

SIMPLIFIED COMPUTATION OF TIMBER FLOOR VIBRATIONS LEVEL DUE TO HUMAN ACTIVITIES

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Abstract. *Timber floors are sensitive to vibrations because of their lightweight. Walking on this type of floor could cause motion sickness for the walkers or the other people in the room. Timber floors have to be designed correctly to ensure a good comfort, especially in countries like France where people are used to the vibration comfort level of concrete floors. This paper proposes new methods to assess the dynamical properties of timber floors, and the accelerations due to the walk of an individual. Experimental and numerical tests are made to evaluate the relevance of the method.*

1 Introduction

1.1 Problematic

Due to timber buildings lightweight, their dynamical properties must be studied carefully. Vibration comfort level is an important aspect of the quality of a building. Discomfort is dependent of the sensitivity of each person, their activities and mainly of vibration physical values (frequencies, accelerations, velocities and displacements). These physical quantities have to be assessed to design correctly timber floors. This paper presents a methodology to predict the frequency of the first floor mode and assess the vibration level from walking of individual.

1.2 State of the art

The ISO-10137 norm [1] gives some clues to size floors and footbridges against vibrations. The main point of this norm is to assess the vibration effects due to different sources on the comfort of users. A criterion based on the root mean square (RMS) acceleration is proposed which depends on the building use (figure 1).

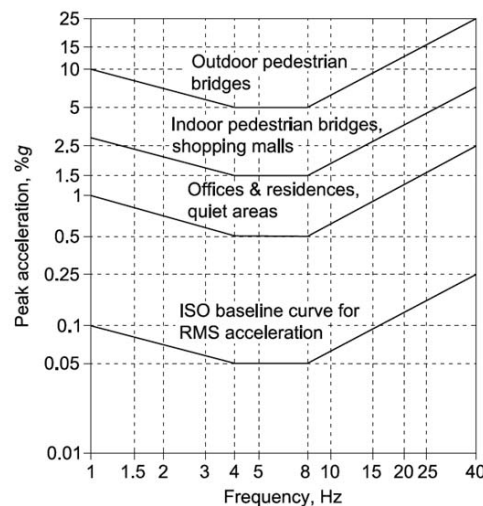


Figure 1: Comfort criterion depending of the frequency and the acceleration of the floor

The Eurocode 5 [2] gives also criteria to assess the comfort of wooden floors. Those criteria are different from ISO ones. This norm focuses on only wooden floors with resonance frequency higher than 8Hz. The other ones have to be evaluated differently. The criteria given are based on the Ohlsson works [4] and depends on the floor velocity due to a theoretical impulsive shock and the floor stiffness. The next edition of the Eurocode will provide criteria for each kind of floors and estimations of the floor acceleration due to the walking of a person. Beyond these norms, a large number of guides exist to design floors regarding vibrations and comfort, including the guide from the American Institute of Steel [3]. This guide gives a method to compute floor acceleration by considering a simplified theoretical model and the average frequency content of load due to walking. This acceleration is confronted to the criteria given by the ISO-10137 [1].

In Europe, HIVOSS guidelines [5] aims to assess the floor comfort with a method called OS-RMS90 (one step, root mean square) [6]. The maximal RMS response of a floor is given

for 90% of kind of walking. Some similar guidelines exist for footbridges, which are also very sensitive to vibrations [7, 8].

Recently, specific studies on wooden floor show that every physical values (displacement, velocity, acceleration and frequency) can be used to judge the comfort of floors. Hu and Chui [9] suggest a empiric criterion based on the ratio between the floor displacement and its frequency. Several kinds of criteria have been reviewed and used on CLT (Cross Laminated Timber) by Weckendorf [10]. Patricia Hamm [11] puts forward that the floor frequency is not a discriminatory factor to provide comfort because some high frequencies floor are evaluated uncomfortable. Then, in 2018, a research group has summarized experimental tests on floors in order to determine an ISO criterion [12]. No consensus has actually been built up on a comfort threshold but in order to be able to use a comfort criterion, the dynamic behavior of timber floors must be well known. Few studies estimate accurately the resonance frequency of timber floors considering their boundaries conditions and orthotropy. Then, Eurocode 5 gives a formula to compute acceleration of a low frequency floor. However, a formula for high frequency floor is missing.

1.3 Objectives and methodology

The purpose of this paper is to define a simplified methodology which can be used by professionals or design department to assess the vibration levels on floors due to human activities. The physical values obtained will have to be compared to a comfort criterion. The assessment of vibration levels requires to identify the floor dynamic properties. First, the frequency of the first floor mode is computed, taking into account wood specificities. Then, according to the properties of the walker (weight, walking frequency), the floor acceleration is determine under theoretical assumptions for low and high frequency floors.

