Building acoustics: From prediction models to auralization

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ABSTRACT

Following the processes of international harmonization, measurement methods for sound insulation material and prediction models for characterization of field situations were recently reviewed. In the area of prediction, a great step was made towards a physically sound and practical method for describing noise sources of airborne and structure-borne sound in buildings, the transmission in the building structure and radiation into the receiving room. The subsystems of a building, its beams, plates and cavities can be assumed to show statistical modal behaviour. Hence the modal density is sufficiently large for purely energetic considerations using, for example, statistical energy analysis. On the basis of this prediction model and its results in frequency bands, an algorithm of digital signal processing can be added which enables modelling of the sound signal flowing through the building and to the receiver. The auralized sound can be used in various applications: The method opens the possibility to demonstrate effects, also in teaching, to investigate sound effects and annoyance, by variation of construction parameters and systematic listening tests or psychoacoustic analysis.

INTRODUCTION

In industrialized countries and particularly in urban areas, noise control in buildings must be considered a matter of public interest and, thus, of political discussion. Accordingly the communication of acoustic problems between experts and non-experts is of crucial importance. Sophisticated tools are available for obtaining information about sound insulation, in the acoustic situation in the laboratory and finally in the building. Improvement of acoustic comfort and protection against noise can be investigated and planned well in research, development and consulting. The acoustic engineer is trained to discuss numerous temporal and spectral details which may lead to an improved acoustic situation for the client. The discussion, however, must be simplified regarding the description of the problem by using single numbers, for instance R_{w}, $D_{\mathrm{nT,w}}$, etc. in order to communicate with acoustically untrained people. Single numbers are also important as a common basis for simple noise control measures for a harmonisation of noise regulations and noise limits. The link between the disciplines of engineering acoustics on the one hand and annoyance research on the other is, usually, a single number, to be obtained from objective measurements or prediction models.

In order to help in building design and to calculate final ratings, however, prediction models are required which yield results in same or similar complexity as measurements, typically data in one-third octave bands between 100 Hz and 3150 Hz or extended to higher and lower frequencies. These prediction models are based on material data and on construction details. They can be treated in the same manner as measurement results and they can be rated to single number.

In many situations, however, existing single numbers do not reflect all dimensions of the problem. Basic research is still required to create new and more specific single number quantities describing the relevant factors of comfort and annoyance with a more specific meaning.

Having this in mind, it is clear that the perfect link between results from acoustic measurement or from prediction models and finally results in single numbers is the technique of auralization. It is the perfect carrier of information from the acoustic expert to the population, to local authorities and to politicians. Auralization is the way of creation of audible sounds based on prediction of sound insulation in buildings.

PREDICTION MODELS

The most simple model approach is based on material data like mass, stiffness and losses. For monolithic constructions this might be easy, but for multi-layers and for lightweight constructions this is a quite demanding task. Construction details can hardly be taken into account in analytic approaches. Furthermore, the weakest part of a construction element is often the connection between different materials, its details with regard to thermal and acoustic insulation are often optimized by trial and error. Nevertheless much progress was made with regard to models of bricks, glass and concrete. Transfer matrix models allow wave type superposition and, hence, prediction of multi-layered wall and floor constructions with several viscous layers, for instance.

The prediction, too, must be valid for finite size elements rather than for infinite areas. Again, the frame, its mechanical connection, the corresponding degrees of freedom of motion and the mounting method becomes more important since the bending wave radiation depends on the modal field and on the interaction of modal anti-phase zones. Also here, for monolithic constructions estimations are possible.

The biggest challenge, however, is given by the fact that not only single walls and floors but complete buildings must be considered. Architecture creates new designs like stepped or staggered rooms, modern lightweight facades are used for new ways of combining modern thermal insulation and energy reduction or for producing solar energy. Flanking transmission along facades became more relevant compared to the situation some years ago.

The challenge of dealing with flanking transmission is not new, of course. For decades building acoustics research has focused on measuring and predicting flanking transmission and to transfer laboratory results to field situations.

EN 12354

The harmonized European standard [EN 12354] has been applied in building practice for several years now. It describes a physical model of sound transmission in buildings based on the performance of building products and elements. In this model, the sound energy in modal systems is considered, as well as its magnitude and its flow through the building elements, the energy exchange between adjacent building elements, and the energy losses. "Systems" in this respect are, for instance, rooms, plates, or beams, thus, sound and vibration field media with boundary conditions. Under steady-state conditions, the basic equations remain rather elementary since the energy balance just requires knowledge of the mean energy, the mean losses, and the coupling mechanisms between the systems. The method to determine the transfer function between source and receiving room must be adequate to cover these aspects. A physical model available for this task is the Statistical Energy Analysis, SEA. The basic publications which were used for the development of the harmonised standard are papers by [Gerretsen1979, 1986]. His prediction model is equivalent to SEA.

The input data for the flanking transmission model can be taken from analytic or numerical calculation or from standardized laboratory measurements. The equations for the prediction of the global sound insulation are basic but complicated in grand total, as they form a set of numerous variations of materials, junctions, room dimensions etc. The results are sound insulation quantities like the sound reduction index, the standardised or normalised sound level difference in one-third octave bands. Now the total sound level difference in terms of D_{nT}, for instance, can be calculated by adding all transmission coefficients, τ, if the sound signals are incoherent:

$$\begin{aligned} D_{\mathrm{nT}} &= -10\log\tau' + 10\log\frac{0{,}32\,V}{S} \\ &= -10\log\tau_{\mathrm{nT}}\ ,\ \left(\tau' = \sum_{i=1}^{N}\tau_i\right) \end{aligned} \tag{1}$$

with V denoting the receiving room volume in m^3 and S the separating wall surface in m^2.

