Accurate and Efficient Prediction of Sound Insulation in Multilayer Structures: a Robust Method validated with Floating Floors

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ABSTRACT

Engineering offices and manufacturers of acoustic building systems or materials often rely on measurement data to determine the adequacy of solutions for specific situations. This typically involves numerous costly and time-consuming laboratory measurements, making it difficult to efficiently explore and optimize various design configurations.

In this paper, a prediction method is presented to accurately and efficiently predict the sound insulation of multilayer structures. Accuracy ensures reliability, while efficiency is crucial for optimization, where numerous simulations are needed, for example to identify the ideal layering or material properties of a(n) (inter)layer. The prediction method accounts for arbitrary layering, finite dimensions, boundary conditions and resulting modal behavior, as well as frequency- and temperature-dependent material properties.

Extensive validation has been conducted using numerous examples with a specific focus on floating floors, demonstrating the model's robustness and reliability. An accuracy of 3 dB in the single number rating is generally achieved using predefined values from a material database. The method achieves higher accuracy when material properties are determined by testing.

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1. INTRODUCTION

Engineering offices and manufacturers of acoustic building systems or materials often rely on measurement data since the alternatives regarding existing prediction software are either too slow (e.g. using finite elements), or too inaccurate (e.g. analytical expressions assuming thin plate theory). This typically results in a difficult process of exploration and optimization of various new or existing design configurations, since it involves numerous costly and time-consuming laboratory measurements. The need for accurate and efficient sound insulation prediction methods is therefore of crucial importance.

Floors are layered elements of solid and/or poroelastic nature and are implemented using the modal Transfer Matrix Method (mTMM) [1, 2], which accounts for arbitrary layering, finite dimensions, simply supported boundary conditions and the resulting modal behavior. The mTMM additionally allows for frequency-dependent material properties, which can be especially important in practical applications.

The computational efficiency of this method is crucial to the development of new design configurations and to the exploration of new materials and material properties, as it enables the exploration and optimization of various design configurations without the need for extensive laboratory testing. The method's robustness and reliability are demonstrated through extensive validation using numerous examples, with a specific focus on floating floors. It is demonstrated that a prediction accuracy of 3 dB can be achieved, even when combining multiple layers such as e.g. leveling screeds and flexible interlayers. Validation on floating floors is interesting since there is a large enough dataset available with many different variations using the same materials.

2. PREDICTION OF THE IMPACT SOUND PRESSURE LEVEL

The prediction of the impact sound insulation of layered finite floors consists of three crucial steps, as displayed in Figure 1: The first step is to express the impact force F in terms of the pressure load that it exerts onto the finite structure, which is elaborated in terms of basic functions in [1].

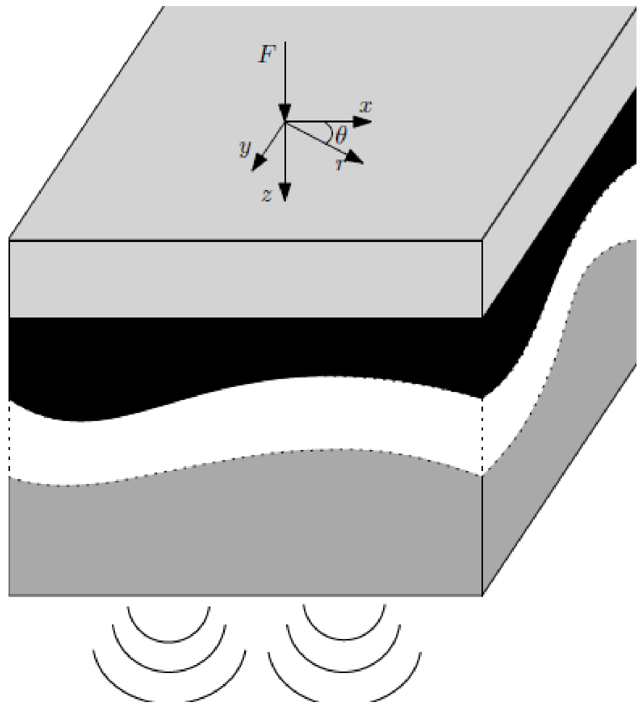


Figure 1: Convention used in the (m)TMM, with the impact force located at the origin of the coordinate system and sound radiation towards the receiver room located at positive z-coordinates. Both Cartesian (x, y, z) and cylindrical (r, θ, z) coordinates are represented.