2 Modal frequencies assessment

The knowledge of the floor dynamical properties is necessary to assess its dynamical response due to human activities, like resonance frequency and modal mass. The first frequency mode of wooden floors can be difficult to estimate because of the wood orthotropy and boundary conditions. A method is suggested introducing some scalars deduced from analytical and numerical studies in order to take into account specificities of wooden floors.

2.1 Basic formulas

Leissa has analyzed the vibrational response of rectangular plates with different boundary conditions [13]. In civil engineering, two combinations of boundary conditions occur frequently : two opposite simply supported sides and two free side (SS-F-SS-F) or four simply supported sides (SS-SS-SS-SS). In situ experiments show that boundary conditions on the sides of floors are more likely simply supported than clamped conditions, but it exists a rotational stiffness which will be discussed further.

The formula for the (SS-SS-SS-SS) boundary conditions can be determined analytically [13] :

$$f_{1_{SS}} = \frac{\pi}{2a^2} \sqrt{\frac{D}{\rho h}} (1 + (\frac{a}{b})^2) \quad (1)$$

$f_{1_{SS}}$ is the resonance frequency of the first mode in the (SS-SS-SS-SS) condition. $D = Eh^3/12(1 - \nu^2)$ is the flexural rigidity, E is Young modulus, h is plate thickness, ν is Poisson's

ratio, ρ is mass density per volume, a and b are respectively the largest and smallest dimensions of the studied rectangular floor.

For the (SS-F-SS-F) conditions, the solution has to be estimated from an analytical equation [13]:

$$f_{1_{2SS-2F}} = \frac{C}{2\pi a^2} \sqrt{\frac{D}{\rho h}} \quad (2)$$

$$C = 0.051\left(\frac{a}{b}\right)^2 - 0.28\frac{a}{b} + 9.86$$

The equations 1 and 2 are standard results for an isotropic plates with ideal boundary conditions. It is the reference frequency f_{ref} for the rest of the computation. The first step is to homogenize the wooden floor and find the equivalent plate. In most cases, wooden floors are strongly orthotropic. The mechanical parameters in the stiffest direction are the only ones considered in the previous formulas. The effect of orthotropy will be considered further. Then, three coefficients will be added to take into account the wood specificities :

$$f_1 = R_c R_\lambda R_F f_{ref} \quad (3)$$

f_1 is the 'real' frequency of the floor. R_c represents the effect of a continuous floor on several supports on the resonance frequency. R_λ represents the effect of orthotropy. This coefficient is always inferior or equal to 1. R_F describes the effect of the added torsional stiffness due to the load at the extremities of the floor. This coefficient is always superior or equal to 1.

2.2 Orthotropy

Several authors have worked on the vibration properties of orthotropic plates [14, 15]. The Jayaraman results [16] have been used in this paper. For several set of boundary conditions with at least two parallel sides simply supported, it is possible to find complex relationship between the resonance frequencies and the flexural rigidity D_x and D_y (describing respectively the flexural rigidity on the strongest and the weakest direction).

A numerical resolution has been realized for several ratio of orthotropy D_x/D_y , and ratios of floor dimensions a/b . The first observation is that for a (SS-F-SS-F) configuration, the orthotropy has a minor influence on the resonance frequency value : the frequency decreases just by 2% for $a/b = 2$ and $D_x/D_y = 20$. Difference are larger for the following modes. For a (SS-SS-SS-SS) configuration, the impact of orthotropy is major. For the same conditions ($a/b = 2$ and $D_x/D_y = 20$), the frequency falls by 39%.

A statistical resolution has been made to establish the factor R_λ . For a (SS-F-SS-F) configuration, it is possible to consider $R_\lambda = 1$ whereas for a (SS-SS-SS-SS) configuration, R_λ is expressed as followed

$$R_\lambda = 1 - (1 - e^{-0.4\frac{D_x}{D_y}} + 0.4)(0.25\frac{a}{b} - 0.021(\frac{a}{b})^2) \quad (4)$$

2.3 Continuous floors

Floors are usually supported on more than two supports. The continuity of the floor can influence its dynamic behavior. In short, the frequency of a span of continuous floor is higher

than its isostatic equivalent if the neighboring span are shorter and inversely. Then, if one of the support can not be considered as rigid (like a wood joist assembly), it has to be considered in the computation by considering a spring instead of a rigid support. Two situations are presented in this paper.

- **One span floor supported by a rigid support and by a spring.**



Figure 2: One span floor

The spring stiffness can be estimated with the average stiffness of a beam resting on two flat supports separated by a length of L.

$$k = \frac{120EI}{L^3} \quad (5)$$

Thanks to numerical computations, it is possible to compute the ratio R_c which linked the frequency of the beam on rigid support and spring with the frequency of a beam on two rigid supports (figure 3).

