On the use of scaled models in building acoustics

Volker Wittstock[a], Martin Schmelzer[b] and Christoph Kling[b]

[a]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
[b]Physikalisch-Technische Bundesanstalt, PTB, Working group 1.71 'Building Acoustics', Bundesallee 100, 38118 Braunschweig, Germany
volker.wittstock@ptb.de

Experimental studies of physical effects in building acoustics are usually time consuming and expensive. This is mainly caused by the building costs but also by the experimental effort. It is, thus, desirable to use another method for the investigation of basic effects in building acoustics.
Building acoustic problems are characterized by the interaction between airborne and structure-borne sound fields. It is, therefore, possible to use scaled models when both sound fields are treated correctly. This means that the wavelengths in the airborne and in the structure-borne sound fields have to be scaled in the same way. With a significant reduction of all lengths (typically 1:8), the costs can be reduced drastically and nearly all model parameters can be changed separately. Due to these advantages, this technique is used in PTB's building acoustics group.
This paper gives an overview on the physical background of scaled models, reports on validation experiments and on several applications, e.g. investigations of the influence of temperature and static pressure, damping effects, geometry influence on the sound insulation of walls, the measurement of the flanking transmission of walls and the measurement of suspended ceilings.

1 Introduction

One main focus of research work in building acoustics is to develop a physical understanding of the excitation, propagation and radiation of sound in buildings. In principle, this work can be done by analytical or numerical calculations or by experiments. For the latter, the use of scale models may be considered, which reduces the building costs drastically and enables a geometric parameter variation in a wide range. After a short introduction to the scale model technique, the paper gives an overview of the research work at PTB's building acoustics group, carried out using scaled models.

2 Basic idea

The case of airborne sound transmission between two adjacent rooms is considered to derive the basic idea of the scale model technique (Fig. 1). The sound source in the sending room feeds an airborne sound field which not only excites the separating wall, but also the flanking elements. Structure-borne sound fields develop on those elements which radiate sound into the receiving room.

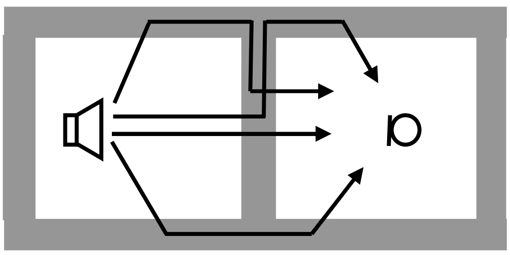

Fig. 1 Sound transmission between two adjacent rooms.

This situation is now to be investigated by an experimental setup which is much smaller than the usual two 50 m³ rooms but shows the same physical phenomena. Firstly, the airborne sound field in the rooms has to be similar to the original case. The similarity is achieved when the ratio between the wavelength and the room dimensions is constant. This means that a reduction of all the dimensions by a factor of *m* can be compensated by increasing the measurement frequency by the same factor.

The structure-borne sound fields in the model and in the original case also have to be similar. These fields mainly consist of bending waves but longitudinal or other wave types may also exist. To show the same behavior, the ratio between the wavelength and the dimension of the solid body must be the same in the model as in the original. This can be ensured by using a material with the same speed of longitudinal waves, i.e. the same ratio between the Young's modulus and the material density. Scaling all dimensions of the walls (length, width, thickness) by a factor of *m* ensures then that the structure-borne sound fields are similar when the frequency is increased by the same factor.

The amount of energy transmitted from the airborne sound field to the structure-borne sound fields basically depends on the ratio between the airborne and the structure-borne wavelengths. This ratio is the same in the model and in the original case and, thus, the physics of the excitation is modeled correctly. The same argument applies for the transmission of sound on the different flanking paths and for the radiation of sound. Hence, all the main features of the original situation are well simulated in the model.

