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ACCURATE AND EFFICIENT PREDICTION OF SOUND INSULATION IN MULTILAYERED STRUCTURES: A ROBUST METHOD VALIDATED WITH GLAZING EXAMPLES

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ABSTRACT

Engineering offices and manufacturers of acoustic building systems or materials often rely on measurement data to estimate whether building solutions will be of sufficient acoustic quality. 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 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 glazing, demonstrating the model's robustness and reliability. An accuracy of $1-2\,\mathrm{dB}$ in single number rating is generally achieved using default non-product specific material data. The method achieves higher accuracy when material properties are determined from testing.

Keywords: *airborne sound insulation, layered elements, glazing, viscoelastic interlayers*

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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 sound insulation prediction methods which are both accurate and efficient is therefore of crucial importance.

In this paper, a robust method is presented, which is designed to accurately and efficiently predict the sound insulation of multilayer structures with varying elements such as wall leafs and cavities. Wall leafs can consist of layered elements of elastic, viscoelastic and poroelastic nature and are implemented using elastodynamics theory. The modal Transfer Matrix Method (mTMM) [1, 2] envelops this theory and additionally accounts for arbitrary layering, finite dimensions, simply supported or antisymmetric boundary conditions and the resulting modal behavior. The mTMM also allows for frequency-dependent material properties, which can be especially important in practical applications. Viscoelastic interlayers are a particular type of interlayer that can be present in these layered wall leafs, since the material properties depend both on frequency and temperature. This dependence on temperature is expressed through the Williams-Landel-Ferry equation [3, 4], while the dependence on frequency is accounted for using the Generalized Maxwell-Wiechert model [5]. Cavities are assumed to be 'hard-walled' with

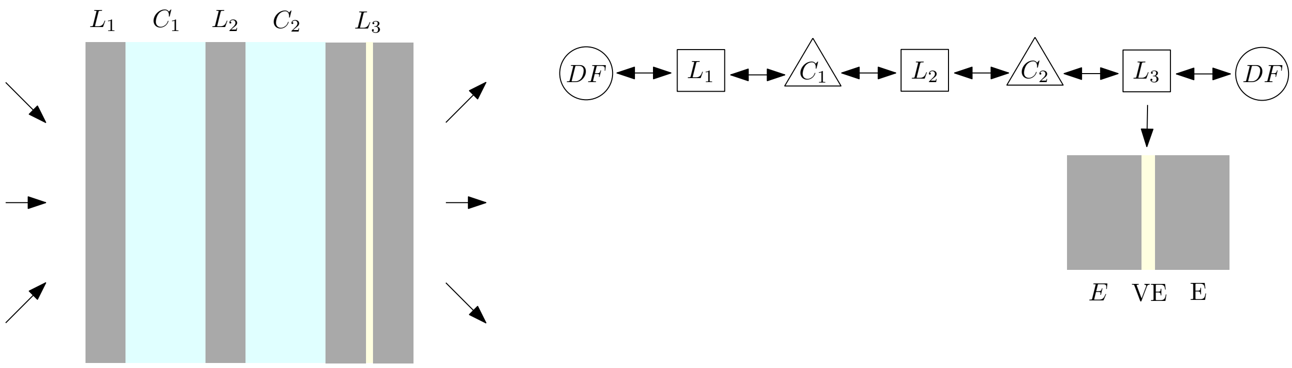

Figure 1. Glazing system with three wall leafs L_1, L_2 and L_3, separated by two cavities C_1 and C_2. The third wall leaf is layered, consisting of two elastic (E) layers with a viscoelastic (VE) in between. The outer wall leafs are coupled to diffuse fields (DF).

finite dimensions and the interaction between cavity and adjoining wall leafs is accounted for [6].