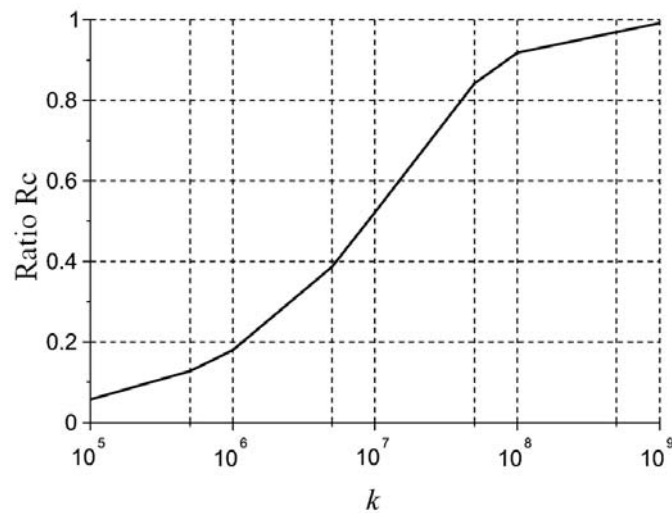


Figure 3: Impact of the spring stiffness on the reatio R_c for a one span floor supported by a rigid support and a spring

The ratio R_c drops when the spring stiffness decreases and moves toward 1 when stiffness increases.

- **Two-spans floor supported on two rigid support and one spring**

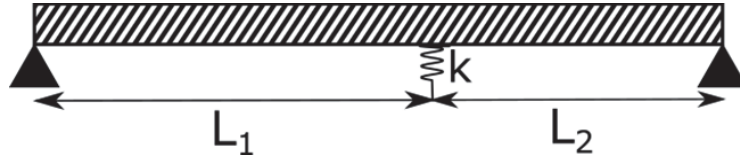
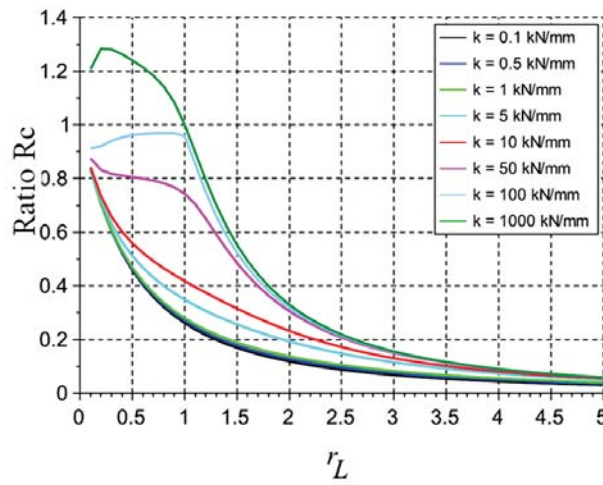


Figure 4: Two spans floor

This configuration is very usual when a floor is supported by two walls at its extremities and a wood joist (figure 4). Considering the first span of length L_1 , the ratio R_c corresponds to the resonance frequency of this span divided by the resonance frequency of a equivalent isostatic span with the same length supported on two rigid support. Results are given in figure 5.


Figure 5: Impact of k and r_L on the ratio R_c for a two spans floor with a spring support in the middle

The ratio R_c will be dependent of the stiffness of the joist, symbolized by a spring and the ratio between the length of the span $r_L = L_2/L_1$. When the stiffness of the spring is very high, $R_c > 1$ for $r_L < 1$ and $R_c < 1$ for $r_L > 1$. It illustrates the fact that a short span next to a large span increases the rigidity of the large span. Then, when spans have the same length, the ratio R_c is equal to one. When the stiffness of the spring decreases, the ratio R_c drops regardless of the r_L value. When the spring stiffness is very low, the continuous floor can be considered as an isostatic floor with a length $L = L_1 + L_2$.

2.4 Wall effect

Loads are often applied on the sides of the floor which can increase its rotational stiffness, and so increase its natural frequency. Experiments have been realized at the FCBA technological institute: natural floor frequency have been measured on CLT or joist-OSB floor while applying an increasing force at their extremities. When the clamping force increases, the floor resonance frequency increases until a threshold. This phenomenon is complex. When a clamped force is imposed on the floor, a rotational stiffness is added but locally, the floor 'crushes' a little in the wall axis. (see figure 6).