3 Examples

3.1 Static pressure influence

An analysis of the sound transmission path [1] revealed that there is a systematic influence of the static pressure on the sound reduction index. Two effects account for this influence. Firstly, the sound power radiated by a vibrating structure into the receiving room is in direct proportion to the sound impedance in air and thus to the static pressure to the power of –0.5. Secondly, the sound pressure produced in the sending room by a sound power is equally dependent on the sound impedance, i.e. on static pressure. Since the sound reduction index is the ratio between the sound powers, it is in indirect proportion to the static pressure. This result was derived theoretically and experimental proof was considered to be important.

The availability of some measurement data were available that could be used to verify the theoretical results was initially ascertained. Two kinds of measurement results were found.

The first kind of data sets comprises repeatability results. These are obtained in the same test suite for the same test specimen over a period of some weeks. Due to the weather, static pressure slightly changed over the measurement period. Unfortunately, these variations would account for only a 0.2 dB change in the sound reduction index. This is a small amount in comparison to the standard deviation of repeatability which is typically 0.4 dB. The effect of static pressure and temperature cannot therefore be derived from repeatability data.

The other kind of measurement data consists of reproducibility results. Since these results were obtained at different laboratories at different geographical altitudes, the static pressure variations led to a change in the sound reduction index or in the normalized impact sound pressure level of up to 0.5 dB. But the standard deviation of reproducibility is of the order of 1.2 dB. This means that the use of different test suites leads to much larger changes in the measurement results than meteorological effects.

The uncertainty of the measurement results is thus too large to allow any static pressure or temperature influence to be identified in the two cases.

It follows that there are two different approaches to verify the theoretical results by experiment. The first approach would consist of a significant decrease in the measurement uncertainty. But even with a considerable increase in the measurement efforts, it appears to be doubtful whether the required accuracy can really be achieved.

Therefore, the second approach was used where the effect is artificially amplified by changing the static pressure more substantially. This is achieved by integrating a wall test facility scaled down by a factor of 12 in a pressure vessel in which the static pressure could be reduced down to 307 hPa in 2 dB steps.

The test specimens are selected so that frequency ranges below, at and above the coincidence frequency, different material properties like mass per area, damping and stiffness and different resonant effects are covered. For this purpose, four different single- and two different double-shell structures were selected.

The measured sound reduction indices of all test specimens reveal a strong influence of the static pressure in all frequency ranges. In the case of single-shell specimens, the theoretically predicted static pressure influence is confirmed by the measurement results (Fig. 2) whereas the static pressure influence is even stronger for the double-shell specimens (Fig. 3). This experimental verification could be obtained without too much financial effort due to the scale model technique.

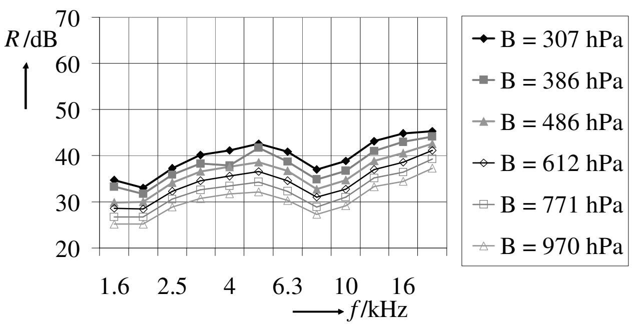

Fig. 2 Sound reduction index *R* of a 1.5 mm aluminium plate at different static pressures *B*.

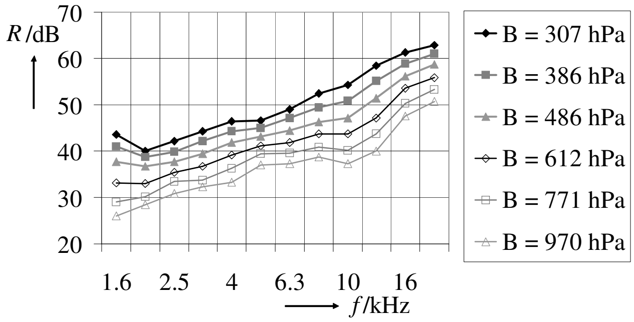

Fig. 3 Sound reduction index *R* of a double-shell specimen consisting of a 3 mm hard board (m´´ = 2.55 kg/m²) and a plastic film (m´´ = 0.25 kg/m²) with 34 mm spacing at different static pressures *B*.

