Challenges for acoustic calculation models in "Silent Timber Build", Part 2

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ABSTRACT

The project "Silent Timber Build" will develop new prediction tools for timber structures. There are several challenges that have to be overcome to provide a full prediction tool. The differences in weight, stiffness and density for wooden structures compared to traditional, heavy and more homogeneous structural material have repercussions on how the sound propagates throughout the structures, affecting the sound and vibration insulation performance and also theories to be used in prediction models. The project will use Finite element simulations (FEM) and Statistical Energy Analysis (SEA) approaches to predict acoustical behavior of light weight timber constructions. This article, following another article Part 1, will focus on medium and high frequency range calculations. Statistical methods will be used in the medium and high frequency, where the acoustic performance of wooden building components (walls and floors) is generally limited by the presence of structural links and couplings. Statistical Energy Analysis (SEA) has proven to be an efficient approach, providing robust vibroacoustic models in this frequency region. The extension of statistical methods towards the low frequencies has to be evaluated, especially regarding time responses of impact noise on floor systems. For full-scale building, Virtual SEA method will be used as well as analytic SEA approach in frequencies low enough in order to optimize the overlap to FEM.

Keywords: Sound, Insulation, Transmission, modeling, FEM, SEA, VSEA

I-INCE Classification of Subjects Numbers: 51.3; 51.4

1. INTRODUCTION

The costly process of using test buildings is common, even though the obtained measurement results are not directly applicable to buildings of slight different construction1. Prediction models, despite their highly usefulness for designing new buildings and preventing severe and costly changes in the aftermath of construction, are still very much lacking today. The conjunction of several methods, namely the Finite Element Method (FEM) and Statistical Energy Analysis (SEA) for developing efficient and robust predictive tools over the whole frequency range of interest is of crucial importance if time and costs are to be saved. The latter will be one of the main aims of the aforementioned "Silent Timber Build" project.

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2. SEA for high frequencies

SEA method estimates the level of vibratory energy stored in local modes of the various weakly coupled subsystems, i.e. subdomains separated from each other by significantly reflective boundaries. The modelling starts then by partitioning the system into subsystems characterized by the type of waves expected to propagate within the related subdomains. Mechanical plates and shells subsystems incorporate flexural, extensional and shear wave energies, assumed to be uncorrelated variables within the subdomain. Acoustic cavities only incorporate extensional wave energy.

Energy is estimated in each subsystem in a frequency band B (ω_B being its central frequency) and the key variable is the subsystem modal energy e_n calculated by dividing total energy E in B by the number of subsystem modes N in band B (i.e. $e_n = E/N$) and total energy is related to mean subsystem squared velocity by next relationship $E = m\langle \bar{V}^2 \rangle$ where m is the mass of the subsystem.

As shown in [1], the energy equilibrium of the system is dependent on e_n as the power flow between two subsystems is proportional to difference in their modal energies. For a subsystem carrying modal energy e_i and coupled to a set of subsystems carrying modal energy e_j, this equilibrium is described by the following power-balanced equations which state the injected power by external forces applied to m-subsystem is equal to injected power in m + transferred power to the n-coupled subsystems.

$$\frac{P_{in}^{i}}{\omega_B} = \eta_i N_i e_i + \sum_{\text{j/ j coupled to i}} \left[\eta_{ij} N_i e_i - \eta_{ji} N_j e_j \right]$$

η_{ij}, η_{ji} are the Coupling Loss Factors (CLF) and η_i the Damping Loss Factor (DLF).

When packed into matrix, the power-balanced equations are simply written $\boldsymbol{P}/\boldsymbol{\omega}_{\mathbf{B}} = \mathbf{L} \cdot \mathbf{N} \cdot \mathbf{e}_{\mathbf{N}}$ where $\mathbf{L}$ is the loss factor matrix and $\mathbf{N} \cdot \mathbf{e}_{\mathbf{N}}$ the total energy vector per subsystem. CLF are reciprocal and reciprocity states that $\eta_{ij} N_i = \eta_{ji} N_i$. SEA power-balanced equations are applicable to all dynamical systems excited by random forces and the loss matrix is becoming a valid representation of the power exchange when all subsystems exhibit local modes resonating within B.