This phenomenon depends on several parameters : the ratio a/b , the wall thickness of the

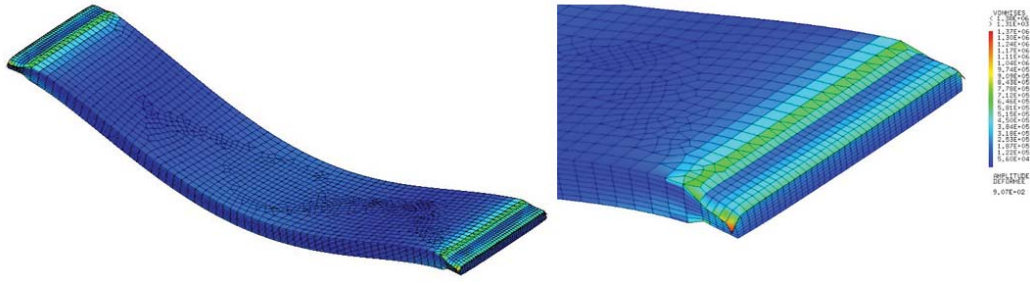


Figure 6: Deflection of a CLT beam with a clamped force at its extremities. The deflection is amplified by 100

wall hw , the floor thickness h , the floor length L , the Young modulus in the direction of the wall load E_z and the force F applied by the wall. A numerical statistical study with finite elements has been made to determine the frequency of a (SS-SS-SS-SS) floor with wall load at its extremity and leads to the following R_F expression.

$$R_F = \sqrt{\frac{1}{\alpha F \cdot 10^{-4}}} \text{ if } R_F < \sqrt{\frac{1}{\beta}}$$

$$R_F = \sqrt{\frac{1}{\beta}}$$
(6)

with

$$\alpha = (0.87(\frac{a}{b})^{-0.7}(-0.44L + 3)) \frac{9.2 \times 10^{-2} 5hw - 8.7 \times 10^{-2}}{h} \frac{0.6}{0.6}$$

$$\beta = 0.74((\frac{a}{b})^{-0.2} L^{-0.5} (2h + 0.2) hw^{-0.4} E_z^{-0.09})$$
(7)

Several parameters are involved in this phenomenon. In practical terms, it will be difficult to assess precisely these values. Furthermore, even if the wall load can affect the floor frequency, this effect seems limited as illustrated by in situ measures in a building [17]. Our recommendation is to consider $R_F = 1$. The real frequency should be a little higher than the calculated one.

2.5 Modal mass

The modal mass can be computed with the following formula [18] :

$$M_{mod} = \frac{M}{ab} \int_S \delta^2(x, y) dS$$
(8)

with M the floor total mass and δ the floor modal displacement. In case of isostatic floors with rectangular shapes, it is possible to compute easily the modal mass of the first mode :

$$M_{mod} = \frac{M}{2} \text{ in the SS-F-SS-F configuration}$$

$$M_{mod} = \frac{M}{4} (2 - \frac{a}{b}) \text{ in the SS-SS-SS-SS configuration}$$
(9)

In case of complex floor shapes, continuous floors or stiff partition, the modal mass can be strongly altered and more often its value will be lower than the one predicted by equation 9.

3 Acceleration on floor due to walking

3.1 Footstep model

A simplified model is considered to represent the floor first mode (figure 7). The mass M is equal to the modal mass M_{mod} of the first mode and the stiffness $K = \omega_1^2 M$ with the first resonance pulse $\omega_1 = 2\pi f_1$.

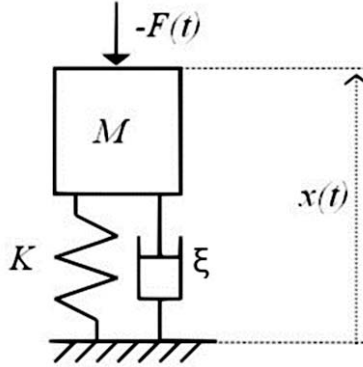


Figure 7: Spring-dashpot system

The HIVOSS guide [5] proposes to model the force load due to a footstep as below:

$$\frac{F(t)}{Q} = \sum_{i=1}^8 K_i t^i \quad (10)$$

With $F(t)$ the footstep load, Q the weight of the walker in Newton and K_i a parameter defined in [5]. With this formulation, the ratio $F(t)/Q$ is given on the figure 8.

The AISC guide [3] formulates a series of footstep load with the following formula :

$$F(t) = \sum_{i=1}^4 Q \alpha_i \sin(i\omega_1 t) \quad (11)$$

With α_i a parameters different for the walking frequency and its harmonics. For the walk, Murray gives the values of α_i : $\alpha_1 = 0.4$, $\alpha_2 = 0.07$, $\alpha_3 = 0.06$, $\alpha_4 = 0.05$. The decrease of the parameters α_i broadly follows the function $\alpha(f) = e^{-0.4f}$.

