Prediction of the Sound Insulation of Double Leaf Facades with Openings for Natural Ventilation

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Abstract

This paper explores the reliability of acoustical simulation for the prediction of the sound insulation of double leaf facades with openings for natural ventilation. The subject of the study is an experimental modular double-leaf wall with multiple opening possibilities. Different elements can be opened in both (i.e., internal and external) layers, so that multiple opening configurations can be studied both empirically and computationally. The actual acoustical performance of the wall was captured through parametric laboratory measurements. The respective configurations were then modelled using a state-of-the-art room acoustics simulation program. Thereby, alternative representations of the double leaf facade were considered. In one representation, the facade layers were explicitly modelled in terms of two separate entities with the facade cavity as an interstitial space. In other representations, the sound transmission through the wall and the acoustical coupling between openings on the two layers were modelled as separate processes. The initial acoustical model was calibrated by comparing the measured and the simulated reverberation times in the laboratory's two chambers. Specifically, the calibration involved the adjustment of the absorption properties of surfaces of the laboratory chambers so that an improved match between the measured and simulated reverberation times could be achieved. Computer simulation and laboratory measurement results pertaining to the sound insulation of the experimental wall were compared for multiple opening configurations. The results illustrate the potential as well as the considerable limitations of acoustical performance simulation toward prediction of the sound insulation of double-leaf wall systems. Likely reasons for this circumstance as well as potential improvements are discussed.

1. Introduction

Computer simulation techniques have increased the potential for the evaluation of buildings' acoustical performance (Svensson 2008). Computer simulations in room acoustics have been widely studied in the last 50 years (Vorländer 2013). A number of commercial acoustic simulation tools have been developed and are already in use, most of them following principles of classical geometric acoustics. Their reliability and usability in room acoustics is tested and discussed (Vorländer 1995, Bork 2000, 2005, Mahdavi 2011). Some acoustical simulation applications have advanced their algorithms for calculating sound transmission through partition elements (Rindel and Christensen 2008).

Following up on a previous report (Bajraktari et al. 2014), this contribution explores the reliability of acoustical simulation for predicting the sound insulation of double leaf facades (DLF) with openings for natural ventilation.

2. Approach

The Department of Building Physics and Building Ecology at the Vienna University of Technology has conducted studies for developing a double leaf façade that allows natural ventilation while providing sufficient sound insulation (Mahdavi et al. 2012, 2013). Thus, a modular flexible instance of a double leaf facade is installed in our laboratory (Fig. 1 and 2) placed in the opening between two adjacent reverberant chambers. The source room and receiving room of the laboratory have a floor surface of 30.4 m² and 30.6 m² respectively and a

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height of 6.8 m. The experimental DLF (dimensions 3.1 x 3.1 m) consists of two layers (0.43 m apart from each other) of acoustically reflective chip-board panels tightly mounted on aluminium bars. In a grid structure of 5 x 5, each layer has 25 dismountable chip-board square panels (dimension 0.50 x 0.50 m).

Fig. 1 – View of the experimental double-wall with the frame structure for the installation of flexible (individually removable) modular components.

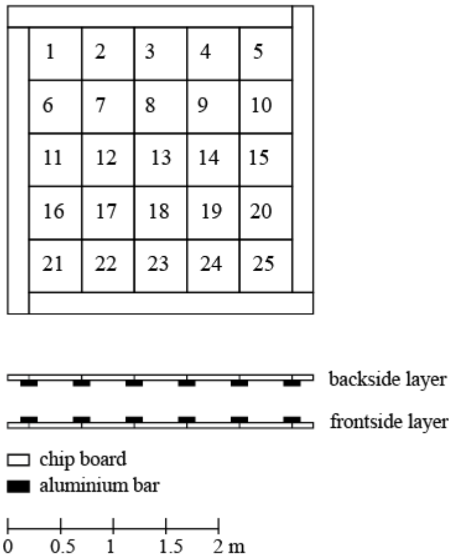


Fig. 2 – Schematic illustration of the double-layered modular experimental wall.