This method 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 glazing. Validation on glazing is particularly interesting since all these elements (wall leafs, cavities, viscoelastic interlayers) can all occur separately or combined in any desired order. The ability to accurately predict sound insulation is crucial for optimizing design configurations and exploring new materials and material properties. By reducing the reliance on costly and time-consuming laboratory measurements for experimental design optimization, this approach facilitates the development of effective acoustic solutions for a wide range of applications.

2. SOUND INSULATION PREDICTION

Walls and floors typically consist of several structural parts, such as leafs and cavities. A wall leaf consists of at least one solid layer, and layered wall leafs can contain varying element types, e.g. an elastic layer or a viscoelastic interlayer which is used in laminated glazing. Cavities are assumed to be hard-walled, and can either be filled with fluid or with porous material. The sound insulation prediction approach is graphically represented in Fig. 1. It starts by indicating all leafs and cavities, and using the corresponding mathematical approach for each leaf or cavity, as will be discussed in the following subsections 2.1 and 2.2. The coupling between wall leafs and cavities is briefly discussed and finally the computation of the diffuse sound insulation is included.

2.1 Wall leafs

Layered elements such as wall leafs or floating floors are 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 the shear waves. The elastodynamics theory also successfully captures key physical phenomena such as the coincidence effect and 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 viscoelastic nature (also poroelastic layers, but these are not present in glazing) can all be implemented and combined into a single wall leaf. Material properties can be frequency-dependent, but also temperature-dependent in the case of viscoelastic interlayers. The prediction approach for these interlayers is elaborated in detail in section 3, since they are often used in glazing.

In the mTMM, the boundary conditions of a wall leaf are accounted for by decomposing the out-of-plane displacements of the leaf into sinusoidal basis functions [1], which correspond to antisymmetric boundary conditions for thick wall leafs. These basis functions represent mode shapes of the wall leaf 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.

2.2 Cavities

Cavities are modeled as 'hard-walled' three-dimensional cuboid acoustical spaces. A modal approach is applied, where the mode shapes or the basis functions of the cavity are taken to be the normalized mode shapes of a hard-walled, rectangular cuboid cavity [7]. The dynamic stiffness of the cavity is then expressed in terms of its natural frequencies and loss factor, determined by the speed of sound and mass density of the fluid and the reverberation time of the cavity or the loss factor of the fluid. Note that this is an analytical approach, such that the computational efficiency for cavities is very high. A cavity can either be filled with a specific fluid (e.g. air, argon, krypton) or with a porous material. In case of a porous filling, the porous material can be implemented as an equivalent fluid, e.g. by using the Delaney-Bazley-Miki model [8, 9], which employs the flow resistivity to determine the complex, frequency-dependent sound speed and mass density of the equivalent fluid.

2.3 Coupling of wall leafs and cavities

Coupling of the wall leafs and cavities is achieved by employing the acoustical pressure in a cavity as an excitation of the adjoining wall leaf, while the displacements of a wall leaf are used as an excitation of the adjoining cavity. Since modal approaches are used for both the wall leafs and cavities, this coupling strategy is called a modal-interaction model [6].

2.4 Diffuse sound insulation

The modal-interaction model finally allows the calculation of the diffuse sound insulation. This is not straightforward due to the finite wall dimensions, but a correct calculation is achieved by employing the diffuse field reciprocity relationship [12], so that the ensemble mean of the sound transmission coefficient $\hat{\tau}_{12}$ [10, 11] can be evaluated as

$$\hat{\tau}_{12} = \frac{8\mathrm{V}_1}{c\mathrm{S}\pi\mathrm{n}_1}\mathrm{Tr}\left(\tilde{\mathbf{D}}_{\mathrm{dir}}^{(1)}\mathbf{D}_{\mathrm{tot}}^{-H}\tilde{\mathbf{D}}_{\mathrm{dir}}^{(2)}\mathbf{D}_{tot}^{-1}\right), \qquad (1)$$

with V_1 the volume of the sending room, c the speed of sound, n_1 the modal density of the sending room and S the surface area of the interface between structure and room. $\mathbf{D}_{\mathrm{dir}}$ denotes the direct field dynamic stiffness matrix, whereas $\mathbf{D}_{\mathrm{tot}}$ represents the total dynamic stiffness matrix of the structure, including all wall leafs, cavities and their coupling. The imaginary part of a matrix is denoted with a tilde.

