

VIBROACOUSTIC ANALYSIS OF WOOD FLOOR PANELS WITH POROUS MATERIALS: EXPERIMENTAL CALIBRATION AND FINITE ELEMENT MODELING

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Abstract

This study focuses on improving the vibroacoustic properties of wood floors by adding porous materials in the low-frequency range. It combines experimental tests and numerical finite element modeling to assess the impact of these materials. The finite element formulation used for the porous material is based on Biot-Allard theory and takes into account both the solid and fluid phases of the material. Three-point bending tests are carried out to determine the mechanical properties of glulam. A case study examines a wooden floor panel subjected to an impact force, with and without porous material, to assess radiated sound power levels. A global sensitivity analysis identifies key parameters, such as floor thickness, Young's modulus of the wood, and airflow resistivity of the porous material, which influence the vibroacoustic response. The results show that the addition of porous material significantly reduces vibration and noise.

Keywords: Porous material, Timber floor panel, Vibroacoustic, Numerical modeling.

1 INTRODUCTION

Timber floor panels are a crucial construction element in residential and commercial buildings, used for structural and finishing floors [1]. Their acoustic and vibration design significantly impacts comfort, safety, and sustainability. Poor vibroacoustic properties can cause high noise and vibration transmission, disrupting privacy and productivity. Damping materials, such as viscoelastic layers or porous materials, can reduce vibration and improve sound insulation [2-4]. The connection between the panel and the supporting structure also affects the panel's vibroacoustic behavior based on previous studies [5-7]. Eurocode 5 sets serviceability limit states (SLS) for timber floors based on vibrational factors like fundamental frequency, unit point load deflection, and unit impulse velocity response [8].

Researchers are increasingly exploring the vibroacoustic properties of timber floor panels. Yang et al. [9] conducted an analysis of cross-laminated timber (CLT) panels using wave and finite element (WFE) methods, finding good agreement at low frequencies but diverging at higher frequencies. Caniato et al. [10] proposed a new frequency model for impact noise from bare floors and compared wooden structures to traditional technologies. Homb and Conta [11-12] conducted experimental investigations on the vibroacoustic behavior of long-span floor systems made of stiff floor elements with high-rotational-stiffness supports. Biot's displacement-pressure model was used in this study to understand the strong interaction between wood structure and porous material in timber floor panels [13].

This study includes a thorough investigation into the behavior of a timber floor panel, with a particular focus on noise-radiation difficulties and improving vibration control in the low-frequency domain. To attain these objectives, the study takes a novel method and investigates the usage of a porous-material layer. The paper is organized into three major sections. The first section presents the finite element modeling of the coupled fluid-structure-poroelastic system, using Biot theory to model the porous material. The second section describes the coupled system studied, including the dimensions and materials used for the wood floor and the porous material. The paper then presents the analyses and results obtained, including the evaluation of radiated sound power levels and the impact of adding porous material.

2 FINITE ELEMENT MODELLING

We consider a coupled fluid-structure-poroelastic system consisting of an elastic structure (Ω_E) clamped at boundary Γ_u and subjected to external forces \vec{F}^d on Γ_t . It has a density ρ_E . The structure is coupled to a compressible, non-viscous fluid (Ω_F) with properties including speed of sound c_A and density ρ_A . The fluid-structure interaction occurs at interface Σ_{EA} . A poroelastic Material (Ω_P) is bonded to the structure and in contact with the fluid. The fluid-poroelastic interface is denoted Σ_{AP} and the structure-poroelastic interface is Σ_{EP} . The exterior normals for each domain are \vec{n}_E , \vec{n}_A and \vec{n}_P , respectively (Figure 1).

The porous material is modeled using Biot's theory, which applies when the material has an elastic matrix. It is characterized by the fluid phase properties (porosity ϕ , static flow resistance σ , tortuosity α_∞ , viscous length Λ and its thermal length Λ') and the solid skeleton properties (Young's modulus E_S , Poisson's ratio ν_S , structural damping coefficient η_S and its density ρ_S). In total, the poroelastic material is defined by nine key parameters that influence its behavior in the coupled system.

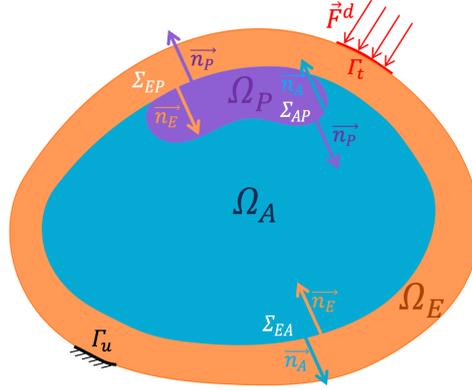


Figure 1: Coupled fluid-structure-poroelastic problem [15].