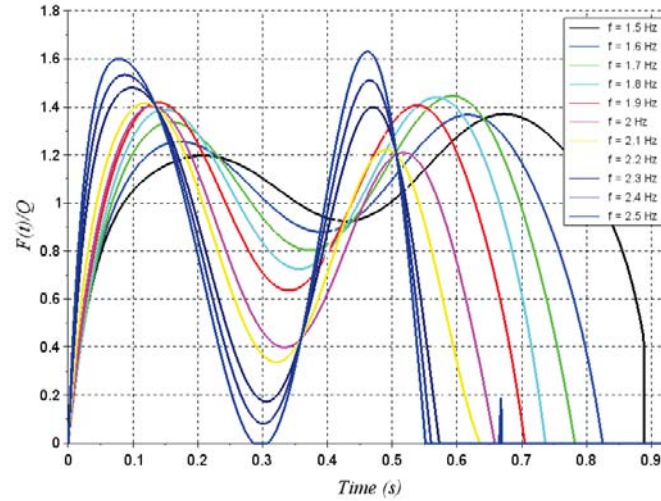


Figure 8: Ratio $F(t)/Q$ for different walking frequencies. The first peak correspond to the load produced by the heels and the second to the load induced by the toes

3.2 Low frequency floor

The next version of Eurocode 5 proposes a formula to compute the acceleration of a low frequency floor subjected to walking loads. Several assumptions are made :

- Only the first mode is considered, the floor is reduced to a simple spring-dashpot system as presented on figure 7.
- The main acceleration is due to the floor solicitation at its resonance frequency. The effect of the other frequencies are neglected.

Under these assumptions, the system acceleration for a walking load can be written :

$$a_{Lf} = \frac{\alpha(f_1)Q}{2\xi\sqrt{2}M_{mod}} \quad (12)$$

ξ is the first modal damping of the floor. $Q/(2\xi M_{mod})$ is the response of a spring damping system to a harmonic oscillation with an amplitude Q at its resonance frequency. α is the amplitude of the footsteps signal at the floor resonance frequency and is equal to $\alpha(f_1) = e^{-0.4f_1}$. The factor $1/\sqrt{2}$ takes into account the responsiveness of the walker to the effective acceleration. The expression is multiplied by a factor 0.4 in Eurocode to take into account that the walker is rarely in the center of the floor span. The factor has not be used here.

3.3 High frequency floor

For an high-frequency floor, the second EUROCODE 5 assumption which was previously presented is invalid. The load at the resonance frequency of the floor is marginal, but the effect of the other frequency of the load can not be neglected. In fact, the load can be considered as quasi-static regarding to the floor resonance frequencies and the floor accelerations are then induced by the floor free vibrations.

By using the formulation of the footstep load proposed by HIVOSS (equation 10), it is possible to determine the maximal load during a walk F_{max} .

$$F_{max} = Q(0.5f_{step} + 1.5) \quad (13)$$

With f_{step} the frequency of the footstep load.

By considering the simplified spring-dashpot system and a quasi-static response of the system during the load increase, the displacement of the mass can be written :

$$\Delta u = \frac{F_{max}}{K} \quad (14)$$

Then, at the end of the load increase, the system freely oscillates and the mass acceleration is equal to :

$$a = -\frac{F_{max}}{K}\omega_1^2 \cos(\omega_1 t) e^{-\xi\omega_1 t} = -\frac{F_{max}}{M_{mod}} \cos(\omega_1 t) e^{-\xi\omega_1 t} \quad (15)$$

Generally, persons have a walking frequency inferior to $2.3Hz$. A conservative simplification can be made by considering $F_{max}/Q = 2.4$.

The ISO 2631-1 norm [20] proposes to compute the effective acceleration as the maximal RMS value of 1s of the signal, to take into account the load variability. To obtain the effective acceleration on 1s of a sinus which decreases exponentially, the maximal acceleration have to be multiplied by a factor :

$$V_{eff} = \frac{1}{2} \sqrt{\frac{((2\xi^2 + 1)e^{2\xi\omega_1} - 1)e^{-2\xi\omega_1}}{\omega_1\xi^3 + \omega_1\xi}} \quad (16)$$

By the way, the maximal effective acceleration for a high frequency floor can be written :

$$a_{Hf} = F_{max} V_{eff} \frac{Q}{M_{mod}} \quad (17)$$

3.4 Validation

The equations 12 and 17 can be used to determine the acceleration due to a walker whatever the floor resonance frequencies. The expression 12 should be used when the frequency of the floor is under $8Hz$, otherwise the expression 17 is more appropriate.

The formula 10 has been used to create a representative load of ten footsteps with a footstep frequency of $2Hz$. The dynamic response of a spring-dashpot system to this load has been computed for different values of system frequency and for a damping of 2% . The maximum of acceleration computed during the test is confronted with formulas 12 and 17 (figure 9).

In this theoretical example, these formulas allow to conservatively predict system maximal effective acceleration. They have also been confronted to experimental tests.