The frequency-dependent results of eq. (1) are then fed into the rating procedure. In an attempt to condense the acoustic performance into one number, the "single number" is defined. It may well happen that cases of complaints and severe problems are taken to court for a final decision. Complaints about low-frequency noise, below 100 Hz, or the violation of speech privacy, both not included in the interpretation of the weighted standardized sound level difference modified by spectrum adaptation term, $D_{\mathrm{nT,w}}+C_{\mathrm{tr}}$, are examples which cannot be decided by straightforward means, neither by the expert nor by the local authorities or the judge in court. A general demand for acoustic comfort can hardly be defined in such cases since the actual situation of the noise problem, the activities of humans affected and the context of the situation must be considered, too. Therefore the importance of the areas of noise effects, annoyance research and related fields can be expected to grow in the future.

As discussed by [Rasmussen2004], among others, in European countries a formally "harmonized" noise rating system was introduced, but in fact in Europe 24 different specific single number quantities are in use to describe the same thing: protection against noise from neighbours. What is desirable is more research on noise effects in various situations in the living and work environment and, in consequence, modern tools like sophisticated instrumentation, a few general rating systems based on sound levels as "first approach", and some others added with more specific meaning, expert systems for the reduction of complex information into a single number of "annoyance", "acoustic comfort", "speech privacy", "health protection". This goal can only be reached by expanding intensive studies of noise effects and by expanding the question of each test towards comfort and health effects caused by mid and low sound levels.

AURALIZATION

The term "auralization" is well known in room acoustics, but so far not in building acoustics. The principle of auralization is illustrated in figure. 1. It shows the basic elements of sound generation, transmission, radiation and reproduction. From figure 1, it becomes clear that the coupling between the blocks needs special attention. In room acoustics, there is hardly an effect of the room on the source (although a singer might adapt his or her voice when singing in a reverberant room). Typically, the signal transmission path is modelled in forward direction only (without reaction). In building acoustics, however, the situation changes completely. The velocity injected into a system of beams and plates depends strongly on the kind of vibration source and on the mobility of the transmitting element.

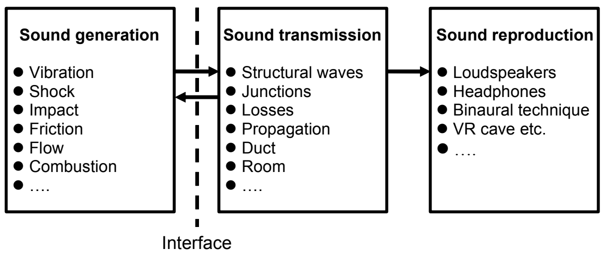

Figure 1. Principle of auralization

Provided, the transfer functions of the elements are known from calculation or measurement, the signal transmitted in the building structure or room is processed by convolution. Accordingly, the transfer function is the transfer function of a "filter". To illustrate this point further, some examples are given in the next sections.

Eq. (1) can also be expressed by using squared sound pressures:

$$p_{\mathrm{R}}^2 = p_{\mathrm{S}}^2\,\frac{\tau_{\mathrm{nT}}\,T}{0{,}5\ \mathrm{s}} \tag{2}$$

with p_{S} and p_{R} denoting the sound pressure in the source and the receiving room respectively and τ_{nT} denoting the (standardised) transmission coefficient. It should be noted that τ_{nT} , like τ', is composed of the sum of all transmission paths (see figure 2 and eq. (1)).

In terms of sound pressure signals flowing through the building structure and rooms, the equation reads [Vorländer et al 2000a]:

$$p_{\mathrm{R}}(\omega) = p_{\mathrm{S}}(\omega)\sum_{i=1}^{N} f_{\tau,i}(\omega)e^{-j\omega\Delta t_i} f_{\mathrm{rev},i}(\omega) \tag{3}$$

with $f_{\tau,\mathrm{i}}$ denoting interpolated filters related to the transfer functions between the source room and the radiating walls and Δt_{i} denoting the relative delays in the receiving room. $f_{\mathrm{rev,i}}$, is the transfer function between the radiating wall i and the receiver. $f_{\tau,\mathrm{i}}$ must have the same one-third octave band spectrum as the corresponding path transmission coefficient, and $f_{rev,i}$ is a classical room transfer function derived from the impulse response between the wall and the receiver. The radiation from the walls can be sufficiently modelled by using equivalent point sources in their centres.

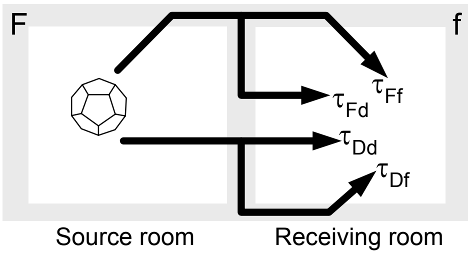

Figure 2. Room to room situation with sound transmission over various paths denoted by indices with capital letters for the building element in the source room (Direct or Flanking) and with lower case letters for the building element in the receiving room (direct or flanking).