Because SEA is an inductive theory, [2], there is currently no formal way to mathematically derive the CLF for the K, M stiffness and mass matrices respectively of FE models, except in some simple academic cases. It is why CLF and modal densities are generally predicted from analytical wave theory by assuming modes can be considered as interfering uncorrelated waves. Alternately inverse methods may be applied to identify the Loss matrix. Related measurement technique is called Experimental SEA (ESEA). Squared transfer velocity is recorded over the whole system under power calibrated excitation source, source being applied at a turn at each of the subsystems [3, 10]. An experimental velocity matrix can thus be built from which SEA parameters such as DLF, CLF and mass can be identified (in a similar way than virtual SEA described in next chapter which works on calculated velocity matrix synthesized from FE modes).

SEA is coupled to transfer matrix approach for analysing sound transmission of acoustic sound "packages" strongly coupled to supporting plates. It is thus providing useful method for the noise radiation prediction of large timber-framed structures as well as structure borne sound vibration as shown in [4, 6, 10].

3. FEM/SEA for medium frequencies

3.1 Managing FE models in the MF range

When frequency increases, as seen previously, taking into account all available modes would require too large FE models to be tractable by current computers. It would also be a useless action as the local modes are very sensitive to structural imperfections. Their intimate behaviour description needs then to take into account by statistical methods. When structural defaults are incorporated in the model at the FE scale, the resulting FE model is made stochastic.

Stochastic FE modelling is an extensive domain of research, leading to search for reduced models [11, 12] for limiting CPU from supercomputer and obtaining decent resolution time and robust dedicated statistics about analysed systems and underlying materials, all features not really available for timber frame buildings. More affordable alternate modelling techniques have to be addressed for building acoustics.

3.2 Virtual SEA (VSEA) analysis for creating SEA model from FE

The Virtual SEA technique [7, 8, 9] is addressing the MF problem by describing the system state by its vibratory energy, integrated over frequency bands (1/Nth octave band or constant bandwidth) and geometrical subdomains in a similar way to SEA. The system has then to be split into subsystems associated to each subdomains and a relationship between subsystem energies is provided by the energy conservation law.

In VSEA method, the energy-based coefficients, coupling the various subsystems, are calculated from a FE related model. The FE mesh is refined enough to extract high-order eigenvalues $\boldsymbol{\omega}$ in the mid-frequency range as well as mode shapes X from FE mass and stiffness FE matrices following:

$$\left[\mathbf{KX} - \mathbf{M}\boldsymbol{\omega}^2\right]\mathbf{X} = \mathbf{0} \tag{3.1}$$

Extracted eigenvalues and mode shapes constitute a projection basis for computing an approximation of the diffuse vibratory state of the system, assumed to be a representative asymptotic behaviour when damping is low.

This vibratory state is estimated over a discrete set of reference FE nodes which map the system. To simulate a diffusion state, the responses at reference nodes are computed from rain-on-the-roof excitation. In practice, a unit point force $\boldsymbol{\delta}(\mathbf{x}_e)$ is applied at a turn to each of the reference nodes in the successive directions x, y, z of the global axis and the responses are calculated for each individual load case at a particular node for all reference nodes. The individual unit nodal load gives a generalized force expressed as:

$$\mathbf{F}_i = \int_{\mathbf{D}} \boldsymbol{\delta}(\mathbf{x}_e)\mathbf{X}_i(\mathbf{x})\mathbf{dx} = \mathbf{X}_i(\mathbf{x}_e) \tag{3.2}$$

For each excited node, velocity response is synthesized in the frequency domain from eigenvalues and modeshapes following:

$$\dot{\mathbf{u}}_{er} = j\omega\sum_{\mathbf{i}}\mathbf{q}(\eta,\boldsymbol{\omega},\boldsymbol{\omega}_i)\mathbf{X}_i(\mathbf{x}_r)\mathbf{X}_i(\mathbf{x}_e) \tag{3.3}$$

with e and r denoting respectively the excitation and the response node, η being the modal DLF, with same value for all modes in a B and q the complex modal amplitude.