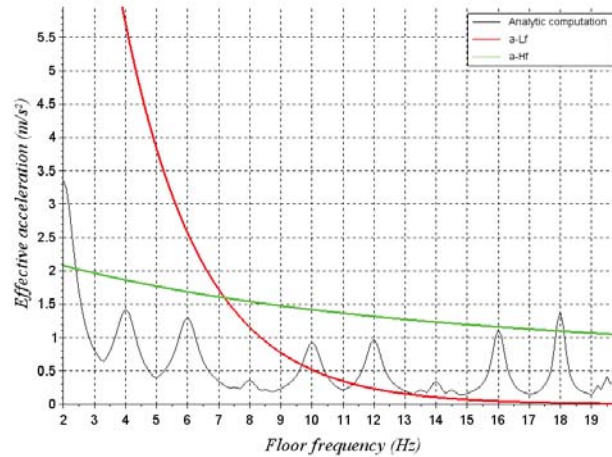


Figure 9: Comparison between accelerations predicted by equations 12 and 17 and the maximal effective acceleration of a spring-dashpot systems with different resonance frequencies subjected to a sequel of ten footsteps with $f_{step} = 2Hz$



Figure 10: Test floors : Joist-OSB floor (left) and CLT floor (right)

4 Experimental and numerical analysis

4.1 Presentation of the experiments

Two floors have been designed and tested, a squared joist-OSB floor and a squared CLT floor of 4.5 metres in length (figure 10). They have been nailed to a piece of wood to ensure a simply supported condition at two of their extremities in order to be in a (SS-F-SS-F) configuration.

Experimental modal analysis have been done on test floors. With a grid of accelerometers and a CMIF (complex mode indicator function), the mode shapes and the mode frequencies have been identified. The most important modes have been discriminated by using an AutoMAC [19]. The two floors are high frequency floors with a resonance frequency of 17.5Hz for the joist-OSB floor and 13.8Hz for the CLT floor.

Walking experiments have been done on each of the test floors. Around 30 persons have walked along the center span of the floors with several accelerometers located on the displacements peaks of the first five modes (figure 11).

The weights, the average step frequencies and the kind of shoes of each person participating to the experiments have been recorded. The floor maximal effective acceleration during the test



Figure 11: People walking on instrumented test floor

has been computed with the method recommended by ISO 2631-1 norm [20] for a transient solicitation:

$$a_{RMS}(t_0) = \sqrt{\frac{1}{T} \int_{t_0-T}^{t_0} a(t)^2 dt} \quad (18)$$

The effective acceleration is computed for short windows of width $T = 1s$.

4.2 Numerical model

A numerical model using shell or cubic finite elements has been created for each test floors in order to understand phenomena occurring during the walk and to make a sensitivity analysis. The measured parameters (Young's modulus and density) of each joist have been considered. Its accuracy has been estimated by confronting numerical modal analysis and experimental modal analysis. An example is given on figure 12.

The numerical model and the experimental results have a very good correlation on a MAC analysis for the first six modes. Dynamical computations are realized using a footsteps load along the center of the floors span. The system is reduced on the first 30 modes to reduce computation times and then solved with an explicit integration scheme. The HIVOSS footstep load (equation 10) is used with randomly generated mass and frequency chosen through a representative distribution law. The maximal effective acceleration is computed just as the experimental tests, with the equation 18.

4.3 Campaign results and interpretation

The effective acceleration identified experimentally and computed numerically can be plotted according to different factors. The most relevant ones seem to be the weight of the walkers and their walking frequencies (figure 13 and 14).

Results are similar for CLT floor. The numerical and the experimental results have the same order of magnitude (figures 13 and 14). Numerical results are broadly superior to experimental

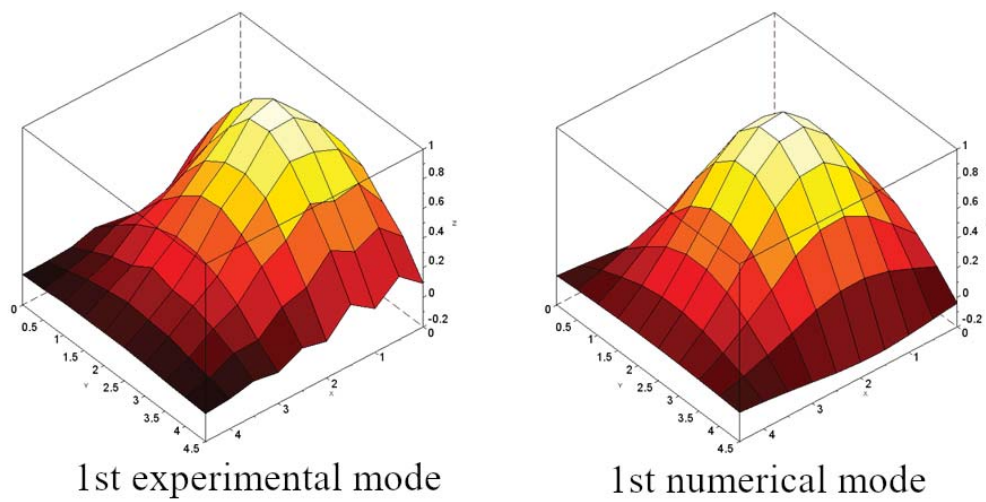


Figure 12: First mode computed numerically and identified experimentally for the joist-OSB floor

