ACOUSTIC SIMULATION OF TIMBER FLOORS PERFORMANCE USING NUMERICAL MODELS

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At present, no consolidated methods for the simulation of the acoustic performance of timber floors, such as cross laminated timber or glulam assemblies, are available. Simulations using combined Finite Element Analysis (FEA) with Statistical Energy Analysis (SEA) have been made, predicting the transmission loss with satisfactory accuracy. However, impact sound insulation could not be computed with the same degree of accuracy. The determination of the material’s input data of such inhomogeneous, layered and non-isotropic media still remains a significant issue. The Transfer Matrix Method (TMM) is a widely-applicable powerful tool to model wave propagation through laterally infinite media of different nature, including isotropic or orthotropic, elastic, viscoelastic, poroelastic solids and fluids. This study investigates the applicability of a homogenisation approach developed within the TMM framework, already used to evaluate the sound insulation of massive building walls, to compute the acoustic performance of cross laminated timber (CLT) floors. In order to validate the proposed model, a comparison was carried out between numerical and experimental results.

**Keywords:** impact sound insulation, timber floors, homogenisation approach, TMM

1. **Introduction**

Classical prediction approaches used in building acoustics can be easily applied to homogeneous monolithic structures but are hardly applicable to layered, inhomogeneous and anisotropic systems. Moreover, it is generally more difficult to predict the sound insulation performance of lightweight timber building partitions than to evaluate the acoustic performance of traditional massive structures. Combined
Finite Element (FE) and Statistical Energy Analysis (SEA) methods have been specifically developed for timber assemblies, showing promising results to predict sound transmission loss and impact sound insulation [2, 3]. The transfer matrix method (TMM) represents an alternative powerful tool to investigate wave propagation and sound transmission through different media [4]. This method, widely used especially in automotive and aerospace acoustic design, has also been successfully applied to investigate the transmission loss of building partitions [5, 6], since their layered structure can be easily modelled using the TMM approach. However, it is not straightforward to determine the elastic properties of timber partitions such as cross laminated timber (CLT) or glulam panels. These kinds of structures are nowadays widely used both as inner or façade walls and as floors. However, as shown by recent studies, their sound insulation performance needs to be improved by using linings and properly designed acoustic treatments [7, 8, 9, 10]. Due to their peculiar layered substructure, CLT panels may exhibit an orthotropic behaviour. In order to evaluate their dynamic response, CLT panels can be modelled either as an orthotropic elastic solid or according to a multi-layer shell model [11]. Moreover, the vibro-acoustic response of CLT panels can be accurately computed by means of a simplified model based on orthotropic thin plate assumptions [12, 13], even though frequency-dependent elastic properties are required in order to take into account the influence of rotatory inertia and shear deformation, at high frequencies. In this study, a homogenisation approach has been used in order to overcome the difficulties related to the determination of all the independent elastic constants characterising non-isotropic media. The bare CLT panel is modelled as an equivalent homogeneous isotropic medium, with the same density and thickness of the considered partition, characterised by frequency-dependent apparent elastic properties, which are determined from the experimental sound insulation of the bare structure, by using a minimisation algorithm based on the TMM framework.

After a brief review of the TMM, the minimisation algorithm, used to evaluate the apparent frequency-dependent elastic properties characterising an equivalent homogeneous medium, is described in section [3]. The proposed homogenisation approach, which is based on the minimisation between the experimental sound insulation of the wall and the transmission loss numerically computed, has been already applied in previous studies to masonry brick walls showing promising results [6]. The aim of this paper is to investigate its applicability to CLT structures, evaluating both the airborne sound insulation provided by different CLT panels, as described in section 4.1, and the impact noise level, outlined in section 4.2. The reliability of the proposed approach is finally evaluated by comparing numerical results with experimental data in section [5].

2. Transfer Matrix Method

In the TMM framework the investigated structure, assumed to be laterally of infinite extent, separates two semi-infinite fluids. The acoustic field variables on the surface \( S_1 \) are related to the variables describing the acoustic field on the opposite surface \( S_2 \) according to the general formalism:

\[
V(S_1) = [T] V(S_2)
\]  

(1)