3. VISCOELASTIC INTERLAYERS

Laminated glazing makes use of viscoelastic (polymer) PolyVinylButyral (PVB) interlayers. The mechanical properties of these PVB interlayers are not only frequency-dependent, but they also depend on temperature. These effects can be accounted for by using the generalized Maxwell-Wiechert model and William-Landel-Ferry model [3, 4], respectively.

3.0.1 Generalized Maxwell-Wiechert model

At the small-strain regime, viscoelastic effects can be characterized efficiently by using the Generalized Maxwell-Wiechert model, taking into account the time/frequency-dependency of the shear modulus [5]. This model is constructed from parallel combinations of a spring and a damper placed in series, which are placed in parallel with a single elastic spring [13]. The elastic springs in combination with the viscous dampers provide dynamic stiffness in case of fast loading conditions, while the elastic spring represents the quasi-static stiffness. The elements in the Maxwell model can be derived experimentally using dynamic mechanical analysis (DMA) [13]. The time-dependency of the shear relaxation modulus can be expressed as [13]:

$$G(t) = G_\infty + \sum_{i=1}^{n} G_i \exp -t/\tau, \qquad (2)$$

with G_∞ the long-term shear modulus, G_i and τ_i the shear modulus and relaxation time of a viscoelastic unit (spring-damper pair), respectively. The number of viscoelastic units is denoted by n. The properties of the viscoelastic units are inversely related as follows:

$$\tau_i = \frac{\eta_i}{G_i}. \qquad (3)$$

The long-term shear modulus is related to the instantaneous shear modulus G_0 by [13]:

$$G_0 = G_\infty + \sum_{i=1}^{n} G_i. \qquad (4)$$

Substitution of Eqn. (4) into Eqn. (2) yields [14]:

$$G(t) = G_0 - \sum_{i=1}^{n} G_i \left(1 - \exp 1 - t/\tau_i\right). \quad (5)$$

The shear relaxation modulus in the time-domain G(t) can also be expressed in the frequency domain as [5]:

$$G(\omega) = G_0 - \sum_{i=1}^{n} \frac{G_i}{(\omega\tau_i)^2 + 1} + \mathrm{i}\sum_{i=1}^{n} \frac{G_i\omega\tau_i}{(\omega\tau_i)^2 + 1}. \quad (6)$$

This expression can be subdivided into the real part representing the storage modulus, which determines the elastic behavior. The imaginary part of the resulting expression constitutes the loss modulus, representing the energy dissipation [5]. It has been demonstrated in [5] that the storage and loss moduli of several types of viscoelastic interlayer are subject to high differences due to the use of specific additives and plasticizers, and to differences in the measurement techniques.

3.0.2 Williams-Landel-Ferry equation

The dynamical shear modulus $G(T, \omega)$, which depends on both temperature and frequency, obeys the following relation:

$$G(T, \omega) = G(\mathrm{T}_0, \alpha_T \omega), \quad (7)$$

with $\mathrm{T}_0 = 20°C$ the reference temperature. The horizontal shift parameter α_T [3, 4] is proportional to the loss factor, given by

$$\alpha_T = \frac{\eta(T)}{\eta(\mathrm{T}_0)}. \quad (8)$$

For most polymer systems, the loss factor $\eta(T)$ is well-represented by the empirical Vogel–Fulcher law

$$\eta(T) = B \exp\left(\frac{\mathrm{T_A}}{T - \mathrm{T_V}}\right), \quad (9)$$