VERIFICATION AND EXAMPLE APPLICATION

For a more correct verification, recordings and measurements on a real building situation were carried out. The situation consisted of two adjacent office rooms in the Institute of Technical Acoustics. The reverberation times and the sound reduction index were measured and used as input for an auralization. Additionally, sounds of different sources were recorded with two dummy heads and a microphone in the source and receiving room, and compared in a listening test. Two auralized versions were used and compared with the recordings. The reverberation times at 500 Hz are T_{source}(500 Hz) = 0.54 s and T_{recv}(500 Hz) = 0.69 s. The measurements of level differences were carried out according to [EN ISO 140-4]. Five microphone positions in each room and 2 speaker positions in the source room were chosen. The measurement setup can be seen in figure 3. For the measurement of level differences, a sweep signal was replayed from a two-way loudspeaker system, and the sound pressure levels in both rooms were recorded. The measured and auralized standardised sound level differences $D_{nT} = L_{source} - L_{recv} + 10\log(T_{recv}/0.5\ s)$ and the reverberation times in one-third octave bands are shown in figure 4.

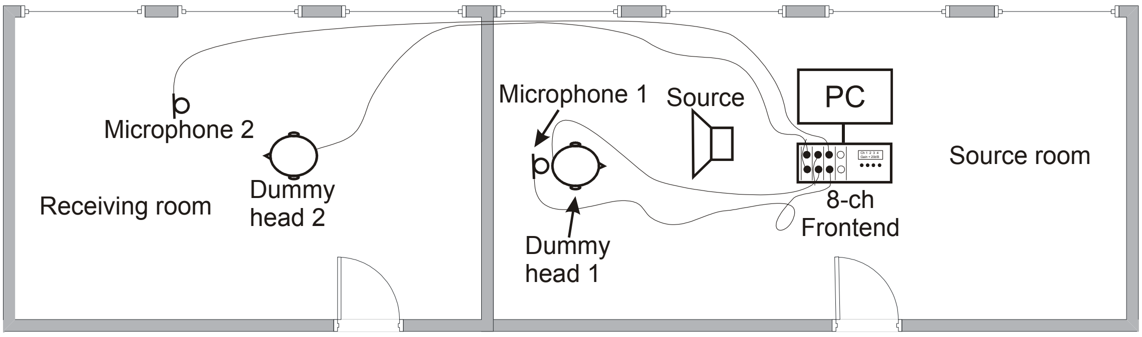

Figure 3. Verification test: measurement and auralization.

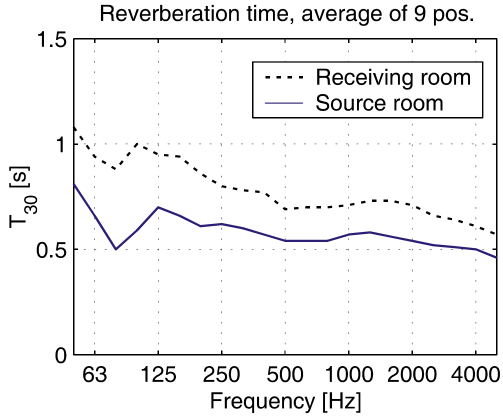

Figure 4. Reverberation times in source and receiving room.

The deviation of the auralized level differences from the measured level differences is mostly below 1 dB. Only at low frequencies a deviation of more than 2 dB occurs. These uncertainties are acceptable since they occur in measurements at these low frequencies anyway due to modal effects. For the auralization "measurement", only one point in the receiving room was chosen.

Comparison with simple equalization

A much simpler approach for an auralization is to just generate an acoustic filter (equalizer) from the level differences and to neglect the room acoustical properties in the receiving room. This was also done for the room situation described above, and a comparison between detailed and simple auralisation was carried out by listening tests. For this, sound recordings were made with the setup as seen in figure 3. Different sources were replayed (or performed live) in the source room and the signals were recorded in both rooms simultaneously with dummy heads and microphones. From the microphone signal in the source room, an auralization of the receiving room signal was done and compared to the real recording in the receiving room.

In a listening test, subjects had to judge differences in level and colouration and the naturalness of the signals in paired comparisons [Thaden2005]. From these comparisons, it can be deduced that the level differences are reproduced correctly by both algorithms (deviations below 1.7 dB). The colouration is better reproduced by the detailed auralization. The

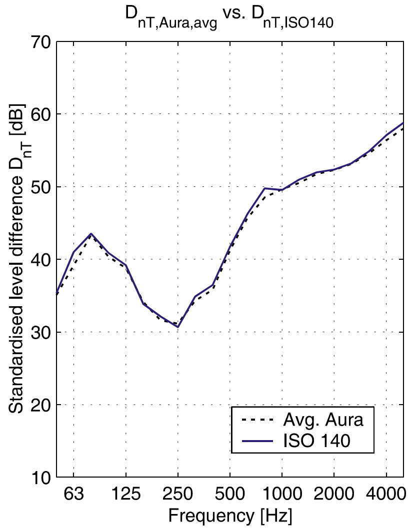

Figure 5. Standardized sound level difference of auralization and measurement.

difference in colouration between auralization and real recording was judged between “just noticeable” and “small”. The detailed auralization is judged to produce slightly more “natural” signals, that is, they better meet the expectations which the subject had from the sound field in the receiving room

Sound insulation and speech intelligibility

In listening tests related to speech intelligibility in buildings or in open-plan offices, it could be shown that simple single number rating procedures are not generally correlated with speech privacy [Vorländer et al 2000b]. For the tests, speech was replayed in the source room and recorded or auralised in the receiving room. These auralised and recorded speech sounds were presented to subjects who were asked to repeat the words they understood. From the ratio of understood words to the total number of presented words, a speech intelligibility number was deduced. At this point, the importance of the reverberation in the receiving room comes into play.