3.2 Wall test facility

Based on the scaling studies, a miniature version of a building-acoustics wall-test facility has been designed to the scaling factor 1:10 [2], which meets the requirements for a standardized test facility of ISO 140-1. Solely the flanking transmission has - intentionally - not been suppressed to enable better studying of the damping and transmission effects. In the model test facility, the sound reduction index of acrylic plates of different thicknesses was measured in different mounting situations according to the standard.

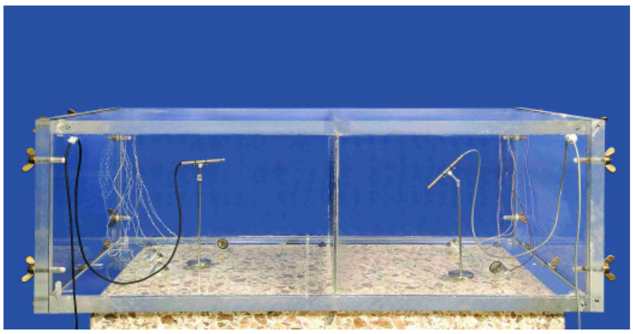

Fig. 4 Scale model of a wall test facility made of acrylic glass.

It could be demonstrated that the sound reduction index determined in the model on acrylic plates corresponds well with the damping of a comparable solid wall which was measured in a "real" wall-test facility. In particular, such typical effects as coincidence, thickness resonance and the behaviour of elastic mountings could be emulated very well both qualitatively and quantitatively (Fig. 5, Fig. 6).

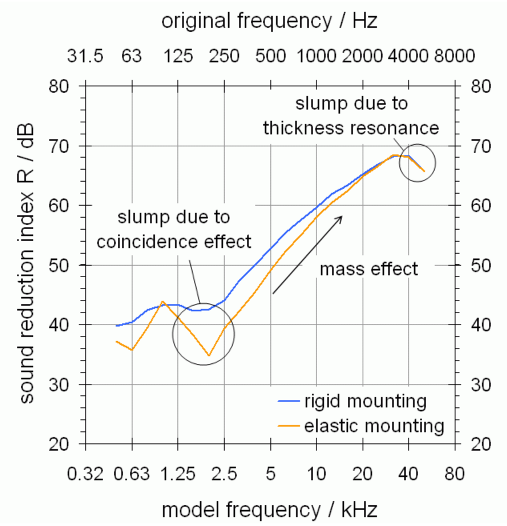

Fig. 5 Sound reduction index of a 24 cm lime brick wall.

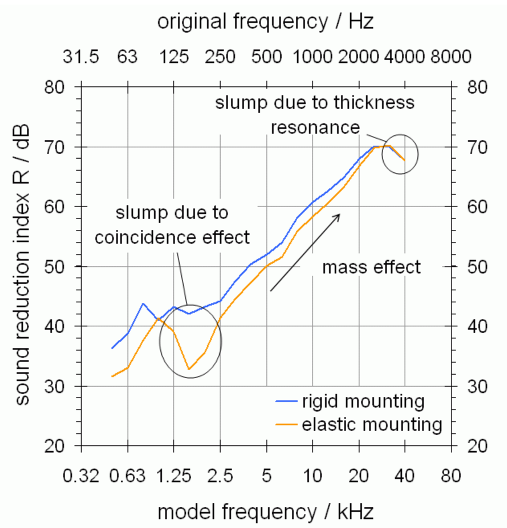

Fig. 6 Sound reduction index of a 25 mm acrylic glass wall.