This flexible construction allows us to parametrically modify a number of relevant variables that affect the sound insulation of double leaf facades. Namely, opening area (we can open and close one or more panels in each layer), distance between openings (openings on both layers can be arranged so as to face each other, or to be shifted – see Figure 3), and cavity sound absorption (we can increase the cavity's mean absorption by adding absorption panels in the cavity space between two layers). Sound insulation properties of a comprehensive sequence of DLF configurations were captured via systematic laboratory measurements (Mahdavi et al. 2012, 2013). These configurations are summarized in Table 1.

For simulation, the modelling of the geometry of both acoustic laboratory chambers and the experimental DLF in between was done via SketchUp 8.0 (TNL 2012). This geometry was modelled in a relatively simple fashion (see Figure 4), as adding further details to geometry did not have a noteworthy impact on the simulation results (see also Bork 2005, Siltanen et al. 2008).

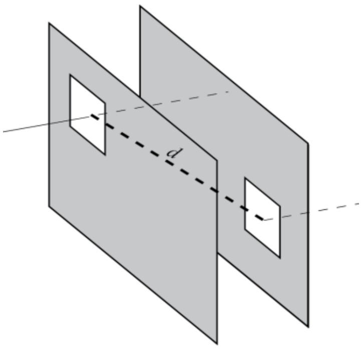


Fig. 3 – Illustration of distance between open elements (d).

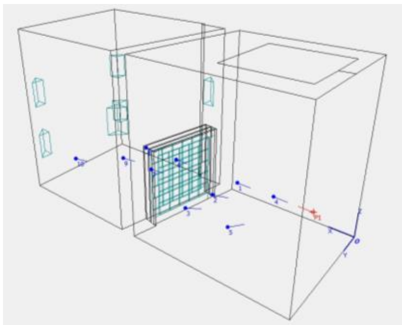


Fig. 4 – Screenshot of the simulation model.

The respective configurations were then modelled and simulated using Odeon 12.0 (Odeon 2013). Odeon combines image source method and ray-tracing for calculating room acoustic parameters (Christensen and Koutsouris 2013).

Alternative representations of the double leaf facade were considered for simulation (Fig 5). In representation A, the facade layers were explicitly modelled in terms of two separate entities with the facade cavity as an interstitial space. In representations B and C, the sound transmission through the wall and the acoustical coupling between openings on the two layers were modelled as separate processes. The latter is approximated with tubes connecting respective openings in the first and second layer.

Table 17 – Measured and simulated configurations of DLF (see Figure 2 for the numeric code of the elements). Note that the elements' distance (d) denotes the spatial distance between the centre points of the open elements (Fig. 3).

Configurations simulated in alternative models			Code of the open elements in the front layer	Number of added absorption panels	Code of the open elements in the back layer	Number of added absorption panels	Distance d (m)
A	B	C					
1	1	1	none	none	none	none	
2			none	none	all	none	
3			7	none	all	none	
4			1	none	1	none	0.43
5			1	none	7	none	0.83
6			1	none	13	none	1.48
7			1	none	19	none	2.16
8			1	none	25	none	2.86
9	9	9	6, 16	none	6, 16	none	0.43
10			6, 16	none	7, 17	none	0.66
11	11	11	6, 16	none	8, 18	none	1.09
12			6, 16	none	9, 19	none	1.56
13	13	13	6, 16	none	10, 20	none	2.05
14			1, 6, 11, 16, 21	none	1, 6, 11, 16, 21	none	0.43
15			1, 6, 11, 16, 21	none	3, 8, 14, 18, 23	none	1.09
16			1, 6, 11, 16, 21	none	5, 10, 15, 20, 25	none	2.05
17	17	17	6, 16	ten panels	6, 16	none	0.43
18	18	18	6, 16	ten panels	8, 18	none	1.09
19	19	19	6, 16	ten panels	10, 20	none	2.05
20			1, 6, 11, 16, 21	ten panels	1, 6, 11, 16, 21	none	0.43
21			1, 6, 11, 16, 21	ten panels	3, 8, 14, 18, 23	none	1.09
22			1, 6, 11, 16, 21	ten panels	5, 10, 15, 20, 25	none	2.05
23	23	23	6, 16	ten panels	6, 16	ten panels	0.43
24	24	24	6, 16	ten panels	8, 18	ten panels	1.09
25	25	25	6, 16	ten panels	10, 20	ten panels	2.05
26			1, 6, 11, 16, 21	ten panels	1, 6, 11, 16, 21	ten panels	0.43
27			1, 6, 11, 16, 21	ten panels	3, 8, 14, 18, 23	ten panels	1.09
28			1, 6, 11, 16, 21	ten panels	5, 10, 15, 20, 25	ten panels	2.05