In a first test, the simple and the detailed auralization were compared. The intelligibility was 0.79 for the detailed auralisation opposed to 0.96 for the simple auralisation. This is easy to understand as introducing reverberation decreases speech intelligibility. In a comparison between real recordings and the detailed auralization, the intelligibilities were 0.56 (real) and 0.53 (detailed auralization). This shows that the intelligibilities are reproduced correctly.

The listening tests performed should allow a comparison between the subjective criterion "speech privacy", the objective parameter speech intelligibility and sound insulation quantities in a situation of speech transmission from the source room to the receiving room. Sound signals were taken from the "Göttinger Satztest" (Göttingen sentence test), which is a list of sentences covering the statistical distribution of linguistic phomens of German language. This test was developed for experiments in audiology and hearing aids research.

Of course, speech intelligibility depends not just on the absolute level, but on the signal-to-noise ratio, too. Therefore the consideration must include the background noise level and its spectrum, the absolute signal level and the sound insulation. In this study, the background noise was not varied but fixed by choosing steady state pink noise with an absolute level of 20 dB(A). The level of the speech in the source room was chosen to be 80 dB(A) („loud speech“). 17 test subjects participated, mainly assistants and students of the institute. The set-up used was just a CD player and a high-quality electrostatic headphone. To avoid any influence of uncontrolled background noise, the test was performed in the highly isolated anechoic chamber.

The auralized speech signals corresponding to the six cases of sound insulation (SSt = sound insulation class 53 dB, 56 dB and 59 dB) were presented to the test subjects who were instructed to repeat the words understood in the break between two sentences. The test co-ordinator marked the correctly recognised words in a list for further statistical evaluation. For each room situation 30 sentences were used with in total 150 words. The speech intelligibility was calculated from the number of correctly repeated words divided by the total number of words presented. Each test sequence was composed from 200 sentences which lasted 20 - 30 minutes for each test subject.

The results are shown in figure 6. They illustrate that different quantitative speech intelligibility results may be obtained although the same single number rating is present. Furthermore, it is easily possible to achieve higher speech privacy already with SSt 2 (compared with SSt 3), even if the single number rating is 3.6 dB less. The reason is, of course, the specific sound insulation spectrum in case SSt 2A with an extreme low pass characteristic which allows no formants and consonants to be transmitted into the receiving room.

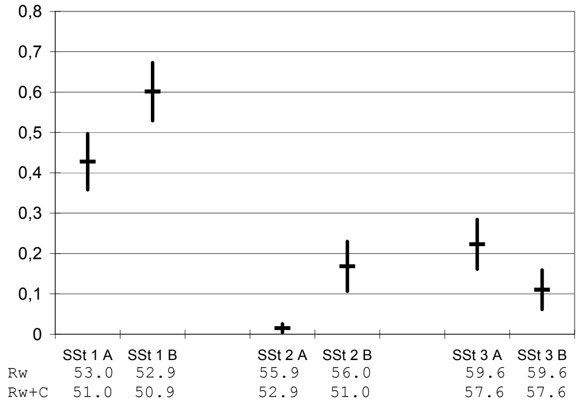

Figure. 6. Results of the listening tests. Shown is the mean value of the percentage of speech intelligibility and the 90% confidence intervals.

It is also interesting that R'_w+C seems to be useful for separation of the cases SSt2, where the insulation in case A is rated 2 dB higher than in case B. But in cases SSt 1 and 3, C is identical in A and B, respectively and could not predict the differences in speech intelligibility.

Many other details can be investigated. The coloration of the speech and the quite low level are related to the sound insulation spectrum and to the spectrum of the background noise. Hence these first results can only be interpreted in these special cases. They cannot be generalised. Partly it was extremely difficult to concentrate on the speech signal, since the level was very low. It is therefore desirable to replace the subjective tests by an objective method for determination of a suitable speech intelligibility index. Perhaps the most elementary parameter, the "Speech Transmission Index" STI, which depends on the signal to noise ratio in different frequency bands is sufficiently robust. This must be checked in future.

An appropriate future study could be based on statistical (Monte Carlo) simulations of room-to-room situations, on automatic convolution of the sound insulation impulse responses with speech, on objective evaluation of speech transmission indices from the auralised signals, and on multidimensional statistical evaluation of correlations between the single number ratings and the STI in dependence on absolute level, sound insulation curves and background noise spectrum. At least, it was shown in this study that the auralisation tool is very useful in this respect. Extensive laboratory or field measurements and subjective tests can be replaced by computer simulation.