ones. It can be explained by the fact that, in the numerical model, the footsteps are very regular with a constant walking frequency whereas during experimental test, the walking frequency varied slightly which induced a lower impact of the harmonics of walking frequency. With the numerical model, the effective acceleration increases with the weight of the walker (figure 13). The uncertainties are greater experimentally and it is difficult to extract a tendency. The same observation can be made by confronting the effective acceleration with the walking frequency (figure 14).

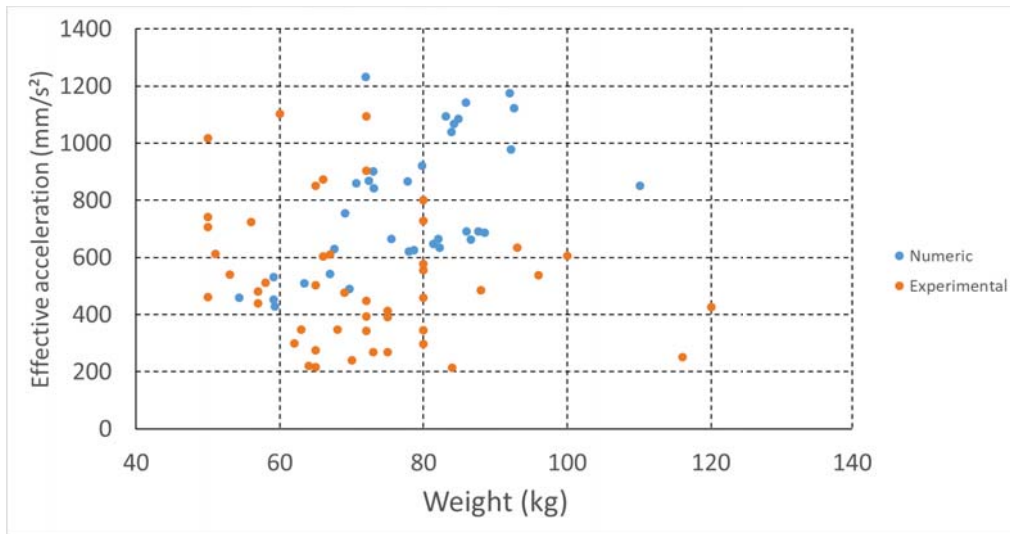


Figure 13: Maximal effective acceleration depending on the weights of the walkers on the joist-OSB floor

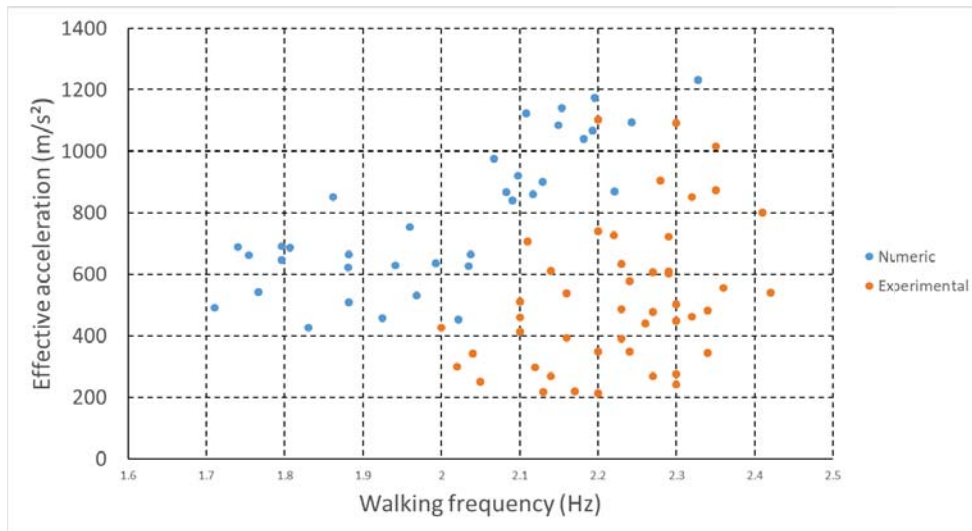


Figure 14: Maximal effective acceleration depending on the walking frequency of the walkers on the joist-OSB floor

4.4 Confrontation to simplified computation

The equation 17 enables a conservative estimation of the acceleration due to the walk of an individual. This formula has been confronted to experimental results. Figure 15 gives an example of results for a 80kg person walking on the joist-OSB floor.