The difference between B and C models is based on the tubes' length. In B, the length of the tubes is determined by the actual distance between openings in the experimental wall (see Table 2). After comparing the error in weighted sound reduction index of B simulations to the actual length of the tubes, in model C the tube length is adjusted accordingly to reduce the error.

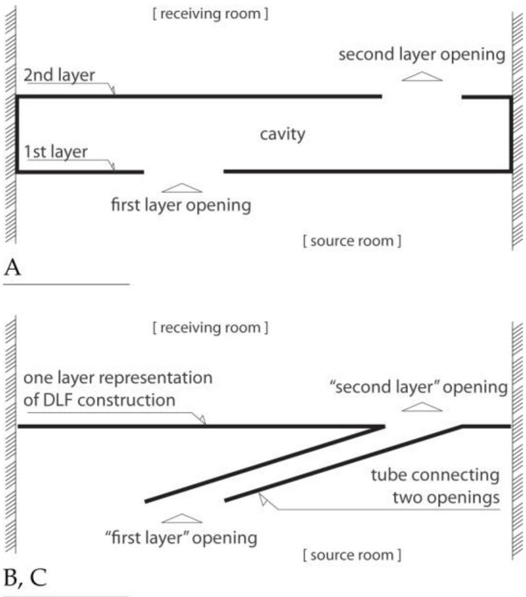


Fig. 5 – Alternative representations of the DLF A model (above) and B and C models (below).

The initial acoustical model was calibrated through an iterative process (Tugrul et al. 2012). Thereby, absorption coefficients of certain surface materials (namely the laboratory chambers' envelopes) were adjusted to achieve a better match between the measured and the simulated reverberation times in the laboratory's two chambers.

Materials and their absorption coefficients were chosen from the existing library, related literature sources, and when available, from producer specifications. In models B and C, the estimated mean absorption coefficient of the DLF cavity is assigned to the tube surfaces.

As to the simulation settings, "Precision" setting was used, as well as transition order 2, number of late rays 32000, impulse response length 5000 [ms]. The calculation of sound transmission from one space to another in Odeon is handled so that a certain fraction of sound "particles" are let through the transmitting "wall" and the rest are reflected back, whereas energy is adjusted by multiplying in both cases with respective factors (Rindel and Christensen 2008). Sound reduction index in third-octave bands for the transmitting "wall" must be given, and in this case, it is taken from the laboratory measurement results.

The aforementioned configurations (Table 1) were computed using the calibrated simulation model – in total 28 configurations were simulated in model A, and 10 of them were also simulated using models B and C. Subsequently, the simulation results were compared with measurement results. Thereby, measured and simulated reverberation times as well as frequency-dependent and weight sound reduction indices were compared.

3. Results

3.1 Reverberation time (T)

In general, for all the models (A, B, and C), a good agreement between simulated and measured reverberation time values was achieved (Figure 6). The errors (particularly in the low-frequency range) may be due, in part, to the fact that the simulation neglects the complex vibrational behaviour of the double layer structure (Bajraktari et al. 2014). Hence, simulation delivers the same values for configurations 1 and 2 (taking into account simply the surface absorption properties), whereas measurements reflect the behaviour of the entire complex structure (in this case of the DLF) (Figure 7).