Sound insulation and work performance

The so-called Irrelevant Speech Effect (ISE) was investigated at the Institute of Work, Environmental and Health Psychology at the Catholic University of Eichstätt-Ingolstadt together with the Institute of Technical Acoustics at RWTH Aachen University. The ISE describes the influence of irrelevant background speech on verbal short-term memory performance of subjects and is important, e.g. for open-plan offices or classrooms. It is, therefore, a quantity describing the reduction of work efficiency due to a disturbance of concentration. The content of speech is irrelevant for the task. In investigations, the subjects have to recall a series of 9 numbers ranging from 1 to 9 which are visually presented in randomised order. In previous investigations it was found that the intelligibility of background speech has nearly no influence on the performance since the error rate of the test was almost equal for German and Japanese speech (with German subjects) and for reversed speech signals (see overview article from [Klatte et al 1993]). Also, no influence of the level of speech between 40 and 76 dB was found. In our experiment four different sounds were presented as background: Speech in the source room at 55 dB(A), auralized speech in the receiving room at 35 dB(A) but with different speech intelligibilities due to different shapes of the sound insulation curves, and pink noise at 25 dB(A). First results show that there is a significant difference between the performances for the two auralised signals at 35 dB(A) with different intelligibilities and also between the speech in the source room and the speech with bad intelligibility, but not between the source room speech at 55 dB(A) and the speech at 35 dB(A) with good intelligibility [Schlittmeier et al 2004], see figure 7. From this first experiment, the conclusion could not be drawn that it is the speech intelligibility that matters and not the level. In a second experiment, speech intelligibility and content of speech are disentangled by using Japanese speech. This experiment is currently under preparation.

These investigations show that the question of disturbance, annoyance and acoustic comfort may depend significantly on non-acoustical factors like speech semantics, information content in the signal, as well on the attention which is paid to recognise, to hear, and understand the meaning.

IMPACT SOUND INSULATION

Compared with that described above, auralization of impact sound generated by walking on a floor is significantly more difficult. At first, it must be noted that all data of the impact noise levels of floors are defined on the basis of the ISO tapping machine. If one attempts to auralize the noise of a person walking on the above floor on the basis of standardised impact sound levels, the tapping machine excitation must be

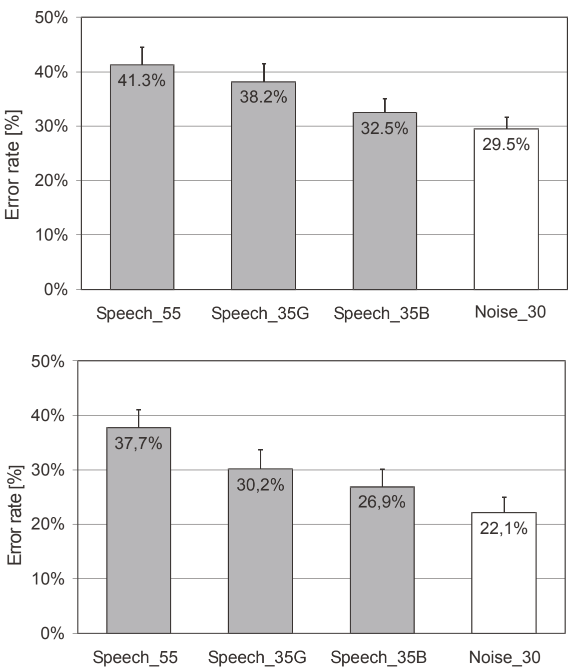

Figure 7. Total error rate when speech signals are replayed in ISE experiment. German language presented to German test subjects (top). Japanese language presented to German test subjects (bottom)

extracted from the measured data. This could be achieved by dividing the impact sound spectra by the force excitation of the standard tapping machine. Thus, a transfer function can be defined by assuming the injected force to be invariant on various floor constructions. This is, however, only a rough approximation since the injected force and the resulting velocity in the (upper layer of the) floor construction depends on the floor mobility. This problem, however, is difficult to be solved, even for the case of only linear transmission.

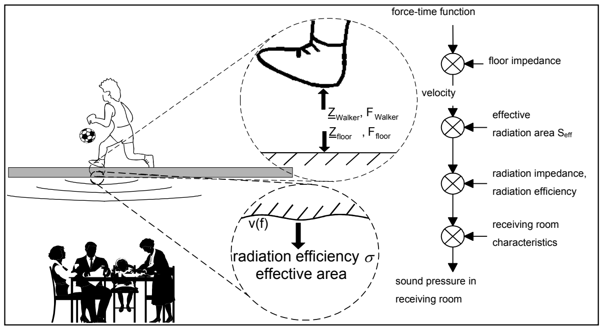

Figure 8. Prediction of impact sound excitation

Measurements of floor impedances and input forces of various excitations are still under investigation, see below. As soon as the velocity in the floor construction is known, the procedure of creating a filter for auralisation is quite similar to that described for airborne sound:

$$p_{\mathrm{R}}(\omega) = F_{\mathrm{walker}}(\omega)\frac{p_{\mathrm{TM}}(\omega)}{F_{TM}(\omega)}\sum_{i=1}^{N} f_{\tau,i}(\omega) f_{\mathrm{rev},i}(\omega) \tag{4}$$

with F_{walker} denoting the spectrum of the force-time signal of the actual excitation, p_{TM} deduced from the normalised spectrum (L_{n}) of the tapping machine excitation, F_{TM} the force spectrum of the tapping machine. $f_{\tau,\mathrm{i}}$ and f_{rev},i were defined above (eq. (3)).