At each response node, the synthesized frequency response vector is related to the force vector through the 3x3 FRF complex tensor $\overline{\overline{\dot{\mathbf{H}}_{\mathbf{re}}}}$ reduced to the translational degrees of freedom. Due to our particular nodal excitation, it comes

$$\dot{\mathbf{u}}_{re} = \overline{\overline{\dot{\mathbf{H}}}}_{re}\mathbf{F}_e = \overline{\overline{\dot{\mathbf{H}}}}_{re}\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{bmatrix} = \overline{\overline{\dot{\mathbf{H}}}}_{re} \tag{3.4}$$

$\left|\dot{\mathbf{u}}_{re}\right|^2$ and $\mathrm{Re}\{\dot{\mathbf{u}}_{ee}\}$ are then frequency band-averaged following:

$$\overline{\left|\dot{\mathbf{u}}_{re}\right|^2} = \frac{1}{B}\int_B \left|\overline{\overline{\dot{\mathbf{H}}_{re}(\omega)}}\right|^2 d\omega \qquad \overline{\mathrm{Re}\{\dot{\mathbf{u}}_{ee}\}} = \frac{1}{B}\int_B \mathrm{Re}\left\{\overline{\overline{\dot{\mathbf{H}}_{ee}(\omega)}}\right\} d\omega \tag{3.5}$$

$\overline{\mathrm{Re}\{\dot{\mathbf{u}}_{ee}\}} = Y_e$ is the real part of input mobility tensor at reference node. This tensor has three eigenvalues. The largest corresponds for plate-like systems to the power injected in the flexural waves of the system and its normalized eigenshape $\mathbf{n}_e$gives the direction of related applied force.

The most probable orientation of the nodal velocity vector is then given by $\mathbf{n}_e$ and a scalar squared velocity can be associated to each node by $V_{er}^2 = \overline{|\dot{\mathbf{u}}_{re}|^2} \cdot \mathbf{n}_e$.

In each band B, the velocity field is then reduced to a square scalar matrix of size NxN (number of reference nodes) and of which each term represents the projected mean squared transfer velocity between two nodes, the mean being performed over B.

Now, the reference nodes have to be grouped together into consistent subdomains to calculate the transfer energies between them. The mean squared transfer velocity over a subdomain D_m including M nodes and excited at a particular node *e* is computed as follows:

$$\left\langle V_{re}^2 \right\rangle_{r\in D_m} = \frac{1}{M}\sum_m \frac{V_{me}^2}{4Y_r Y_e} \tag{3.6}$$

The division by $4Y_rY_e$ is reducing the spatial standard deviation of $\langle V_{De}^2 \rangle$ leading to minimize the effect of sampling point distribution on this reduced transfer velocity matrix and also to maximize the contrast between the various potential subdomains.

The B-partition into subdomains of $\langle V_{De}^2 \rangle$ is performed automatically using the dedicated Peripheral Attraction algorithm which moves iteratively the most attracted node of D_m subdomain by another $D_{m'}$ subdomain to this latter one, based on the attraction force generated by $D_{m'}$ over nodes of D_m. The attraction force is taken proportional to $\frac{1}{M'}\sum_{m'} \left\langle V_{rm'}^2 \right\rangle_{m'\in D_{m'}, r\in D_m}$.

At the end of the iterative process, nodes are grouped into subdomains in which all nodes are strongly internally connected and respecting SEA weak coupling between subdomains.