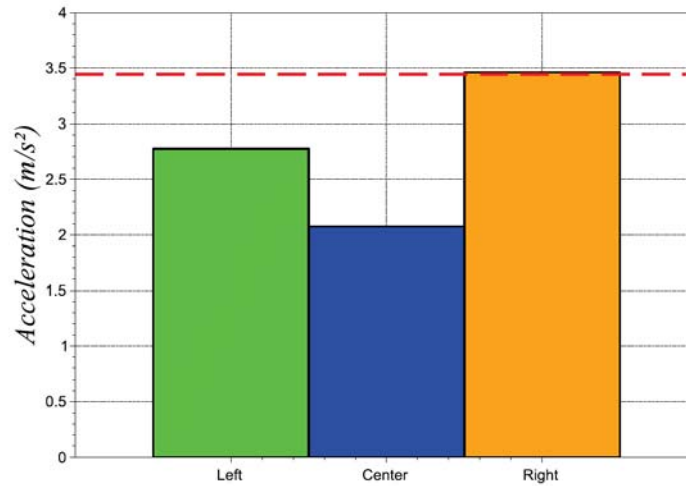


Figure 15: Maximal acceleration measured during the walk by 3 accelerometers on each side of the floor. The dashed line in red corresponds to the maximal acceleration predicted by the formula 17

Note that in this figure, the peak of acceleration is considered, so the coefficient V_{eff} of the equation 17 has not been used. This equation gives an accurate value of the acceleration peak, without overestimating it. Based on all the experiments, a margin coefficient has been created, which links the effective acceleration predicted by the formula 17 with the effective acceleration measured experimentally. Results are given in the form of a boxplot on figure 16.

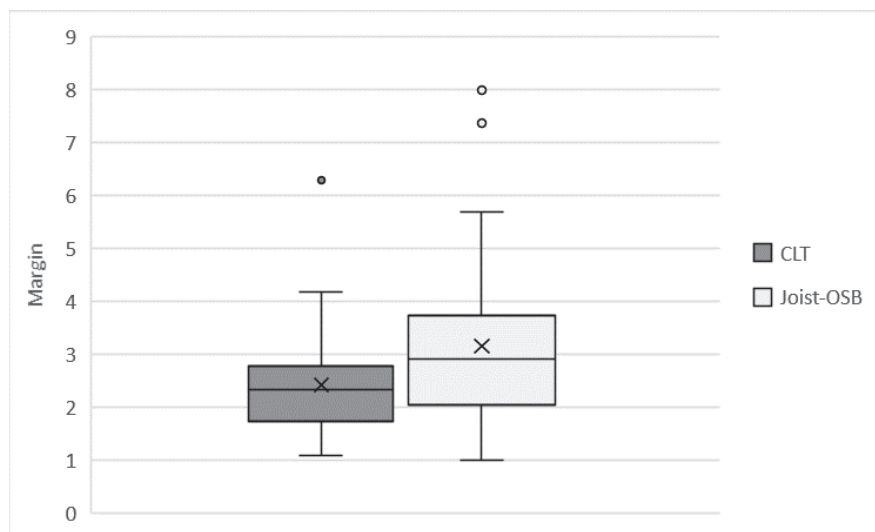


Figure 16: Boxplot of the margin coefficients between simplified formulation and experimental results

The results remain always conservative : the margin coefficient is always superior or very close to 1. On average, the simplified formulation overestimates the floor response, probably because the theory used to build this formula considers an homogeneous floor and a constant walking frequency. By the way, the average coefficient is higher for a joist-OSB floor than for a CLT floor. The joist-OSB floor is very heterogeneous, the joists have different densities and stiffnesses. Moreover, the connections can dissipate some energy. It explains why the joist-OSB floor has a better behavior regarding vibration than the one predicted with the theory.

5 Conclusion

This article presents a new simplified method to compute resonance frequency for a timber floor and its acceleration during walking of an individual. This method is based under theoretical assumptions and numerical computations. The simplified method has been confronted to experimental results on two kind of floors and gives conservative results with a moderate over-estimation. This method has to be applied for in situ floors in order to validate its relevance.

Thereafter, the influence of a group of persons on the floor vibrations will be studied, depending on their activities. Then several ways to mitigate floor vibrations, with construction method adjustment or passive system should be conceived. However, one of the most important step is to define criteria to assess the comfort level of timber floors depending on the physical values of the vibration.

6 Acknowledgements

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