derivatives of the components of the displacement vector. In order to complete the model, a boundary condition must be associated. In our study, two boundary conditions are likely to be used. The first condition is a support condition that assumes that the structure can move only according to the normal $\mathbf{n}$ on the surface of the boundary:

$$\mathbf{u}(\mathbf{x}, t).\mathbf{n} = 0. \tag{4}$$

The second condition is a free condition which supposes the structure is free of its movement:

$$\mathbf{u}(\mathbf{x}, t) \neq \mathbf{0}. \tag{5}$$

Finally, the proposed model is finite element solved using the software "Comsol multiphysics" (https://www.comsol.fr/comsol-multiphysics) in the following form [7]:

$$\left[K - \omega^2 M\right] U = 0, \tag{6}$$

where K is the stiffness matrix according to the stress tensor $\sigma(\mathbf{u}(\mathbf{x}, t))$, M is the mass matrix function of the density ρ. The search for nullity of the determinant $\left|K - \omega^2 M\right|$ allows to obtain the natural frequencies. Finally, the main difficulty here is to define a C elasticity tensor adequate for the different elements constituting the wood floors (wood joists, OSB panels).

3.3.2. The elastic tensor

The elements of the wood floors (wood joists and OSB panels) have particular structural characteristics. As a result, several symmetry hypotheses have been studied, each associated with a particular expression of the tensor of elasticity. In the first hypothesis, the element considered is supposed to be a **orthotropic** material, then having three perpendicular planes of symmetry between them which are $(\vec{e}_1, \vec{e}_2)$, $(\vec{e}_1, \vec{e}_3)$ and $(\vec{e}_2, \vec{e}_3)$. In the second hypothesis, this supposedly orthotropic element also possesses a symmetry of revolution around an axis. The material is said to be **isotropic transverse**. In the third hypothesis, the supposed orthotropic element has this time a symmetry of revolution around its three axes. The material is said to be **isotropic**. The expressions of the transverse isotropic elastic tensor and that of the isotropic elastic tensor are given here [8, 9].

These three tensors of elasticity are expressed as a function of the Young's moduli, Poisson's coefficients and shear moduli characterizing the elements of the wood floors. By looking at the modeling of the structural elements alone (wood joist and OSB panel), the results showed that the value of the natural frequencies is more sensitive to the value of the Young's modules than to Poisson's coefficients and shear modules. As a result, these two last ones were fixed from the literature [10–12]. Thus, the model proposed here assumed function of Young's modules only. For the case of wood, expressions are

proposed in the literature to deduce the radial Young's modulus E_R and tangential E_T from the Young's modulus longitudinal E_L (see Figure 5) [12, 13]:

$$\begin{cases} E_R = \frac{E_L}{10} \\ E_T = \frac{E_R}{2} \end{cases} \tag{7}$$

Thus, the model is perfectly defined since the value of the longitudinal Young's modulus is known. In our case, the wooden joists can come from a non central part of the tree trunk (Fig 5 (b)). As a result, we assume here as a first approximation that the base ($\vec{e_R}$, $\vec{e_T}$, $\vec{e_L}$) is concurrent at the base ($\vec{e_1}$, $\vec{e_2}$, $\vec{e_3}$). For example, for the case of the orthotropic elasticity tensor associated with the wood joist whose length L_b is parallel to the axis $\vec{e}_1$, the following equalities are obtained: $E_1 = (E_L)_b$, $E_2 = (E_R)_b$ and $E_3 = (E_T)_b$.