The VSEA velocity matrix describing the system is at the end given by a scalar rectangular matrix $\langle V_{De}^2 \rangle$ of size $M_e \times N_D$ where M_e is the total number of references, and N_D the number of identified subdomains. Each term of this matrix represents the B-averaged mean squared velocity of nodes which are part of same group D_m when a particular reference node e is excited. The initial FE-synthesized narrow band $\overline{\overline{\dot{\mathbf{H}}_{re}(\omega)}}$ has thus been compressed over both frequency and space (over subdomains) but preserving original excited nodes.

Because $\langle V_{De}^2 \rangle$ has the dimension of a modal energy, the transfer energy of a subdomain is equal to $E_{De} = n_D \langle V_{De}^2 \rangle$ where n_D is the modal density of the subdomain. To identify all n_D and all SEA CLF

$\eta_{D'D}$, between subdomains, the energy conservation principle is applied to the system and because each reference is excited separately, a set of M_e equations can be written in each band B such as $\sum_D \eta n_D \left\langle V_{De}^2 \right\rangle = \frac{1}{\omega_B}$.

The n_D solution vector represents the modal density of local modes related to subdomain D.

As the linear problem to solve is over-determined, n_D is obtained by Singular Value Decomposition (SVD) of matrix $\langle V_{De}^2 \rangle$. Same kind of resolution is applied to CLF between subdomains from following set of equations which applies to one subsystem D and the directly connected subsystems D':

$$[\eta_{D'D}]_{D' \in \{\alpha, N_D\}, D' \neq D} = \frac{-1}{\omega_B \left\langle V_{DD}^2 \right\rangle} \begin{bmatrix} \frac{\left\langle V_{\alpha D}^2 \right\rangle}{\left\langle V_{DD}^2 \right\rangle} - \frac{\left\langle V_{\alpha\alpha}^2 \right\rangle}{\left\langle V_{\alpha D}^2 \right\rangle} & \cdots & \frac{\left\langle V_{N_D D}^2 \right\rangle}{\left\langle V_{DD}^2 \right\rangle} - \frac{\left\langle V_{N_D \alpha}^2 \right\rangle}{\left\langle V_{D\alpha}^2 \right\rangle} \\ \cdots & \frac{\left\langle V_{\beta D}^2 \right\rangle}{\left\langle V_{DD}^2 \right\rangle} - \frac{\left\langle V_{\beta k}^2 \right\rangle}{\left\langle V_{D\beta}^2 \right\rangle} & \cdots \\ \frac{\left\langle V_{\alpha D}^2 \right\rangle}{\left\langle V_{DD}^2 \right\rangle} - \frac{\left\langle V_{\alpha N_D}^2 \right\rangle}{\left\langle V_{DN_D}^2 \right\rangle} & \cdots & \frac{\left\langle V_{N_D D}^2 \right\rangle}{\left\langle V_{DD}^2 \right\rangle} - \frac{\left\langle V_{N_D N_D}^2 \right\rangle}{\left\langle V_{DN_D}^2 \right\rangle} \end{bmatrix}^{-1} \quad (3.7)$$

All field descriptors $\langle V_{De}^2 \rangle$ being obtained by averaging nodal responses there are entailed with variance. This variance is estimated during the compression of FRF spectra and a Monte Carlo solution can be applied to problems (3.6) and (3.7).

The computational steps (3.2) to (3.7) are automated in SEA+ software starting by reading the list of eigenfrequencies and modal amplitudes at selected reference nodes delivered by NASTRAN or ABAQUS software from the original FE model. Detection of subdomains is performed in each band B to optimize the conditioning of $\langle V_{De}^2 \rangle$ in order to provide robust in-line solve of problems (3.6) and (3.7).

Because in each band B, there are several subsystem decompositions which may provide invertible SEA parameter solutions, depending on tolerated mean velocity gap between two subdomains and internal dispersion of velocity inside each of them, all potential solutions are checked by reconstructing initial $\langle \boldsymbol{V}_{\boldsymbol{De}}^2 \rangle$ transfers from the identified SEA loss matrix L and by then comparing reconstructed $\langle \boldsymbol{V}_{\boldsymbol{De}}^2 \rangle$ to directly compressed-from FE $\langle \boldsymbol{V}_{\boldsymbol{De}}^2 \rangle$matrix.