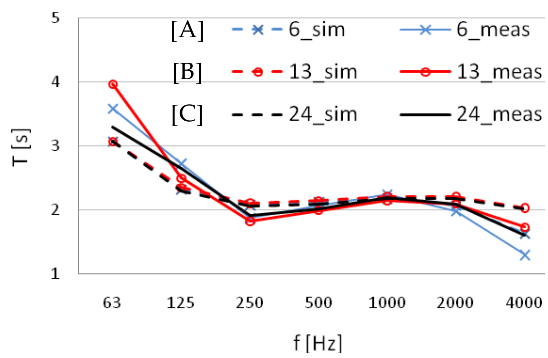


Fig. 6 – Comparison of simulated vs. measured reverberation time (T) in configurations no. 6 (model A), 13 (model B), and 24 (model C) (See Table 1 for the configuration properties).

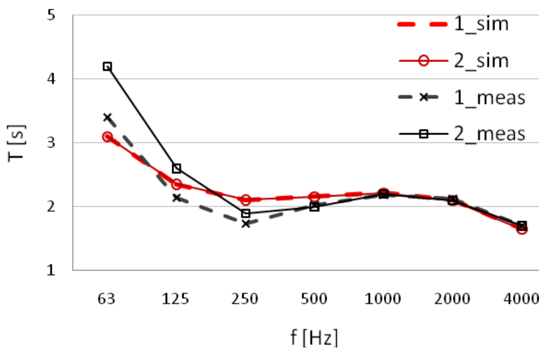


Fig. 7 – Comparison of simulated (_sim) vs. measured (_meas) reverberation time results of configurations no. 1 (both layers closed – double leaf facade) and 2 (one layer closed – single leaf facade).

3.2 Sound reduction index (R)

Figure 8 shows both measured and simulated (model A) sound reduction indices for a number of configurations. Simulation results show large errors especially in low frequencies (125, 250 Hz). At higher cavity sound absorption and with displaced openings the errors tend to become smaller (Figure 8b). The simulation using model B shows a similar performance (Figure 9). The simulation using model C (which is developed after adjusting the length of the tubes in order to compensate for the error found in B simulation results) shows that the alternative modelling of DLF with open elements allows for simple adjustments and leads to better simulation results.

Table 2 shows the overall accuracy of simulation results (for all the models A, B, and C) in terms of R^2 and RMSE, regarding simulated frequency-dependent sound reduction index (R).

Table 18 – Overall performance of the simulation models regarding sound reduction index (comparison only for the 10 configurations modelled with all models A, B, C)

	A	A	B	C
	28 config.	*10 config.*		
R^2	0.79	0.807	0.751	0.807
RMSE	4.3	5.0	5.5	4.5