with $\mathrm{T_A}$ the activation temperature and $\mathrm{T_V}$ the Vogel temperature. Combining both Eqn. (8) and Eqn. (9) leads to [4]:

$$\log \alpha_T = -C_1 \frac{T - \mathrm{T}_0}{T - \mathrm{T}_0 + C_2}, \quad (10)$$

with two constants C_1 and C_2, defined as

$$C_1 = \log \mathrm{e}\left(\frac{\mathrm{T_A}}{\mathrm{T}_0 - \mathrm{T_V}}\right) \text{ and } C_2 = \mathrm{T}_0 - \mathrm{T_V}. \quad (11)$$

Eqn. (10) was proposed by Williams, Landel and Ferry and is known as the WLF equation. The influence of the PVB temperature and the resulting variations in airborne sound insulation of single laminated glazing is demonstrated in Fig. 2, displaying clear variations up to 4 dB in the frequency range around coincidence.

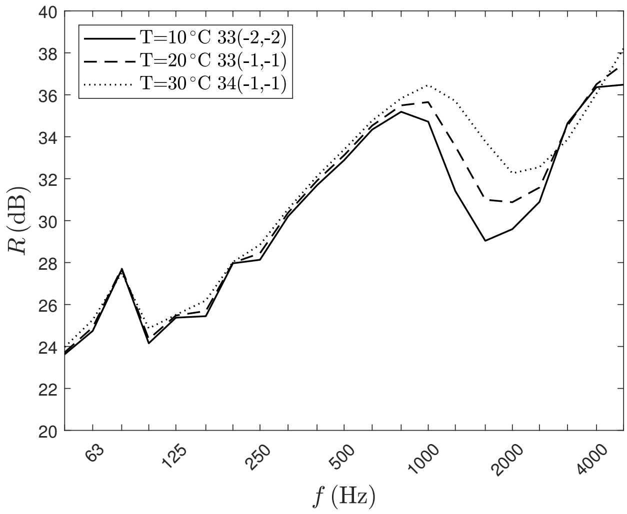

Figure 2. Influence of temperature on the mechanical properties of PVB and the resulting variations in airborne sound insulation of 44.2 glazing.

4. VALIDATION

The model can be showcased effectively using (laminated) glazing examples, since they contain all previously discussed elements: cavities and wall leafs including elastic layers and viscoelastic interlayers. The assumed default material properties of glass and the cavity fluids are listed in Tables 1 and 2, respectively. Note that a loss factor of $\eta = 0.05$ is assumed for the glass panes, which approximately consists of equal parts of internal losses and edge damping [15], i.e. energy loss due coupling of the glass panes through the mounting frame.

Table 1. Material properties of glass: density ρ, Young's modulus E, Poisson coefficient ν and loss factor η.

$\rho\,[\frac{\mathrm{kg}}{\mathrm{m}^3}]$	E [GPa]	ν [−]	η [−]
2500	62	0.24	0.05

Table 2. Material properties of air and Argon: density ρ, sound speed c and cavity reverberation time T.

	$\rho\,[\frac{\mathrm{kg}}{\mathrm{m}^3}]$	$c\,[\frac{\mathrm{m}}{\mathrm{s}}]$	$T\,(\mathrm{s})$
Air	1.2	340	2
Argon	1.784	319	2

The simplest examples are single glass panes. Three single glazing examples with thicknesses of $4\,\mathrm{mm}$, $10\,\mathrm{mm}$ and $19\,\mathrm{mm}$ are simulated and validated with corresponding laboratory measurements in Fig. 3. The simulations successfully capture the physical behavior of the single glazing, including the coincidence effect, resulting in accurate single number ratings with a maximum deviation of $1\,\mathrm{dB}$.

Fig. 4 includes the results of simulations and laboratory measurements of two types of double glazing: 4-10-4 and 6-12-8. Fig. 4 indicates that other than the coincidence effect, also the mass-air-mass resonance is well-predicted, which also results in an accuracy of $1\,\mathrm{dB}$ on the single number rating.