The reconstructed matrix is expressed as $\langle \tilde{\mathbf{V}}_{\mathbf{De}}^2 \rangle = \frac{1}{\omega_B} \mathbf{L}^{-1} \mathbf{I}$. The difference between $\langle \boldsymbol{V}_{\boldsymbol{De}}^2 \rangle$ and $\langle \tilde{\mathbf{V}}_{\mathbf{De}}^2 \rangle$is defined by the Euclidian's distance between them: $\tilde{d}_e = \sqrt{\sum_i \sum_i \left(\tilde{e}_{ij} - e_{ij}\right)^2}$ (averaged term-to-term distance). The partition providing minimum Euclidian distance is retained and its related subdomains are thus becoming SEA subsystems.

Virtual SEA appears as a specific class of stochastic modelling as it transforms a deterministic FE model into a parametric SEA model. The stochastic property of the resulting velocity matrix describing dynamical state is due to both subdomain and frequency band averaging processes: final model is respecting the local modal density of initial model but resonance frequencies are becoming equiprobable over B.

Example of application for building acoustics is shown in Figure 1 (top) where a complex cross-junction between a ribbed multi-layered floor and multi-layered wall is modelled by FE using Nastran software. 8000 eigenmodes are extracted up to 1500 Hz from the FE model. Figure 1 (bottom) is sketching the virtual SEA post-processing leading to 8 SEA subsystems cross-coupled together, providing the CLF (direct and indirect) between all subsystems and their modal densities and allowing transfer path analysis through the power flow computation as shown in Figure 2.