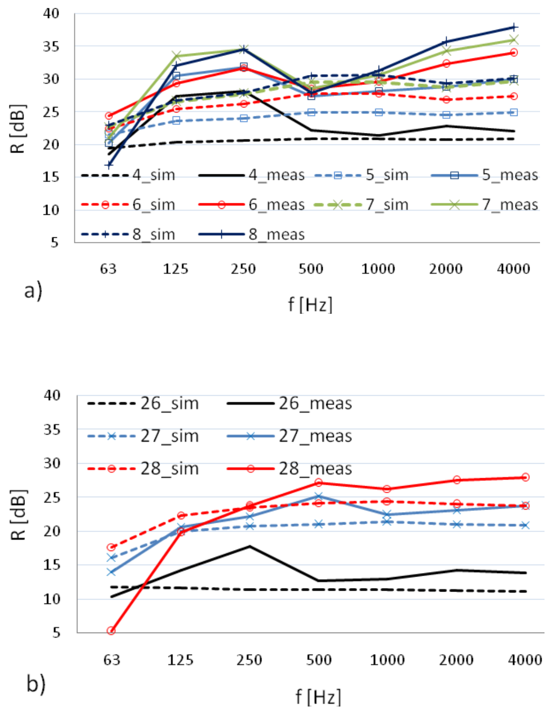


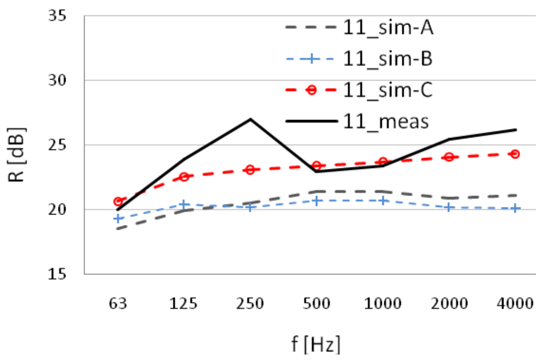
Fig. 8 – Comparison of simulated (_sim, dotted lines) vs. measured (_meas, continuous lines) sound reduction index (R) for two groups of configurations (model A): a) configurations 4-8; b) configurations 26-28 (see Table 1 for configuration specifications).

3.3 Weighted sound reduction index (R_w)

Using simulation results and following the standard procedure (ISO 2013), weighted sound reduction index (R_w) was calculated for each of the simulated DLF configurations. Table 3 shows the overall accuracy of the simulation models (in terms of R^2 and RMSE) with regard to simulation-based weighted sound reduction index values ($R_{w,sim}$).

Table 19 – Overall performance of the simulation models regarding weighted sound reduction index (comparison only for the 10 configurations modelled with all models A, B, C).

	A	A	B	C
	28 config.	*10 config.*		
R^2	0.963	0.974	0.897	0.945
RMSE	2.5	3.4	3.9	2.5



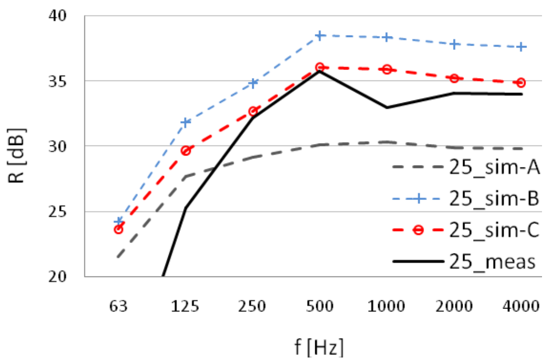


Fig. 9 – Comparison of simulated (model A, B and C) vs. measured sound reduction index (R) for configuration 11 (above) and 25 (below) (see Table 1 for configuration specifications).

4. Discussion

From the comparison results, we can conclude that the simulation results do not reproduce the frequency-dependency visible in the measurement results (Bajraktari et al. 2014). A potential explanation for this circumstance may stem from the fact that the deployed simulation tool currently does not model the complex wave phenomena inside the DLF cavity (Bork 2005, Vorländer 2013). Alternative representations of DLF did not compensate for the simulation tool's limitation, but allowed for simple and intuitive adjustments that led to improved simulation results.

5. Conclusion

The comparison results suggest that currently the acoustical performance of the double leaf facade cannot be accurately predicted using a room acoustics simulation application, even though the simulation model was calibrated using measured values of reverberation time (Bajraktari et al. 2014). Specifically, the frequency dependency of the measured sound insulation of the DLF could not be accurately reproduced via simulation. A contributing factor to this circumstance may lie in the simulation algorithm's disregard of complex wave phenomena in the cavity space between the two layers of the DLF. On the other hand, a better predictive performance could be achieved while computing the weighted sound reduction index values. In this case, a RMSE of 2.5 was achieved. It is expected that ongoing efforts in advanced room acoustics simulation including wave phenomena (Savioja 2010, Kowalczyk and van Walstijn 2011, Borrel-Jensen 2012) could improve the overall performance of simulation tools, leading also to better future results concerning DLF analysis.

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