The vector \( V(S_1) \) represents all the variables needed to define the acoustic field on the surface on the emission side, while the vector \( V(S_2) \) represents all the field variables associated to the interface surfaces between the different layers. The transfer matrix \([T]\) describes the wave propagation through the multilayer structure. The size of this matrix depends on the nature of each layer, such as solid, fluid, or poroelastic [4]. Considering an acoustic wave impinging on the surface \( S_1 \) with a heading angle \( \theta \), the system given in Eq. (1) can be solved, for each given angular frequency \( \omega \), in order to compute the sound transmission coefficient \( \tau(\omega, \theta) \). The sound transmission loss (TL) for a diffuse acoustic field (DAF) can
be computed by integration over the wave heading angle $\theta$ as:

$$TL(\omega) = -10 \log \int_{0}^{\pi/2} \tau(\omega, \theta) \cos \theta \sin \theta \, d\theta$$

(2)

Several extensions of the TMM framework have been published by different authors. It is possible for example, to increase the accuracy of the method at the low frequencies, by computing a geometrical radiation efficiency in order to take into account the finite dimension of the investigated structure [14, 15]. Besides, a correction term can be included in the computation to take into account the contribution of the structure-borne sound transmission through the mechanical connections between different layers [5, 6], which causes a reduction of sound insulation at high frequencies. Moreover, the TMM approach can be used to evaluate the vibro-acoustic response of the structure under various types of excitation, such as turbulent boundary layer, monopole acoustic source and mechanical point forces [16, 17, 18]. This latter type of excitation is of particular interest to evaluate the noise impact levels generated by a tapping machine acting on a building floor structure. However, the exciting force exerted by the tapping machine should be accurately determined according to the investigated structure, as discussed in section 4.2.

3. Equivalent homogeneous medium

Even though CLT panels have become a valuable alternative to traditional construction materials, these elements do not provide an adequate acoustic performance, as it is well documented in the literature [19, 20]. Due to their layered sub-structure and the elastic characteristics of the wood material, CLT plates generally exhibit an orthotropic behaviour [21], which means that they have different elastic properties along mutually perpendicular directions. The elastic properties associated to the principal directions can be experimentally determined by means of wave propagation analysis [22], or by using wave correlation-based experimental methods [23, 24, 25]. However, in this study, the CLT panel was modelled as an equivalent homogeneous isotropic elastic medium, rather than an orthotropic thin plate. In order to estimate the apparent frequency-dependent elastic properties of the equivalent homogeneous layer, a numerical method has been developed within the TMM framework, based on the experimental transmission loss. The geometric properties of the bare building partition, such as its density $\rho$, its thickness $h$ and its dimensions $L_x$ and $L_y$, are used together with the measured TL as input data, while the elastic properties of the equivalent homogeneous layer represent the variables of the algorithm. A non-linear optimization algorithm evaluates the sum square of the differences between the experimental TL and the results of the TMM model, computed by varying the elastic properties within a given range. The algorithm gradually converges towards a minimum providing as result the values of $E$ and $\eta$ of the equivalent homogeneous layer, for each frequency band.

4. Investigated CLT structures

4.1 Airborne sound insulation

A TMM model was implemented in order to investigate a CLT building wall lined with plasterboard. The experimental sound insulation spectrum of the bare structure was used in order to determine the apparent elastic properties of the CLT panel as described in the previous section. The partition – 3.6 m wide and 2.4 m high – is constituted of a 3-ply CLT panel 78 mm thick, with a density of approximately 540 kg/m$^3$. The experimental sound insulation of this partition was taken from a technical report of an extensive investigation regarding the acoustic performance of CLT assemblies conducted by the National Research Council of Canada [26]. The experimental results of several measured structures, both involving
bare CLT panels and lined CLT partitions, were provided, in terms of the TL of the bare structure and the improvement provided by the lining $\Delta TL$. The considered 3-ply CLT panel was lined with a double layer of fire-rated plasterboard, screwed into the wood. Each layer of plasterboard was nominally 12.7 mm thick and with a density of 750 kg/m$^3$. The plasterboard wall was modelled in the TMM code as a solid elastic layer with elastic modulus $E = 1.2\,\text{GPa}$, loss factor $\eta = 0.06$ and Poisson ratio $\nu = 0.3$. The structure-borne sound transmission through the mechanical connection between the plasterboard and the CLT panel was also taken into account, using a well established decoupled approach [6]. Moreover, a thin air-gap was introduced between these two materials, in order to take into account the roughness of the CLT surface, as discussed in NRC Research Report RR-335 [26].