Fig. 5 displays two examples of triple glazing: 4-10A-4-10A-4 and 6-14A-4-14A-6. Contrary to the double glazing examples, the cavities are filled with Argon instead of air to increase the airborne sound insulation. The use of argon instead of air mainly affects the anti-resonance peak just before coincidence, so around $1600-2000\,\mathrm{Hz}$ in Fig. 5(a) and at approximately $1000\,\mathrm{Hz}$ in Fig. 5(b). Simulations have shown that the inclusion of argon instead of air does indeed improve the sound insulation at the anti-resonance frequency, where Fig. 5(a) indicates that this improvement is underestimated, while Fig. 5(b) suggests that the effect is correctly captured in the simulations. This variance can possibly be attributed to the niche effect [16]. Nevertheless, the prediction accuracy of the simulations for triple glazing is still $1\,\mathrm{dB}$, as this niche effect at coincidence occurs at high frequencies and thus has a small influence on the single number rating.

Several examples are included for laminated glazing, both single (cfr. Fig. 6) and double (cfr. Fig. 7). The frequency and temperature-dependent material properties of the PVB interlayers are taken from [17], and it is assumed that the temperature of the PVB equals $20°\,\mathrm{C}$. Three examples of laminated single glazing are displayed in Fig. 6: 33.2, 1212.2 and 10101010.6. The prediction accuracy

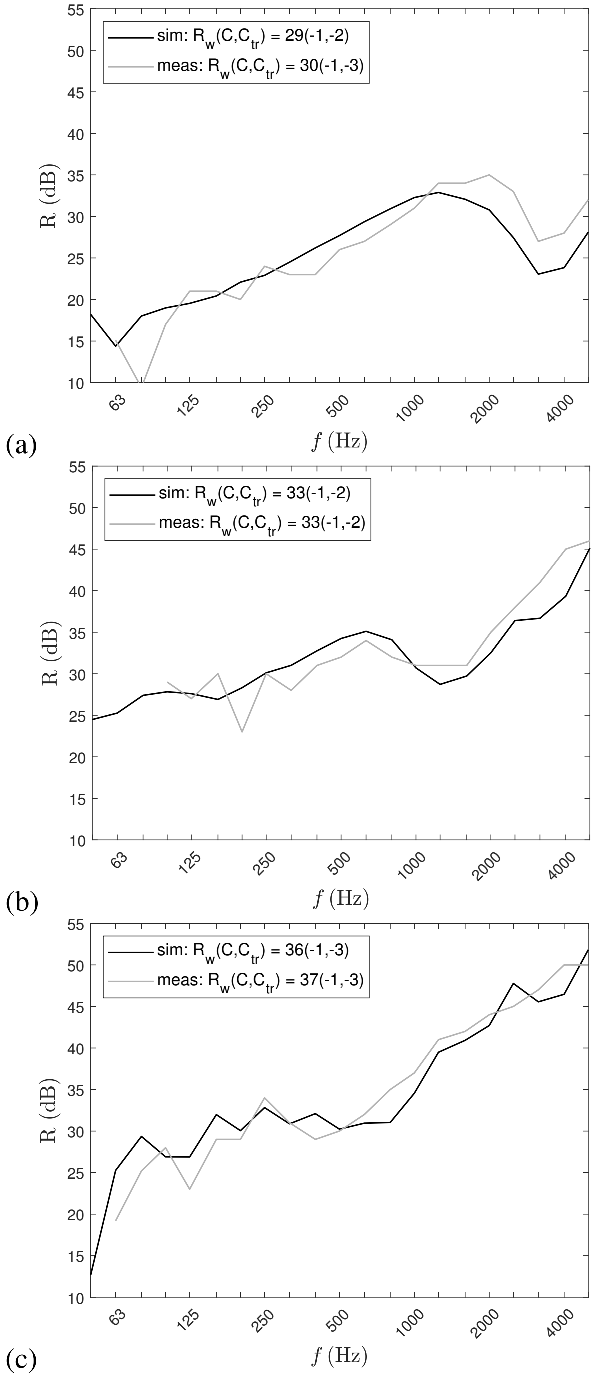

Figure 3. Single glazing: simulation (black) and laboratory measurement (grey). (a) $4\,\mathrm{mm}$, (b) $10\,\mathrm{mm}$ and (c) $19\,\mathrm{mm}$.