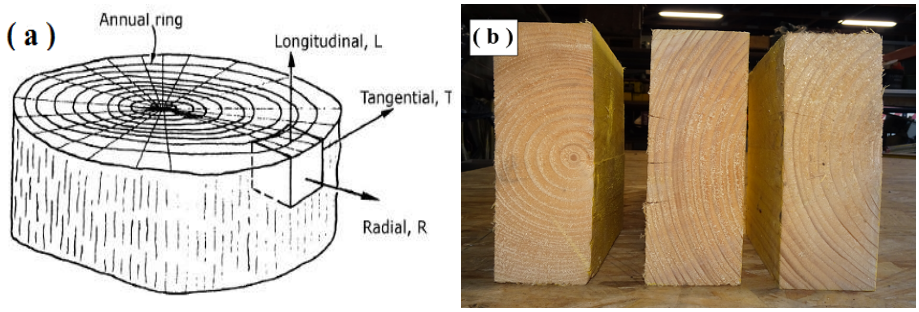

Figure 5: Geometric and mechanical characteristics of wood.

4. MODELIZATION

4.4.1. Determination of longitudinal Young's modulus

The longitudinal Young's modulus of the wood joist and that of the OSB were estimated by an iterative approach by seeking to adjust the first natural frequencies from the FRFs measured to those resulting from the modeling. The free boundary condition is here the most appropriate account of the experimental conditions (wooden joist and OSB suspended by elastic tensioners). For the wood joist case, the three tensors of elasticity (isotropic, transverse isotropic, orthotropic) were considered. On the other hand, in the case of the OSB panel, only the isotropic elastic tensor was taken into account. Only the natural frequencies associated with the modes likely to have been excited because of the retained emission and reception positions are here compared with those obtained by modeling.

In the case of the wood joist associated with the orthotropic elastic tensor and whose length is parallel to the axis $\vec{e}_1$, the value $E_1 = (E_L)_b = 8\ GPa$ of the longitudinal Young's modulus was selected. Using the equation (7), the other modules are equal to $E_2 = (E_R)_b = 0.8\ GPa$ and $E_3 = (E_T)_b = 0.4\ GPa$. A large number of the first measured natural frequencies are found here. For the case of the wood joist model whose length is parallel to the axis $\vec{e}_1$ (symmetry of revolution) and associated with the transverse isotropic elastic tensor, the iterative method allowed to retain the following values of Young's moduli: $E_1 = (E_L)_b = 8\ GPa$, $E_2 = (E_R)_b = 0.8\ GPa$. For where the model is related to the isotropic elastic tensor, the value of the Young's modulus retained is $E = 8\ GPa$. These values are a little low, with respect to the typical values for spruce, between 10 and 12 GPa [14] . Finally, for the case of the potent modeling on the OSB and

associated with the isotropic elastic tensor, the value of the Young's modulus retained is $(E)_p = 6\ GPa$. This value is higher than that found in the literature which is of the order of 3.5 GPa [15]. In all cases, the model thus defined makes it possible to find most of the natural frequencies measured.

4.4.2. Application to wood floors

Finally, the wood floors were modeled taking into account the input parameters previously established. The support condition (see Equation 4) was logically retained for the part of the wooden joists placed on the studs (see Figure 1). For the other limits, the free condition is chosen (see Equation 5). The screwing of the OSB panels on the wooden joists was taken into account during the geometrical construction of the model. As previously, the three types of elastic tensors were studied. The figure 6 presents the results obtained for the transversal floor (see Figure 2 (b)). It is clear that the choice of the isotropic elastic tensor is not adequate The number of natural frequencies is low and the value of the first natural frequency is too high (32 Hz). Moreover, the natural frequencies obtained are not in agreement with those measured.