The second step is to compute the mechanical admittance of the floor, expressing the relation between out-of-plane velocity at the receiver room interface and pressure loading at the impact side. Since floors typically consist of multiple materials, they can be characterized as layered elements and implemented using elastodynamics theory, which accounts for longitudinal and shear wave propagation, as well as their interaction in the form of bending waves.

One of the main advantages over thin plate theory for the prediction of sound insulation is that thickness effects such as thickness resonances are accounted for due to the presence of shear waves. It will be demonstrated in section 3 that thickness resonances in leveling screeds can heavily influence the impact sound insulation improvement of floating floors. The elastodynamics theory also successfully captures key physical phenomena such as the mass-air-mass resonance. This theory is enveloped by the mTMM [1, 2], which is used here.

Layers with materials of an elastic or poroelastic nature can all be implemented and combined into a layered floor element. The mTMM can handle frequency-dependent dependent material properties, which can be particularly useful for flexible interlayers. In the mTMM, the boundary conditions of a floor are accounted for by decomposing the out-of-plane displacements of the floor into sinusoidal basis functions [1], which correspond to antisymmetric boundary conditions for thick floors. These basis functions represent mode shapes of the floor, and they occur at their respective natural frequencies, making the mTMM a modal approach.

Due to the combination of this modal approach and employing analytical solutions for the wave propagation in each layer in the frequency-wavenumber domain, a high computational efficiency is achieved.

The third and last step is to compute the radiated sound power directly from the floor velocity at the receiver room interface. It is demonstrated in [1] that it can be evaluated directly in the wavenumber domain, obviating the need to evaluate modal radiation efficiencies.

3. VALIDATION

The modeling strategy can be showcased effectively using floating floors. In our examples, we used a concrete base and cement screed as outer layers. The inner layers can consist of a combination of a leveling screed and/or a resilient interlayer. The concrete base is 140 mm thick in accordance with ISO 10140-5.

The properties for the resilient interlayers were determined from [3]. The calculated results are compared with measurements in the laboratory of the Belgian Building Research Institute (BBRI). Both the impact sound pressure level L_n and the impact sound reduction ΔL were calculated for each case.

For one case, we examined the impact sound reduction ΔL for 3 different setups. The outer layers are the same for each setup (140 mm concrete and 50 mm cement screed). The inner layers consist of:

1. Only a resilient interlayer
2. Only a leveling screed
3. Both the leveling screed and the resilient interlayer

The properties used for each material are shown in Table 1.

Table 1: Material properties: thickness t, density ρ, Young's modulus E, Poisson coefficient ν and loss factor η.