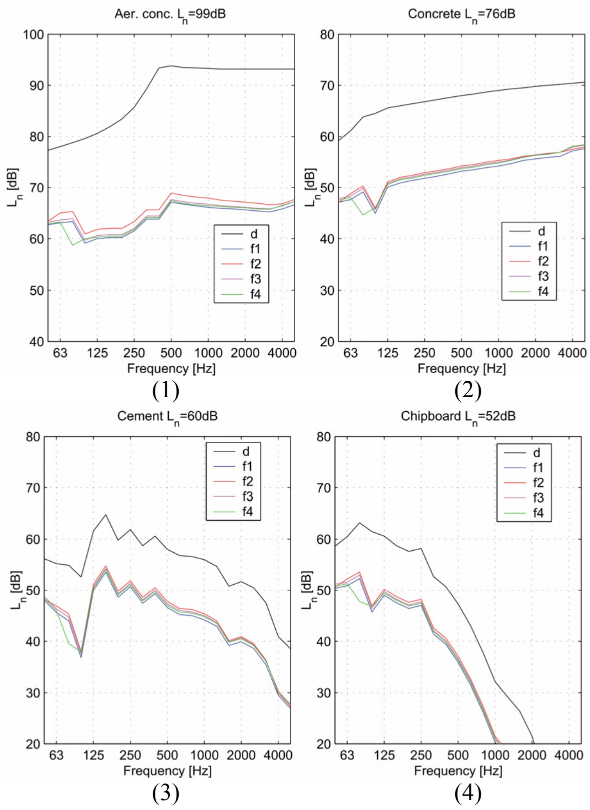

Figure 9. Normalised impact sound pressure levels modelled according to EN 12354, (1) to (4): bare aerated concrete, bare concrete, concrete floating floor, wooden floating floor.

In this first approach, four different room situations were auralized and analyzed regarding their sound pressure levels. For this, the impulse response for the transmission between the force signal in the source room and the sound pressure signal in the receiving room was calculated from the impact sound levels as shown in figure 9 and the room impulse response as described above. The forces of the tapping machine, the modified tapping machine, and a rubber ball according to ISO DIS 140-11 were measured (see figure 10) and force time signals were constructed. To obtain the time signals, several force pulses are appended with an appropriate rate and additionally, jitter in time and amplitude was introduced to get a more natural impression. A convolution of this signal with the impulse response yields the sound pressure signal.

Floor/Covering	$L_{n,w}$	$L_{n,w}+C_i$	L, TM	L, mod. TM
Aerated Conc.	99dB	88dB	99dB	76dB
Concrete	76dB	65dB	75dB	58dB
Cement	60dB	57dB	64dB	55dB
Chipboard	52dB	53dB	58dB	54dB

Table 1. Impact sound levels and levels of auralized signals.

To verify the algorithm, the sound pressure levels of the auralized signals from the sound card were recorded and evaluated. Table 1 shows a comparison between $L_{n,w}$, $L_{n,w}+C_i$, and the levels of the auralized signals for the tapping machine (TM) and the modified tapping machine (mod.TM).

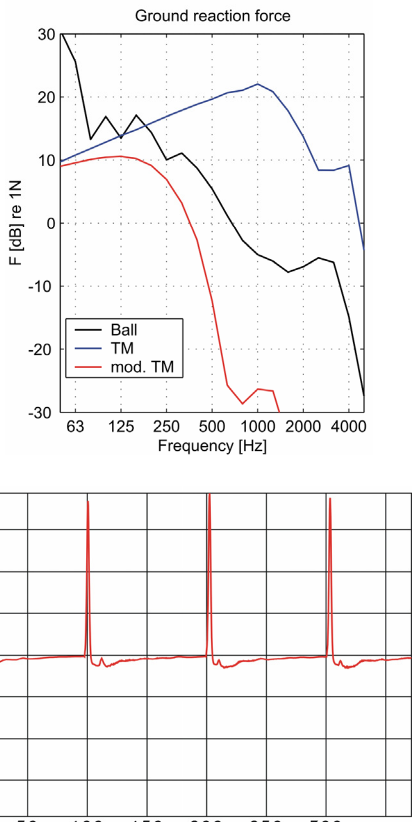

Figure 10. Top: Force spectra of the tapping machine, the modified tapping machine and a rubber ball according to ISO DIS 140-11. Bottom: Force-time signal of the tapping machine.

It can be seen that the values for $L_{n,w}$ and the auralised level of the tapping machine correspond quite well for bare floors, but not similarly well for the floors with additional layers. The modified tapping machine gives rather different level results which correspond better with $L_{n,w}$+Ci. This can be explained by the forces of the two sources. Whereas the tapping machine produces a rather broadband force spectrum, the modified tapping machine only contributes energy up to, say, 400 Hz. Since $L_{n,w}+C_i$ focuses more on lower frequencies, its result seems to be more reasonable than $L_{n,w}$.

The next step will be to account for the impedance of the source (walking person) in relation to the impedance of the floor layer. For this, the impedance of the source must be known as well as the floor impedance. Since measurements of floor impedances are quite well investigated, research is focused on source impedances. In a first try, the static impedance under the foot of a person is measured using a shaker, a force, and a velocity transducer as seen in figure 11.