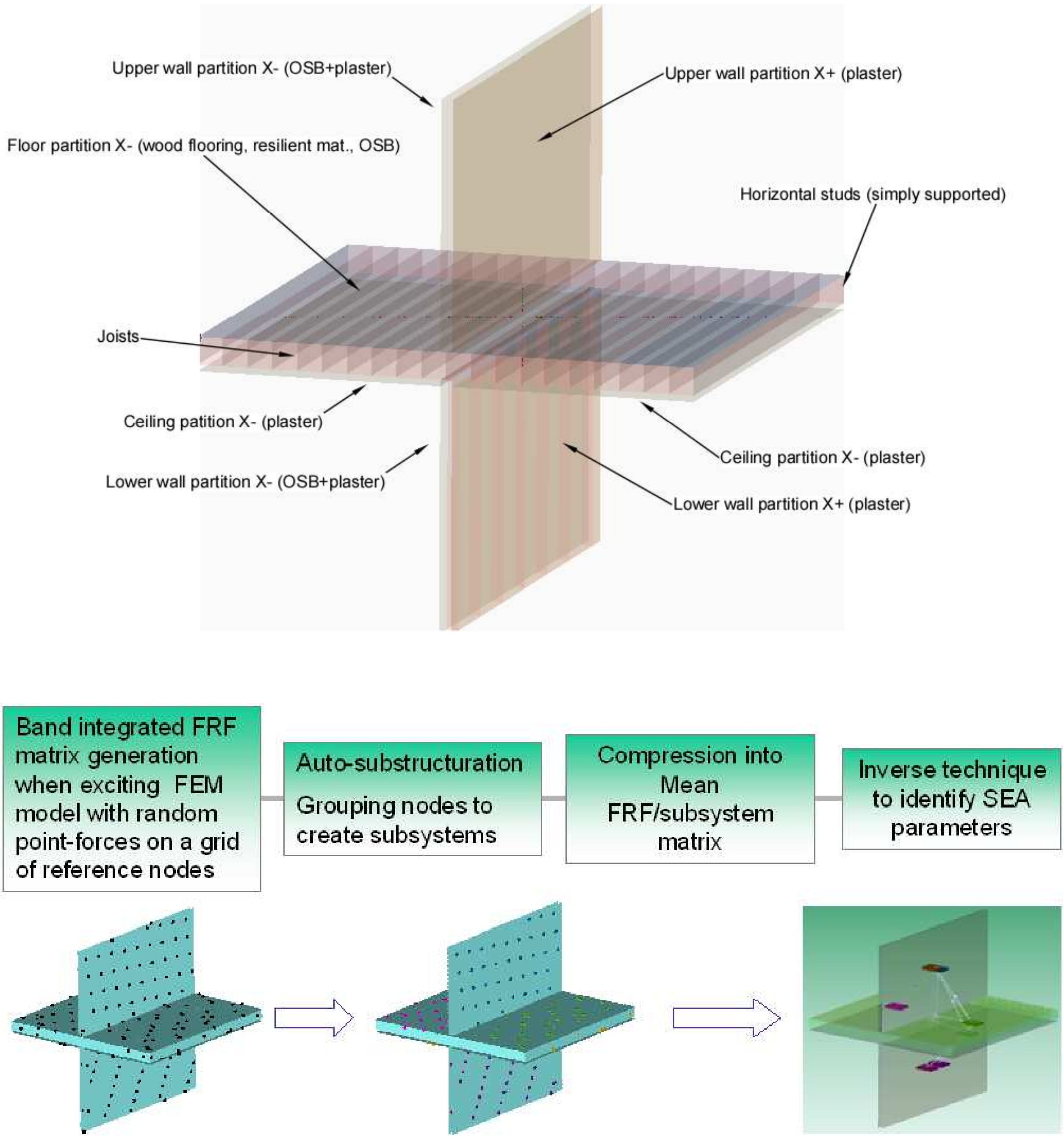

Figure 1. FE modelling of timber frame cross junction (top); Generating VSEA model from complex timber-frame junction (bottom)

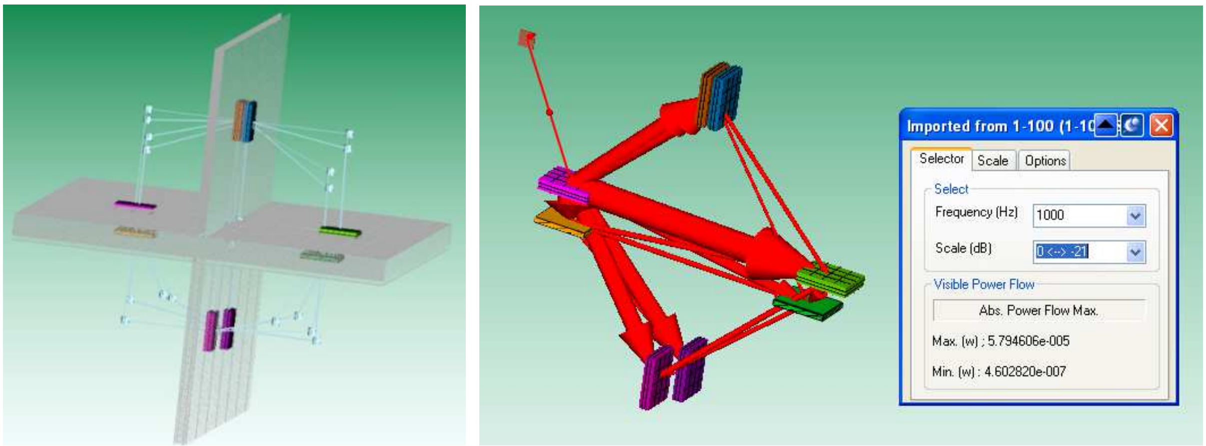

Figure 2: FEM derived VSEA model including all mechanical coupling loss between plate partitions and power at 1000 Hz for point-force excitation of the wood flooring

4. Conclusion and discussions

The prediction method, combining FEM and SEA for evaluating acoustic performance of wood based structures (wall and floors) has been presented and will be investigated within the “Silent Timber Build” project. A few floor structures (most sensitive with respect to acoustic comfort) have been identified and preliminary results are under way.

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