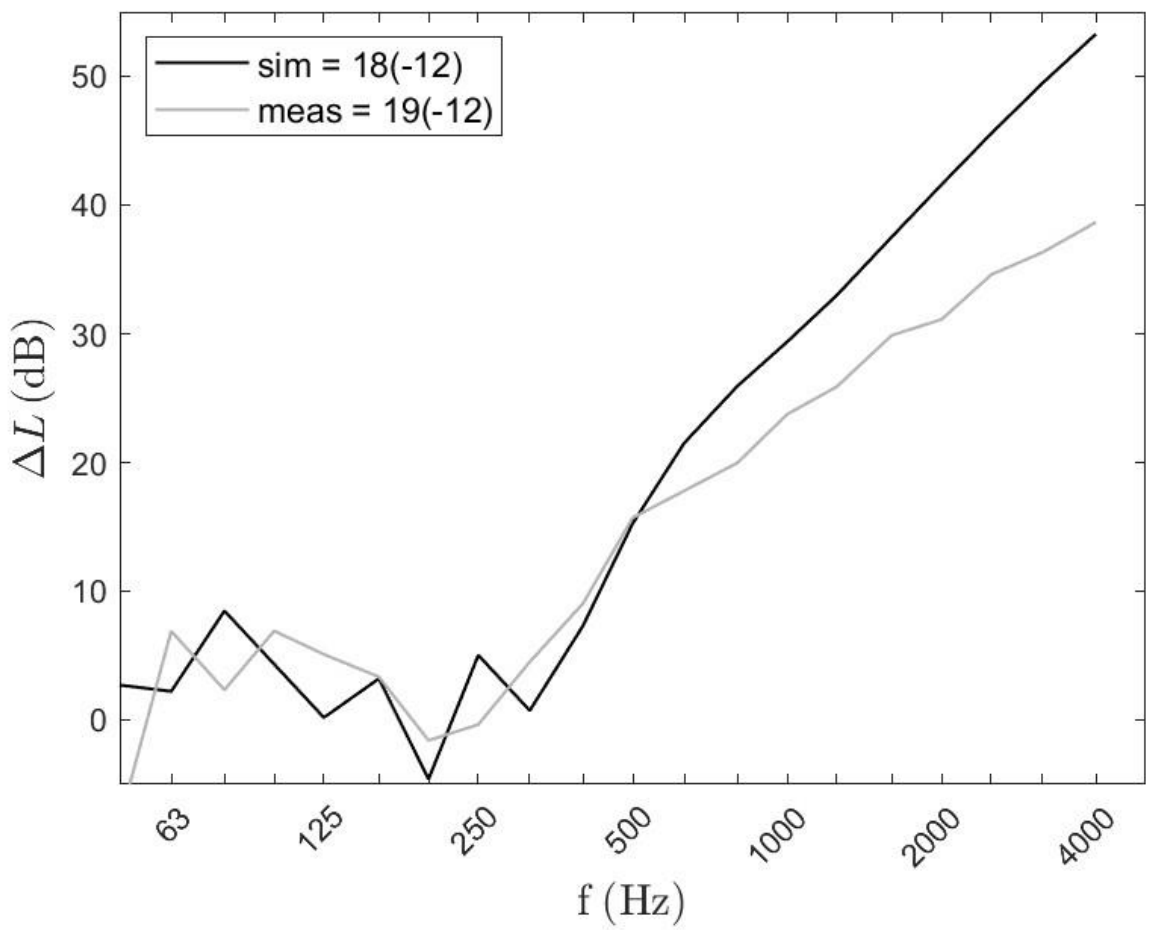
Type	**Material**	**t [m]**	**ρ [kg/m³]**	**E [MPa]**	**υ [-]**	**η [-]**
Base floor	Concrete	0.14	2400	22000	0.2	0.015
Resilient layer	PE-foam	0.008	30	0.4	0.2	0.05
Leveling screed	EPS screed	0.05	327	10	0.4	0.16
Top layer	Cement screed	0.05	1930	10000	0.2	0.015

3.1.RESILIENT LAYER ONLY

The model can very accurately predict the mass-spring-mass resonance frequency of the system. This is predominantly determined by the stiffness of the resilient layer.

Both the measurement and the simulated curves show a large increase in impact sound reduction between 250 Hz and 500 Hz. From 500 Hz onwards the inclination of the slope decreases. This is consistent with the expected behavior of resonantly reacting floors.