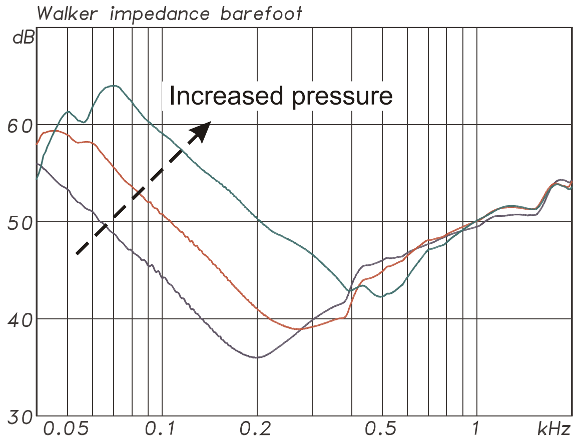

Figure 11. Measurement results of static impedance measurements for bare foot.

Figure 11 shows an example of the impedance of a walker with and without shoes. Clearly, effects of the relative dynamic mass of the leg and the stiffness of the foot or shoe can be seen. When the foot is placed on the measurement setup with more pressure, the stiffness increases and the impedance in the stiffness-controlled region, thus, increases, too.

Since the measurements are carried out in a static condition, the results may differ from the actual impedance during walking. To account for this effect, a measurement method based on a two-port model can be used. The source is modelled as an ideal force source and an inner impedance (two-port Z_f) connected to the floor with an impedance Z_{floor}. Since the two-port is terminated by the force source, a simplification can be done as seen in figure 12. From this model, the open-circuit force F'_0 and Z_s have to be determined. This can be done by two measurements of force and velocity which the parameters, then, can be calculated as shown in figure 13. The impedance then is

$$Z_s = \frac{F_0'}{v_s} = \frac{F_{a1} - F_{a2}}{v_{a1} - v_{a2}} \tag{5}$$

and the open-circuit force is calculated by

$$F_0' = \frac{Z_{a1} + Z_s}{Z_{a1}} \cdot F_{a1} = \frac{Z_{a2} + Z_s}{Z_{a2}} \cdot F_{a2} \tag{6}$$

where $F_{a1,2}$ and $v_{a1,2}$ denote the forces and velocities measured below the source and v_s denotes the short-circuit velocity of the source, respectively

In practice, the measurement is carried out as follows: a source (in this case, the modified tapping machine) “walks” over two measurement setups which can be seen as different load impedances. From the measured forces and velocities, the source impedance and the open-circuit force are calculated.

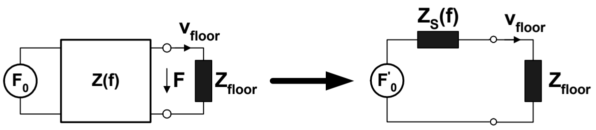

Figure 12. Model of a walker as a two-port, connected to the floor and its simplification

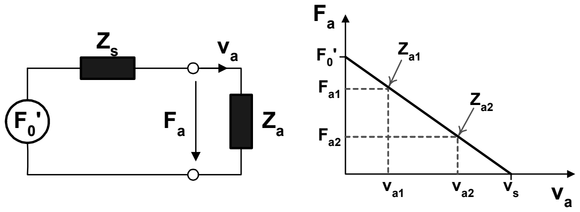

Figure 13. The source can be characterised through F'_0 and Z_s by two measurements of force and velocity

This is explained in more detail in [Thaden2005]. If the floor impedance is known, the actual force injected into the floor can be calculated. Figure 14 shows the source impedance of the modified tapping machine which was measured this way. Except the resonant behaviour of the setup at about 700 Hz, the impedance matches the calculations from [Scholl et al 1999] quite well. The open-circuit force from two measurements as seen in figure 14 fits to the measurements described above.

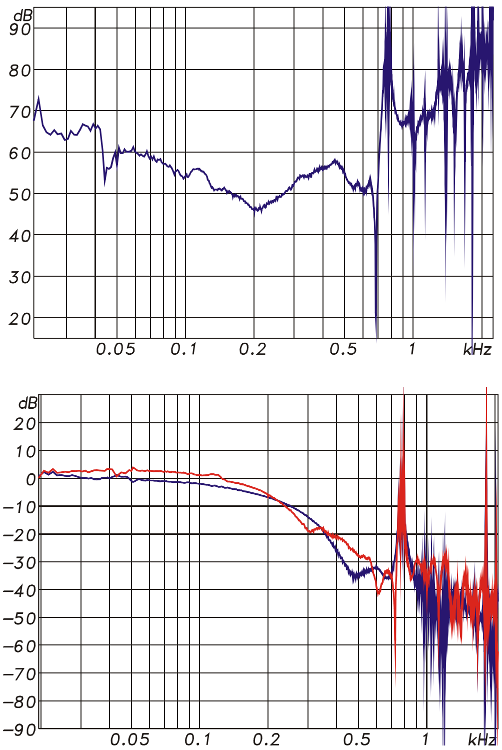

Figure14. Measurement of the modified tapping machine. top: source impedance, bottom: the open-circuit force calculated twice from both forces over the load impedances. (should ideally be identical)

The extended auralization filter must then be generated by using impedance and force relations between source and floor. For characterizing the source, it must be ensured that the open-circuit force is measured. The final formula for signal processing of the receiving room sound pressure is

$$p_R(\omega) = F_{0,\text{walker}}(\omega)\,\frac{p_{TM}(\omega)}{F_{0,TM}(\omega)}\cdot\frac{Z_{i,TM}(\omega)+Z_{a,\text{Floor}}(\omega)}{Z_{i,\text{Walker}}(\omega)+Z_{a,\text{Floor}}(\omega)}\sum_{i=1}^{N} f_{\tau,i}(\omega) f_{\text{rev},i}(\omega)$$
$$= F_{0,\text{Walker}}(\omega)\cdot H_{\text{Filter}}(\omega) \qquad (7)$$

It can be stated that the measurement method works in principle. However, due to rather large technical problems with the measurement setup (mechanical stability of piezo elements, low dynamic range at high frequencies), unfortunately, no further results can be presented yet.