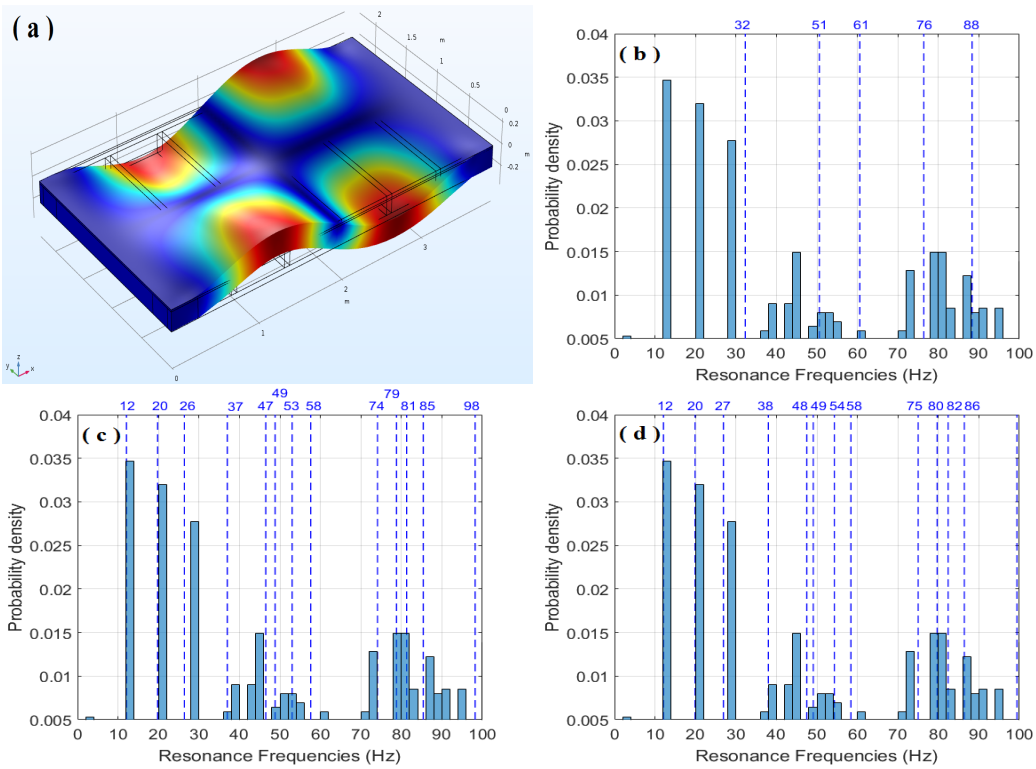

Figure 6: Transversal floor: (a) bending mode corresponding to the natural frequency 49 Hz, comparison between the measured natural frequencies and those resulting from the modeling associated (b) with the isotropic elastic tensor, (c) with the orthtropic elasticity tensor and (d) the transverse isotropic elastic tensor.

Conversely, the natural frequencies resulting from the models based on the orthotropic tensor of elasticity (see Figure 6 (c)) and based on the transverse isotropic elastic tensor (see Figure 6 (d)) are in agreement with those measured. The natural frequencies resulting from modeling related to the orthotropic tensor elasticity are often lower by 1 Hz than those resulting from modeling related to the transverse isotropic elastic tensor. These

results show the importance of the choice of the tensor of elasticity. For the case of the longitudinal floor (see Figure 2 (a)), similar results were obtained.

5. PARAMETRIC STUDY

A parametric study, based on the previously validated model for two types of tensors of elasticity, concludes this work. It aims to estimate the influence of the main characteristics of wood floors as its dimensions and those of the elements (wood joists, OSB panels), but also the densities and Young's modules of the latter. For this, a transverse floor of the same shape as the one studied previously (see Figure 2 (a)) and associated with the transverse isotropic tensor was considered. Initially, it has the following characteristics:

$$
\begin{aligned}
&[L : l : h] = [400 \text{ cm} : 300 \text{ cm} : 19.3 \text{ cm}] \\
&[l_b : h_b] = [7 \text{ cm} : 18 \text{ cm}],\ \rho_b = 496 \text{ kg.m}^{-3},\ [(E_L)_b : (E_R)_b] = [8 \text{ GPa} : 0.8 \text{ GPa}] \\
&e_p = 1.8 \text{ cm},\ \rho_p = 603 \text{ kg.m}^{-3},\ (E)_p = [6 \text{ GPa}]
\end{aligned}
\tag{8}
$$