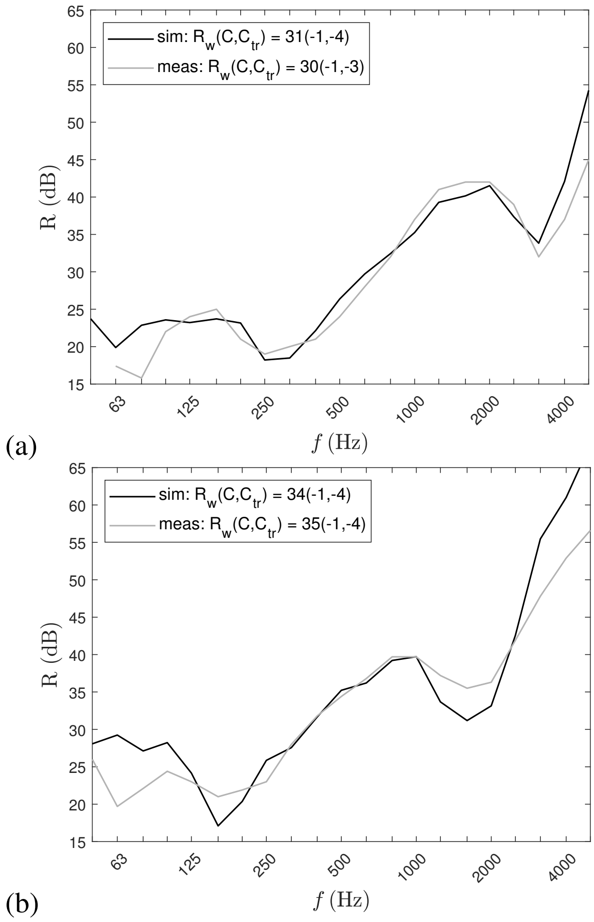

Figure 4. Double glazing: simulation (black) and laboratory measurement (grey). (a) 4-10-4 and (b) 6-12-8.