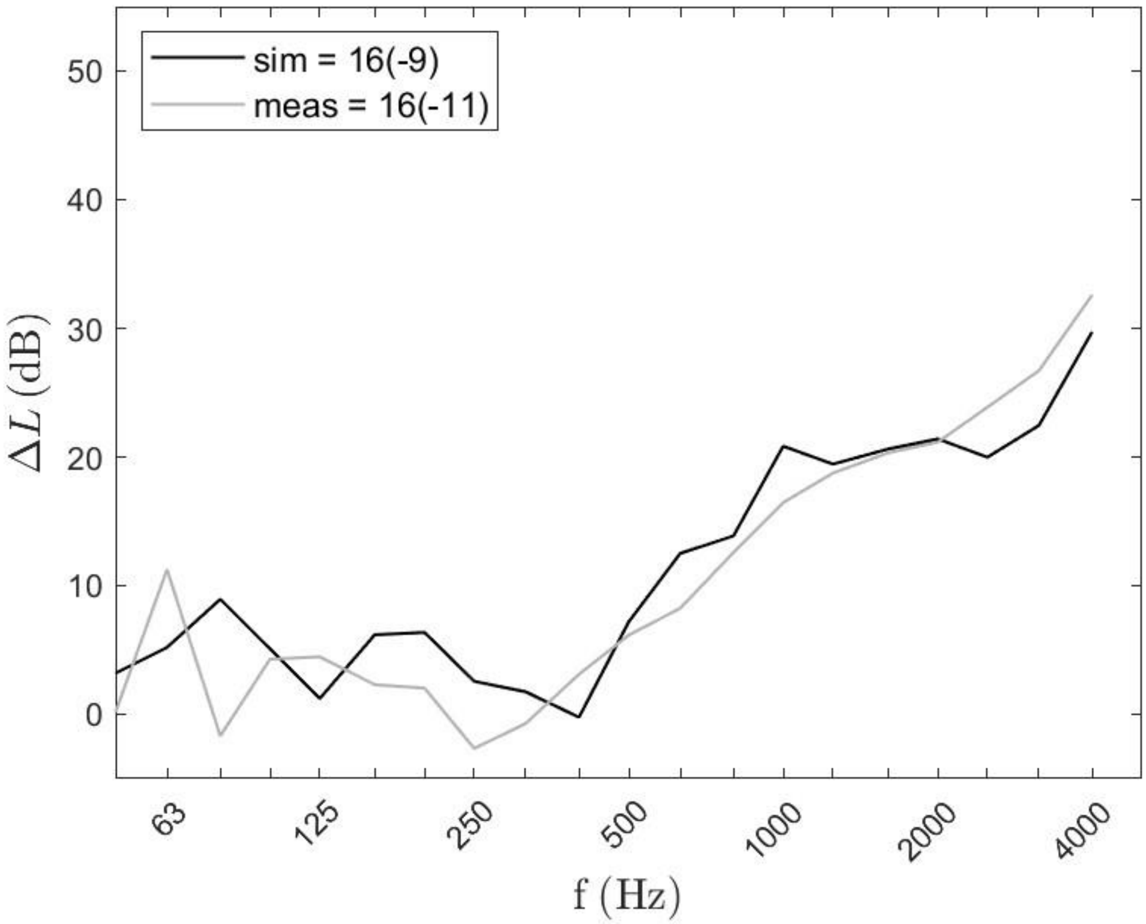
Overall, there is a very good agreement between the measured and the simulated values. The SNR is only 1 dB off from the measured value.



3.2.LEVELING SCREED ONLY

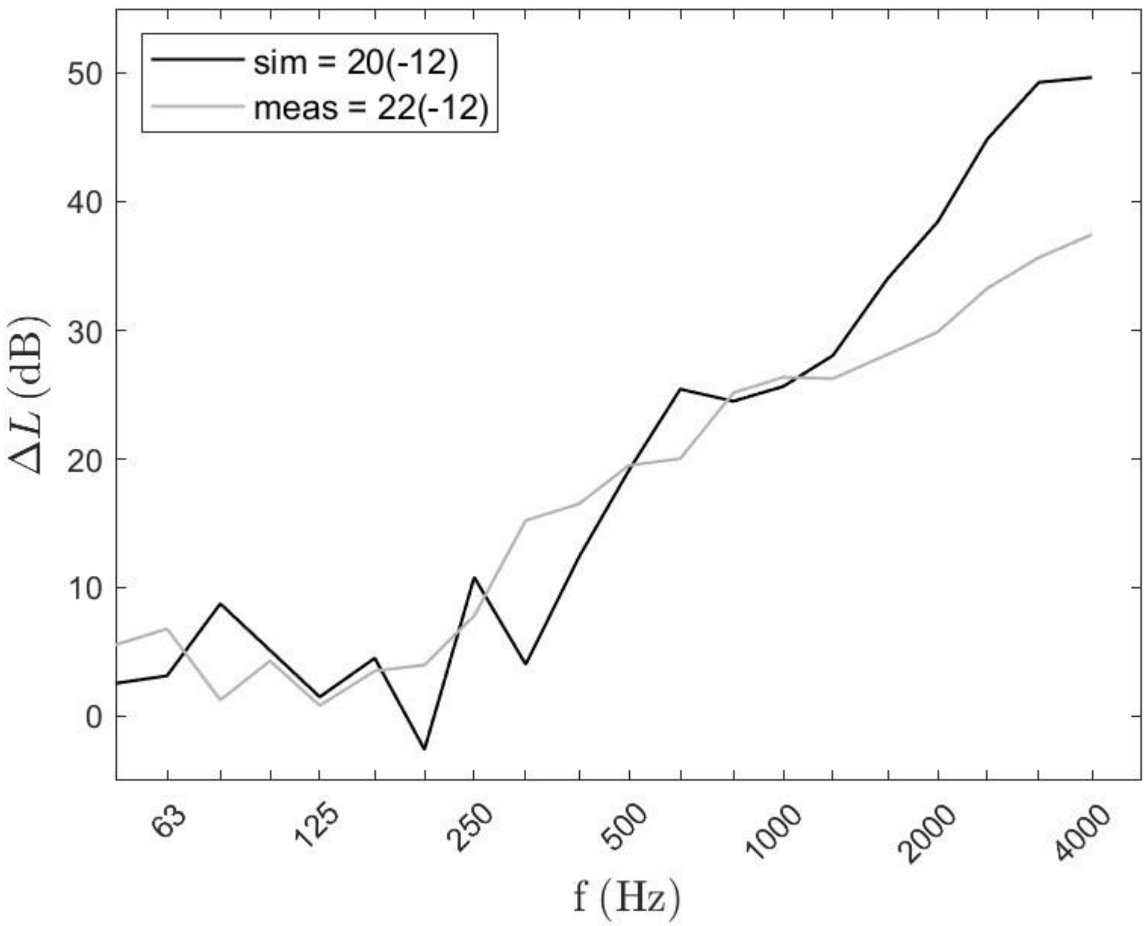
There is also a good correlation when we look at the measured and simulated values for the case with only a leveling screed as inner layer.