4.2 Impact noise levels

The same homogenisation approach described in section [3] was also applied to a 5-ply CLT floor structure 140 mm thick, with a density of approximately 450 kg/m$^3$, with the aim of investigating the possibility to use apparent elastic properties to also compute the impact noise level, generated by a standard tapping machine. It was necessary to determine the impact force exerted by the hammers on the CLT structure. This was derived by Cremer and Heckl for homogeneous structures with high impedance [27], for which a perfect rebound of the hammer can be assumed. However, such assumption is not suitable for lightweight timber structures; it is of fundamental importance in fact, to consider the interaction between the hammers of the tapping machine and the timber floor. In general, with this kind of structures, a bell-shaped spectrum of the applied force is observed [3], with a significant reduction of the high frequency components, compared to high impedance elements, such as a concrete slab. The force spectrum generated by the tapping machine was computed by following a simplified formulation of the approach developed by Brunskog [28]. More accurate results could be found from direct measurements of either the exerted force, or the input mobility of the CLT plate. However, the obtained normalised impact force spectrum, given in one-third octave bands in Figure 1a), is consistent with experimental results obtained from a direct measurement of the impact force of a tapping machine hammer acting on a CLT surface [29], especially in the mid-high frequency range.

![Normalized impact force spectrum](image)

**Figure 1:** Normalised impact force spectrum generated by a standard tapping machine: (a) acting on the 5-ply CLT bare floor; (b) acting on a reference concrete slab.
5. Results

In this section the reliability of the proposed homogenisation approach is investigated by comparing the TL computed by using the TMM with the experimental sound insulation of the considered wall. Figure 2a shows the numerical and experimental transmission loss provided by the bare 3-ply CLT panel. The first coincidence and the critical condition, characterising the typical orthotropic behaviour of a CLT plate, fall within the 400 Hz and the 800 Hz third octave bands respectively. The equivalent isotropic model implemented with frequency-dependent elastic properties was proven to be suitable to predict this particular behaviour. As shown in Figure 2b such characterisation also made it possible to predict with good accuracy the TL provided by the CLT panel lined with a double layer of fire-rated plasterboard. The critical frequency of the the plasterboard layer is clearly identified between the 2000 Hz and 2500 Hz frequency bands. The assumption of perfectly rigid structural bridges is suitable to accurately describe the reduction of sound insulation at high frequencies, due to the structure-borne sound transmission via the mechanical fastenings.

Figure 2: Comparison between the computed transmission loss ($TL_{TMM}$) and the experimental sound insulation of the building wall ($TL_{exp}$): (a) bare 3-ply CLT partition; (b) 3-ply CLT panel lined with fire-rated plasterboard.

The same homogenisation approach was used to evaluate the apparent elastic properties of the 5-ply CLT floor. In Figure 3a the experimental sound insulation is compared to the transmission loss computed by means of the TMM model, considering the partition as an equivalent homogeneous layer. The frequency-dependent elastic properties, obtained from the experimental transmission loss, were also used in order to investigate the vibroacoustic response of the bare homogeneous layer excited by a mechanical force, representing the standard tapping machine. The computed impact noise level is compared with the experimental results in Figure 3b. Even though several approximations were made, especially regarding the determination of the exciting force, a satisfying agreement was found. The computed results are also consistent with the empirical reference curve proposed for the normalised noise impact level by Di Bella et al. [30, reported in Figure 3b] as $L_{n,ref}$, as well as with those proposed by other authors [10,31].
Figure 3: Comparison between numerical (subscript TMM) and experimental (subscript exp) acoustic performance of the 5-ply CLT bare floor: a) TL, sound transmission loss of the 5-ply bare CLT floor; b) $L_n$, noise impact level generated by the standard tapping machine on the 5-ply bare CLT floor.

6. Conclusion

In this paper, the TMM approach has been applied to compute the acoustic performance of a CLT building partition. A homogenisation approach has been proposed in order to evaluate apparent elastic properties, to describe CLT panels as equivalent homogeneous isotropic media. This is based on a minimisation algorithm of the sound insulation of the bare structure, implemented within the TMM framework. By using the experimental TL of the investigated structure, the minimisation algorithm computes a set of frequency-dependent elastic properties characterising the equivalent homogeneous isotropic medium. The reliability of this approach has been investigated by computing the TL of a CLT wall panel, characterised as an equivalent homogeneous elastic solid, lined with a double layer of fire-rated plasterboard. The comparison between the computed TL and the experimental sound insulation showed a good agreement. Moreover, the same approach was applied to determine the apparent elastic properties of a 5-ply CLT floor. The vibroacoustic response of the bare CLT floor was computed by means of a TMM code, in order to evaluate the impact noise level generated by a standard tapping machine. Even though an approximate approach was used to determine the exerted force spectrum, a satisfying agreement was found between numerical and experimental data. Further investigation and validation are required in order to accurately describe the interaction between the standard tapping machine and the CLT floor panel.

References