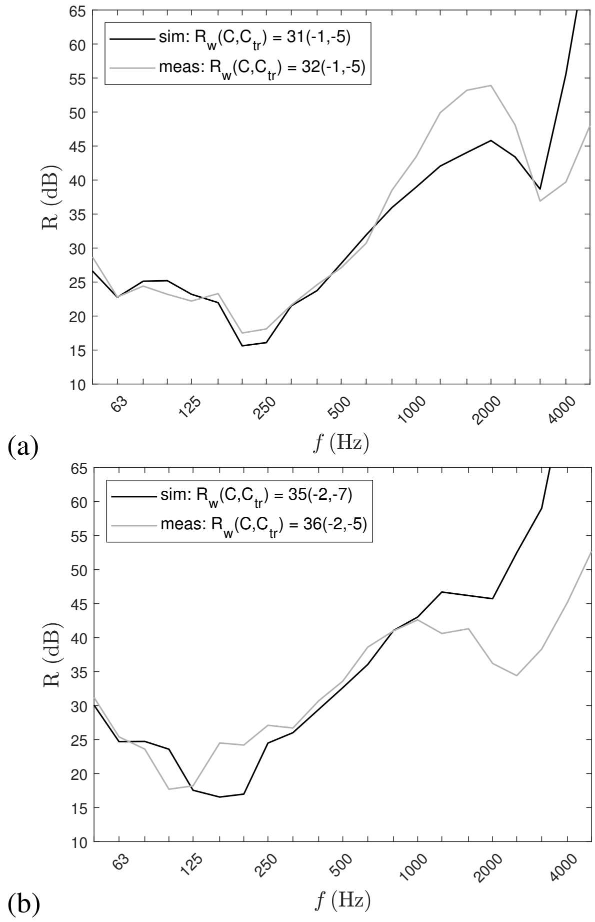

Figure 5. Triple glazing: simulation (black) and laboratory measurement (grey). (a) 4-10A-4-10A-4 and (b) 6-14A-4-14A-6.

for each of the examples is comparable to non-laminated glazing (cfr. $1-2\,\text{dB}$), indicating that both the glazing properties and the assumed frequency and temperature-dependent material properties of the PVB interlayers perform with high accuracy within the prediction model.

The two validation examples for laminated double glazing provide an increasing order of complexity: Fig. 7(a) contains the results for 4-6-33.1 glazing, which has only one laminated glass panel, whereas the results for double glazing with two laminated glass panels (33.2-12-55.2) is displayed in Fig. 7(b). The simulation results for both validation examples contain a spectral shape which is very similar to the measured laboratory values. It is clear that the mass-air-mass resonance and the coincidence phenomenon are correctly simulated and that the sound insulation in the intermediate frequency range as well as low frequencies is accurately predicted. At frequencies above coincidence, however, the simulations indicate a significantly higher sound insulation than measured in the laboratory. This can be attributed to transmission through the mounting frame, which is not included in the simulations. This influence can generally be seen in glazing with high sound insulation, such as the triple glazing in Fig. 5 where this overestimation at high frequencies is also observed. As this effect only appears above coincidence, its influence on the single number rating is very limited, resulting in a prediction accuracy of 2 dB for both examples of the laminated double glazing.