Because of the thickness of the leveling screed, there is a resonance in the material at high frequencies. This results in a plateau in the impact sound reduction. This phenomenon is not accounted for in most prediction models. Using FEM produces a similar result but at a much higher computational cost.



3.3. LEVELING SCREED + RESILIENT LAYER

When both inner layers are combined, we still get a SNR within 2 dB of the measured value. There is still some effect from the thickness resonance of the leveling screed but it is less pronounced. The resilient layer is more effective in this area, reducing the effect of the leveling screed.



Using this case as an example, the method used in this paper can predict the expected impact sound pressure level L_n and the impact sound reduction ΔL of a floating floor for combinations of different layers. This means that manufacturers and researchers can use this method to predict any combination of layers if the properties of the materials are well determined. This eliminates the need for extensive test campaigns where each combination is measured separately.

4. CONCLUSIONS

In this paper, a robust and efficient prediction method for determining the impact sound pressure level of multilayer structures is presented, with a particular focus on floating floors. The proposed method accounts for various factors such as arbitrary layering, finite dimensions, boundary conditions, and frequency-dependent material properties. The results show that the prediction method can achieve an accuracy of 3 dB in the single number rating. The method successfully captures key physical phenomena such as mass-spring-mass resonance and thickness resonances in thicker layers such as leveling screeds.

The prediction of these properties with multiple layers (such as a leveling screed and a resilient layer) using a fast algorithm was previously not possible. This resulted in inaccurate or slow prediction methods or the need for extensive laboratory testing.

Most analytical prediction models will show a constant increase of the impact sound reduction ΔL. This is not the case as measurements show a smaller inclination at higher frequencies. This method better predicts these effects.

In thicker layers (like leveling screeds), there are thickness resonances which are not considered in thin plate theory (which most common methods use). The method in this paper takes these effects into account without increasing the computational cost.

The ability to accurately and efficiently predict acoustic properties is crucial for optimizing design configurations and exploring new materials and various material properties. This method offers a valuable tool for engineering offices and manufacturers, enabling them to reduce their reliance on costly and time-consuming laboratory measurements. By providing a more efficient alternative, the method facilitates the exploration and optimization of acoustic solutions for specific situations. Future work could focus on further expansion of the model to account for additional complexities, such as lightweight floors and periodic structures.

ACKNOWLEDGEMENTS

This research is funded by the European Research Council in the form of the Soprano Proof of Concept grant number 101188255. The financial support of the ERC is gratefully acknowledged.

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