CONCLUSION

Prediction models are the perfect starting point for auralization. Prediction is today important from the viewpoint of design and optimization of building material and for building design as such. Modelling techniques therefore will have a greater importance in the future, including numerical methods like FE. The resulting data can be discussed in full complexity in amplitude and phase spectra, but general estimates in one-third octave bands, similar to measurement results, are well qualified to serve as a basis for discussion of the performance of construction material in relation to the complete building. Here, we deal with global levels, level differences and reverberation times, knowing that the subjective impression is basically dominated by the resulting level and its spectrum. The specific characteristics of the 3D sound field in the receiving room need not be taken into account precisely.

Therefore, auralization of sounds in buildings is possible on the basis of standardized input data from prediction models (and from measurements). The created sounds are plausible in listening impression, and quite accurate in level and one-third octave band spectrum. The method creates the possibility to demonstrate effects, also in teaching, to investigate sound effects and annoyance, by variation of construction parameters and systematic listening tests or psychoacoustic analysis. Rating of sound insulation can hence be studied more easily than with recordings or measurements from real buildings.

Special digital signal processor (DSP) systems are no longer required to solve simulation and auralization tasks. Standard PCs can be used to create auralization filters and to process input signals with these filters. The applications of auralization, therefore, can be widely seen in architectural acoustics, in noise control in buildings, in industrial noise control, and in vehicle acoustics, for instance. New media including the Internet offer an easy access to sound examples. Auralization can hence be expected to remain a growing field of acoustics not only in room acoustics and car industry, but also in building acoustics.

As described above, the technique of auralization can help in studying specific features of the construction concerning airborne and impact sound insulation. Thus not only can the single numbers standardized in national and international documents be used to characterize the situation but new evaluation strategies can be developed. Psychoacoustic tests, for instance, or parameter studies in computer experiments can be used in investigations of annoyance or comfort measures.

More research on noise effects in various situations in the living and work environment is necessary. And, in consequence it should be a goal on an international level to establish better tools like sophisticated instrumentation, a new general rating system with more specific meaning, expert systems for the reduction of complex information into a single number of “annoyance”, “acoustic comfort”, “speech privacy”, “health protection”. This goal can only be reached by expanding intensive studies of noise effects and by expanding the question of each test towards comfort and health effects caused by mid and low sound levels.

Acoustic engineering, a technical solution with "good" acoustic performance requires not only detailed knowledge of technical acoustics and noise control engineering, but a specific strategy to create the appropriate sound. More categories of noise effects, like speech privacy, disturbance of work or annoyance could lead to a better and more specific description of acoustic phenomena and technical solutions, which can also be easily understood by non-acousticians. Only if acoustic problems and solutions are communicated in daily-life language, can the acoustic expert reach the community and the authorities who decide on investment in noise control.

Single number quantities are the right way to achieve better sound insulation in buildings, if we don't restrict this idea by using just dB(A), R_w, STI, $D_{nT,w}$, etc. It is hoped that new methods of simulation and auralization will lead to more cooperation between acoustic engineering and annoyance research on a national and international level.

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REFERENCES

EN 12354, Building Acoustics – Estimation of acoustic performance of buildings from the performance of products. 6 parts.

Gerretsen, E. (1979), Calculation of sound transmission between dwellings by partitions and flanking structures. Applied Acoustics 12, pp. 413.

Gerretsen, E. (1986), Calculation of airborne and impact sound insulation between dwellings. Applied Acoustics 19, pp. 245.

Klatte, M., Hellbrück, J. (1993), "Der Irrelevant Speech Effect": Wirkungen von Hintergrundschall auf das Arbeitsgedächtnis, Zeitschrift für Lärmbekämpfung, 40, pp. 91.

Rasmussen, B. (2004), Sound Insulation between dwellings – classification schemes and building regulations in Europe. Inter-Noise 2004, Prague.

Schlittmeier, S. J., Hellbrück, J., Noise impact on mental performance. Implications for sound environments at workplaces. Proceedings of ICA 2004, : 18th International Congress on Acoustics (2004), Kyoto, Japan.

Scholl, W. and Maysenhölder, W. (1999), Impact Sound Insulation of Timber Floors: Interaction between Source, Floor, Coverings and Load Bearing Floor, Journal of Building Acoustics 6, no. 1, 43–61.

Thaden, T. Brandner, Characterisation of floor impact sources. Proc. InterNoise 2003 Jeju (2003).

Thaden, R., Auralization in Building Acoustics. Dissertation RWTH Aachen University, 2005.

Vorländer, M. and Thaden, R. (2000a), Auralization of Airborne Sound Insulation in Buildings, Acustica united with Acta Acustica 86, pp. 70.

Vorländer, M. and Thaden, R. (2000b), Investigation of speech privacy in buildings by means of auralization. Proc. 2nd FIA, Madrid, October 2000, (CD-ROM). SEA, Spanish Acoustical Society.

Sound examples:
http://www.akustik.rwth-aachen.de/Forschung/Projekte/tritt_aura (English).