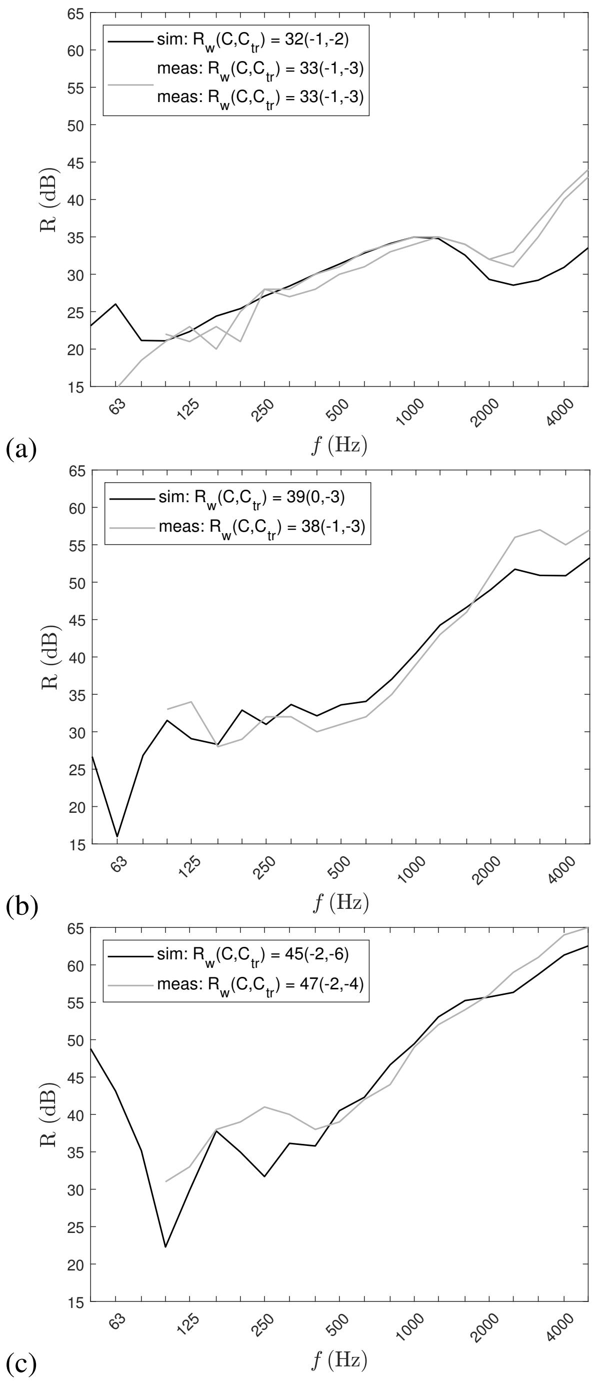

Figure 6. Laminated single glazing: simulation (black) and laboratory measurement (grey). (a) 33.2, (b) 1212.2 and (c) 10101010.6.

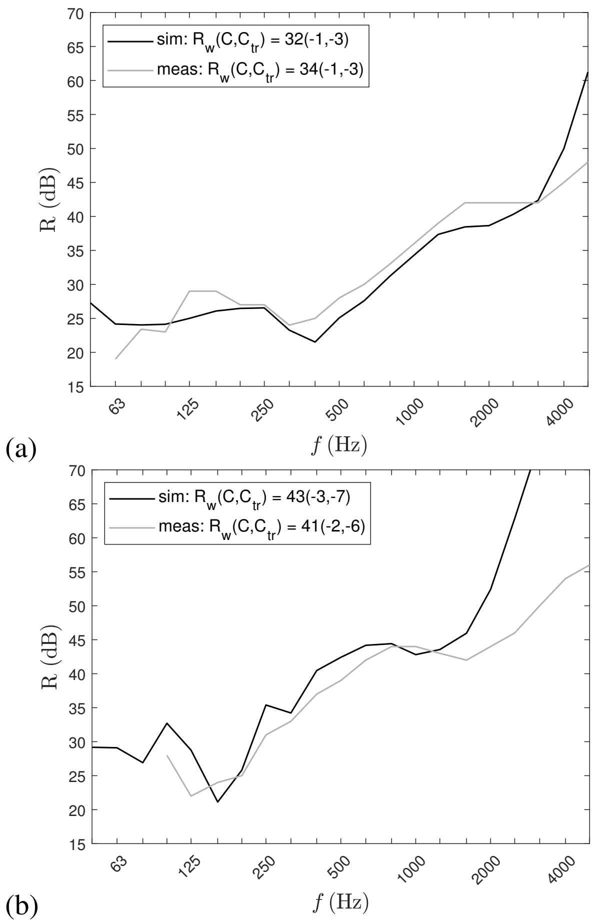

Figure 7. Laminated double glazing: simulation (black) and laboratory measurement (grey). (a) 4-6-33.1 and (b) 33.2-12-55.2.

5. CONCLUSIONS

In this paper, a robust and efficient prediction method for determining the sound insulation of multilayer structures is presented, with a particular focus on glazing examples. The proposed method accounts for various factors such as arbitrary layering, finite dimensions, boundary conditions, and frequency- and temperature-dependent material properties. The results show that the prediction method can achieve an accuracy of $1-2$ dB in the single number rating using predefined values from a material database, and even higher accuracy is attainable when material properties are determined from testing. The method successfully captures key physical phenomena such as the mass-air-mass resonance and the coincidence effect, by using elastodynamics and accounting for material properties that may depend on frequency and temperature, providing reliable predictions for (laminated) single, double, and triple glazing configurations. In addition to the accuracy, the predictions maintain a low computational cost due to the modal approach

The ability to accurately and efficiently predict sound insulation 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 the 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 the influence of frame transmission, double walls with flexible studs, lightweight floors and periodic structures.

6. ACKNOWLEDGMENTS

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