The local equations and the variational formulation of this coupled internal fluid-structure and poroelastic problem can be found in [14, 15, 16]. By introducing the nodal vectors of the displacements of the elastic structure \vec{U}^E and the solid phase of the porous material \vec{U}^S , as well as the nodal vectors of the pressures in the acoustic cavity \vec{P}^A and in the fluid phase of the poroelastic material \vec{P}^F , the following finite element coupled matrix system is obtained from the local equations and the variational formulation of the problem as described in [15]:

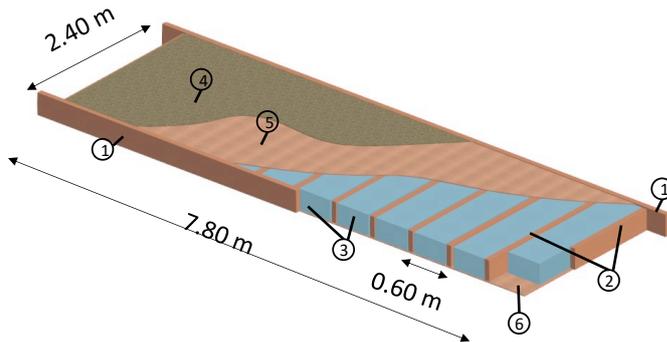
$$\begin{bmatrix} [K_E] - \omega^2[M_E] & -[C_{EA}] & [C_{ES}] & 0 \\ -\omega^2[C_{EA}]^T & [K_A] - \omega^2[M_A] & 0 & [C_{AF}] \\ [C_{ES}]^T & 0 & [K_S(\omega)] - \omega^2[M_S(\omega)] & -[C_{SF}] \\ 0 & [C_{AF}]^T & -\omega^2[C_{SF}]^T & [K_F(\omega)] - \omega^2[M_F(\omega)] \end{bmatrix} \begin{bmatrix} \vec{U}^E \\ \vec{P}^A \\ \vec{U}^S \\ \vec{P}^F \end{bmatrix} = \begin{bmatrix} \vec{F} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

In this system, $[K_E]$ and $[M_E]$, $[K_A]$ and $[M_A]$, $[K_S]$ et $[M_S]$, $[K_F]$ and $[M_F]$ represent the stiffness and mass matrices of the elastic structure, acoustic cavity, solid phase and fluid phase of the porous material, respectively. The fluid-structure and poroelastic phase coupling matrices are denoted $[C_{EA}]$ and $[C_{SF}]$, respectively. In addition, $[C_{ES}]$ et $[C_{AF}]$ are coupling matrices guaranteeing the continuity of the displacement and pressure fields: $\vec{U}^E = \vec{U}^S$ on Σ_{EP} and $\vec{P}^A = \vec{P}^F$ on Σ_{AP} , respectively. Finally, \vec{F} denotes the vector of nodal forces applied to the elastic structure.

This system is solved by a direct frequency method, with the frequency-dependent matrices for the porous material updated at each computational step. This resolution simultaneously provides the nodal displacements of the elastic structure and the porous solid phase, as well as the nodal pressures in the acoustic cavity and in the porous fluid phase.

3 DESCRIPTION OF THE COUPLED SYSTEM

This study investigates a timber floor panel made of laminated elements, with dimensions of 2.40 m in width and 7.8 m in length. The panel consists of two main glulam beams, thirteen joists with 60 cm spaceman, and a 25 mm timber floor connecting the beams in the upper view and 13 mm in the bottom view (Figure 2). The thickness of the porous material is considering equal to 13mm. The study examines two case studies, with and without the effects of porous material on the floor panel. Although the timber material is classified as GL24h, a simple three point bending test has been conducted (Figure 3). The main mechanical properties of wood and porous material are presented in the Table 1.



Details

1. Glulam beams (75 x 225 mm)
2. Glulam joints (75 x 225 mm)
3. Air cavity
4. Porous material ($e_p = 13$ mm)
5. Timber floor ($e_{f1} = 25$ mm)
6. Timber board ($e_{f2} = 13$ mm)

Figure 2. Investigated panel.