3.3 Geometric parameter variation

Scale models can very effectively be used to carry out parametric studies on the influence of geometric parameters.

One question that was addressed in this respect was whether a shift of the structure-borne vibration modes of walls can explain the large standard deviations of reproducibility observed in round robin tests with heavy walls [3]. The basic idea of the investigation was to vary the size and the aspect ratio of the separating wall, whereas the sending and the receiving room were kept constant (Fig. 7). The experimental setup was a 1:8 model of a wall test facility which consisted of 38 mm thick medium density fiber boards (Fig. 8). Test objects were hung on a crane and could, thus, be much larger than the opening of the test facility.

It turned out that the low modal density of heavy panels accounts for an uncertainty of between one and two dB for the laboratory sound insulation in the low third-octave bands. This explains part of the uncertainties observed with heavy walls. Nevertheless, due to the uncorrelated superposition of the third-octave band values, the weighted sound reduction is affected much less. The standard deviation for the modal effect is only between 0.2 and 0.5 dB.

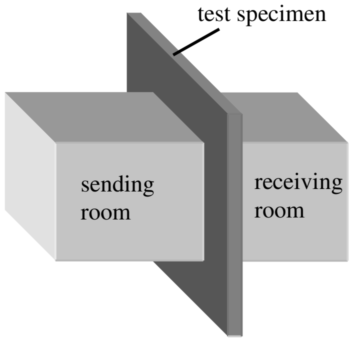

Fig. 7 Basic idea for the investigation of the influence of structure-borne modes on the specimen.

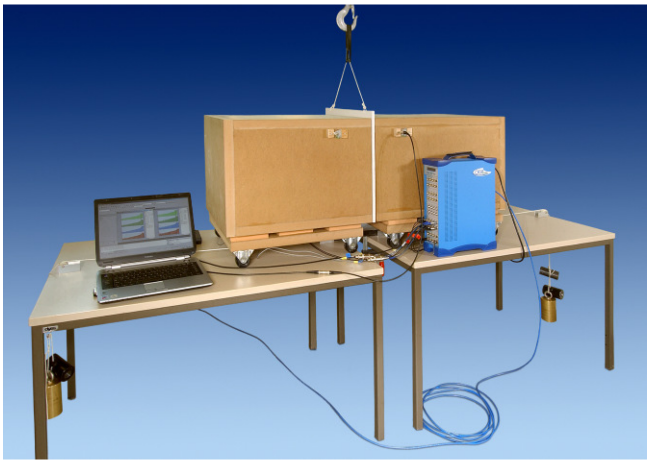

Fig. 8 Measurement setup for the investigation of the influence of structure-borne modes on the specimen.

Another interesting question is whether the sound reduction index of a wall is different when it is determined between two rooms of equal or of different size. The latter is the case in laboratories, whereas the first may be the case in actual buildings. A special model test facility was designed to investigate this effect with back walls which could be shifted. The scaling factor was also 1:8. The experimental investigation comprised 12 different geometries, 6 resembling a laboratory and 6 resembling buildings. The sound reduction index of a heavy and a lightweight test element was determined in all 12 geometries. The main result of this investigation was that the sound reduction index is systematically smaller between two rooms of the same size (Fig. 9) whereas the standard deviation is on average larger for the building situation than for the laboratory situation.

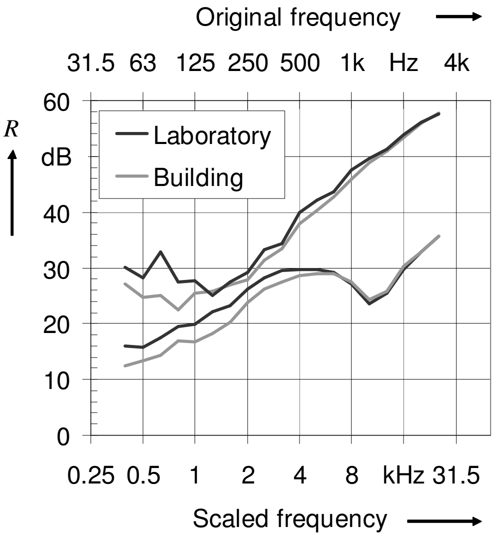

Fig. 9 Mean value of the sound reduction index of a heavy (upper two curves) and a lightweight element (lower two curves) in six different laboratory und building geometry simulations