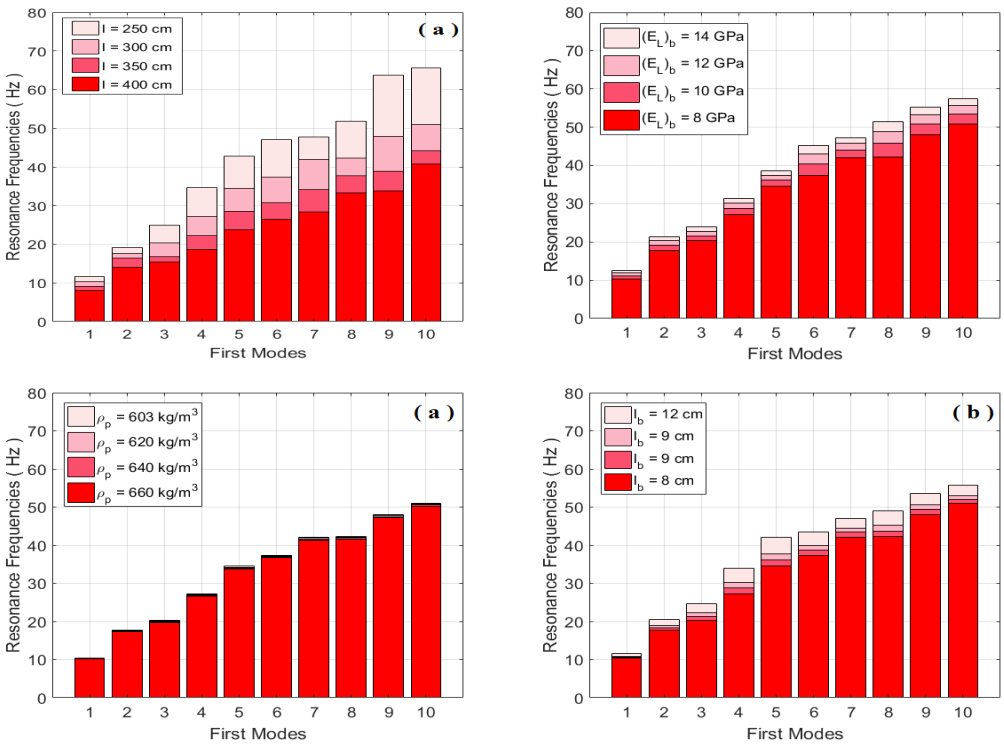

Figure 7: Modeling of the transversal floor for the case of the transverse isotropic tensor: (a) influence of the width of the floor, (b) influence of the Young's modulus of the wooden joists, (c) influence of the density of the OSB panels and (d) influence of the width of the wooden joists.

For example, the figure 7 shows the influence on the values of the first natural frequencies of the width of the floor (see Figure 7 (a)), of the Young's modulus of the wooden joists (see Figure 7 (b)), of the density of the OSB panels (see Figure 7 (c)) and of the width of the wooden joists (see Figure 7 (d)) . The results of this study have shown that the value of the natural frequencies is increasing according to the Young's

moduli, the height and the width of the wooden joists as well as the thickness of the OSB. Conversely, it decreases with width and floor length, density of joist and OSB. Obviously, the dimensions of the floor are the most influential parameters. This is in agreement with existing analytical work [7, 16]. Future work will complete this parametric study.

6. CONCLUSION

The objective of this work was the modeling of wood floors and the study of the parameters that can influence the value of their eigenfrequencies. At first, the eigenfrequencies of the constructive elements assumed in free condition, and those of the wooden floors in support condition at their corners, were estimated from the frequency responses. In order to extract these eigenfrequencies, a numerical approach has been proposed and validated. In a second time, these constructive elements were modeled. In addition, the model introduces the notion of elastic tensor according to the Young model. Three forms of elastic tensors were then studied in order to define the most suitable for these wood materials. In parallel, an iterative approach also allowed to retain the value of the Young's modulus allowing to find the measured eigenfrequencies associated with these constructive elements. The wood floors were then modeled and the eigenvalue values measured were found. Finally, a parametric study was carried out in order to estimate the influence of various parameters related to wood floors. Further works will deal with computation of mobility functions and response to an impact reproducing the excitation due to walking. This should allow to determine the size and number of joists.

7. ACKNOWLEDGEMENTS

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