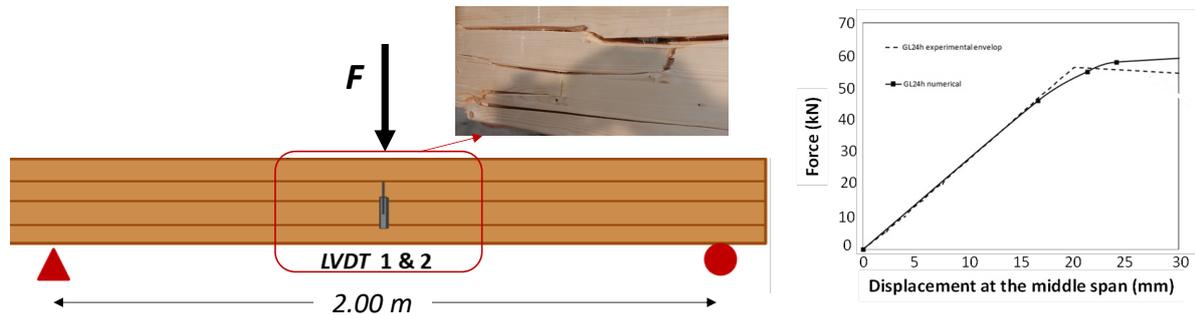


Figure 3. Experimental study.

Table 1. Material parameters.

Elements	Input variable	Description	Values	Units
Glulam	E_1	Young's modulus along axis 1	1.13E+10	Pa
	$E_2 = E_3$	Young's modulus along axis 2 and 3	3.73E+08	Pa
	$\nu_{12} = \nu_{13}$	Poisson ratio in the planes 12, and 13	0.35	-
	ν_{23}	Poisson ratio in the plane 23	0.09	-
	$G_{12} = G_{13}$	Shear modulus in the planes 12, and 13.	2.00E+07	Pa
	G_{23}	Shear modulus in the plane 23	6.25E+08	Pa
	η	Damping	0.0125	-
Porous	ρ	Characteristic density	370	kg/m ³
	λ	Viscous characteristic length	0.00001198	m

	Λ'	Thermal characteristic length	0.00017573	m
	Φ	Porosity	0.99	-
	α	Tortuosity	1.0	-
	σ	Airflow resistivity	10003.000	N.s/m ⁴
Geometry	e_{f1}	Thickness of timber floor layer upper view	0.0250	m
	e_p	Thickness of porous material	0.013	m
	e_{f2}	Thickness of timber floor layer bottom view	0.013	m

In this work, a mesh with tridimensional elements is used for all domains (fluid, beam, joist and wood floor). The solid domains are meshed using quadratic tetrahedral elements with 391932 degrees of freedom. Fluid domains are discretized using four-node tetrahedral elements with 121836 degrees of freedom.

4 ANALYSES AND RESULTS

Figure 4 displays an impact force pulse located in the center of the floor panel (top layer). According to Lietzén et al. [17] this force can cause a medium-weight item to tumble in milliseconds due to shock loading. The force is in the time domain and uses Fourier transformations to reach the frequency domain.

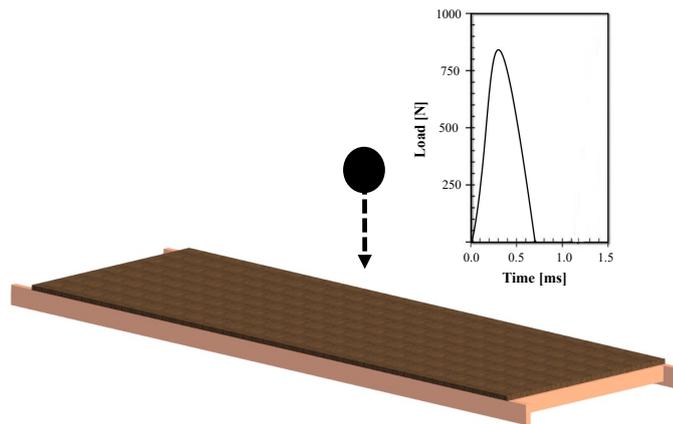


Figure 4. Shock loading.

Our goal is to evaluate the system's radiated sound power levels in one-third octave bands, from 25 Hz to 400 Hz, and in the narrow band from 0 Hz to 400 Hz, on the investigated wooden floor with and without porous material. In terms of noise attenuation, the goal is to illustrate the possible advantages of adding porous material, as represented in the Figure 5. Because of the effects of thermal and viscosity, the porous sound-absorbing substance also lessens noise.