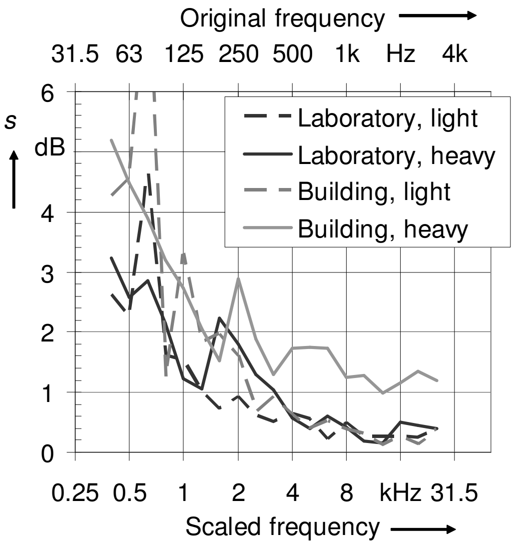

Fig. 10 Standard deviation of the sound reduction index of a heavy and a lightweight element in six different laboratory und building geometries.

3.4 Flanking transmission

The prediction of the sound insulation in buildings requires the knowledge of the flanking sound reduction of flanking components of buildings. Only a few laboratories possess the necessary test facilities for the measurement of the flanking sound reduction. Instead, flanking test objects are usually installed into normal test facilities thereby producing a flanking cavity (Fig. 11).

It was the task of a research program funded by the Deutsches Institut für Bautechnik to examine the influence of these flanking cavities and to clarify under which conditions the flanking sound reduction could be measured using this substitute setup.

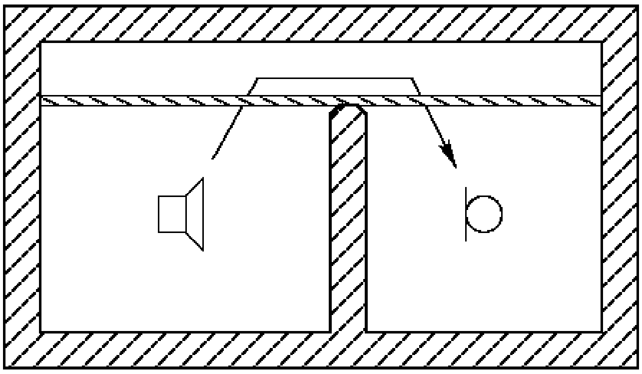

Fig. 11 Layout of a test facility with a flanking test object installed alongside the test facility wall (top view).

Considerable attention was paid to the examination of the paths of sound propagation by incremental changes in the construction of the model test facilities. In doing so, the influence of the test object emerged significantly.

Further changes in the construction were undertaken to vary the thickness of the test object, the depth of the flanking cavity and the damping within that cavity by mineral absorbers. While doing this, the sound transmission through the flanking cavity could be examined.

In particular with single-leaf lightweight test objects installed, a significant influence on the flanking sound reduction was observed by special airborne modes arising inside the flanking cavity. Insertion of absorbing material into that cavity – as a single layer behind the test object or as strips covering floor, ceiling and both walls of the cavity – allows the damping of these airborne sound modes and the sound transmission accompanied by them (see Fig. 12).