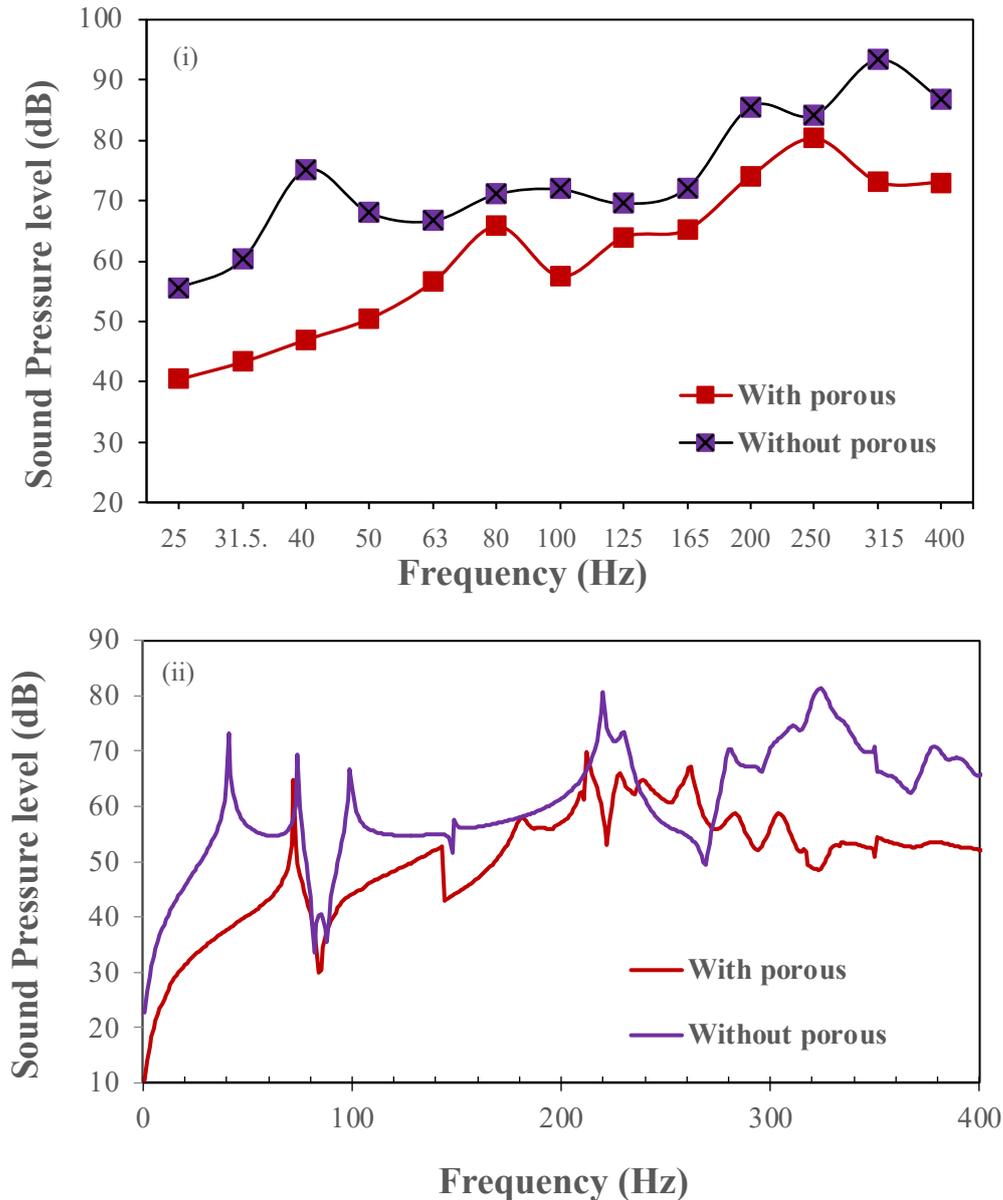


Figure 5. Panel submitted to a shock loading, comparison of a sound pressure level in (i) one-third octave band, (ii) in the narrow band.

To optimize the acoustic insulation of our system in wooden floors integrating a porous material, we performed a global sensitivity analysis. The details of this study are not described in this paper. The main objective is to identify the most influential parameters on the power of the sound radiated through the system at low frequencies. The global sensitivity analysis, using Sobol indices, revealed that geometric parameters such as the thickness of the floor and the carpet are the most determining. In addition, some material parameters such as Young's modulus and the density of the wood also have a significant influence. An additional analysis focusing only on the parameters of the carpet (porous material) demonstrated that the flow resistivity is a key parameter to improve the vibroacoustic response of the system at low frequencies [4].

5 CONCLUSIONS

The following are the major scientific accomplishments and conclusions:

- i. Experimental experiments are carried out to assess the mechanical properties of glued laminated timber, and numerical models are created using the finite element method (FEM). The experimentally determined material parameters are used as input data in the FEM model to anticipate the behavior of the floor panel.
- ii. A finite element model of sound radiation from an elastic structure with a poroelastic layer is provided. The poroelastic material is described using Biot theory, and its behavior is correlated with that of the elastic structure via a symmetrical coupling term. The porous material is divided into two phases: solid and fluid, which are represented in the formulation by the displacement field for solids and the pressure field for fluids. This novel technique has the advantage of decreased computation costs and improved communication across all domains.
- iii. The introduction of a layer of porous material absorbs vibrations and considerably reduces the structure's sound radiation.

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