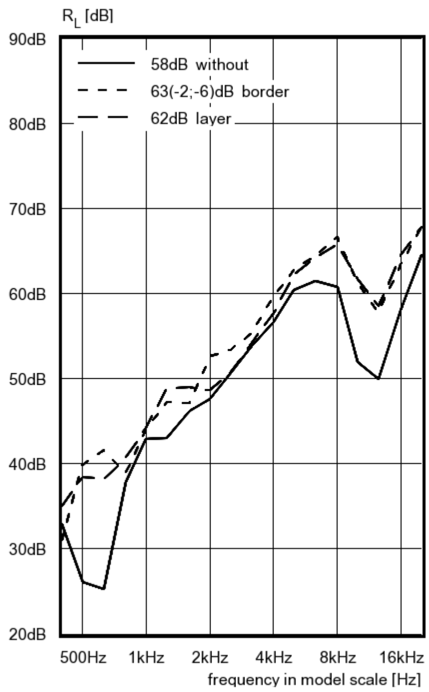

Fig. 12 Flanking sound reduction of a single-leaf test object with cavity damping varied (without damping, with strips in front of the cavity floor, ceiling and walls (border) and with one layer behind the test object); cavity depth 5 cm.

The comparability of measurements of interior building elements, therefore, requires the exact specification of the geometry of the flanking cavity as well as kind and position of damping material within that cavity. On the other hand, as too much damping can lead to an overestimation of the flanking sound reduction, the usability of the measurement results for prediction purposes is no longer given. Using no damping at all in the flanking cavity is thus recommended.

For facade elements a test facility has to avoid any flanking cavities and is to be settled within an anechoic sound field.

Double-leaf test objects showed no sensitivity towards the variations of the cavity at all.

3.5 Suspended ceilings

A similar situation arises in frame construction buildings, where the individual rooms are often separated from one another by lightweight constructions and provided with a suspended ceiling. An air volume and thus a bypass for sound propagation is formed between this suspended ceiling and the solid ceiling above it.

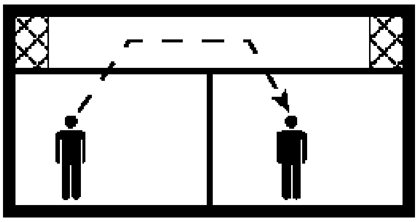

Fig. 13 Layout of a test facility with a suspended ceiling.

The standardized method reduces the multiple-room constellation to two rooms and simulates the air cavity over the multiple-room constellation by lateral absorbers in the ceiling cavity of the limited arrangement (Fig. 13). This arrangement can influence the longitudinal sound reduction of the lower ceiling and can spoil the correct representation of the normally existing multiple-room constellation.

Two types of suspended ceilings were examined: a plate of acrylic glass and layers of fleece superimposed on a perforated metal plate. These two types represent a compact airtight ceiling and a porous ceiling, respectively.

It was shown that suspended ceilings with low absorption on their own, are very sensitive towards the insertion of damping material into the cavity. The compact suspended ceiling without absorbing material upon it, resulted in a monotonous increase of the longitudinal sound reduction with the increasing amount of damping material in front of the lateral walls of the cavity.

When this suspended ceiling was covered with only one layer of absorbing material upon it, the dependency on further sound absorbing material in the cavity was decreased significantly.

Using a porous suspended ceiling, which naturally has a high sound absorption on its own, the dependency on further absorption within the cavity and on other modifications of the cavity vanished almost completely.

For all these ceiling types, the setup according to the standard was sufficient for the measurement of the longitudinal sound reduction, in the case that the segments of the frame construction are in the vicinity of the walls of the ambient room only.

Increasing the amount of sound absorbing material in the cavity increases the longitudinal sound reduction by value significantly, but improves the representation of the real case by the setup according to the standard only slightly.

4 Conclusion

This scale model technique has proven to be a very efficient tool for basic research in building acoustics. It was used for many different applications at PTB where an experimental investigation on an original scale would have been much too expensive. It is planned to extend the model technique to structure-borne excitations of test specimens like the excitation of a floor by a tapping machine.

Acknowledgments

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