BUILDINGS – HOW THEY SOUND

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1 INTRODUCTION

In building acoustics sophisticated tools are available for obtaining information about the acoustic situation in the laboratory and in the field. 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 often be simplified regarding the description of the problem by using single numbers, for instance R_w, $D_{nT,w}$, etc. in order to communicate with acoustically untrained people. Single numbers are also important as a common basis for noise control measures, for political discussions and for a harmonisation of noise regulations and noise limits.

Acoustic engineering in buildings is related to acoustic comfort. 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 $D_{nT,w}+C_{tr}$, are examples which cannot be decided straightforward, 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 future. What can acousticians contribute? They can develop more sophisticated tools for rating sound insulation.

The link between the disciplines of engineering acoustics on the one hand and annoyance research on the other is, ideally, a single number, to be obtained from objective measurements or prediction models. 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.

Particularly the technique of auralisation can be beneficial for subjective tests on acoustic comfort. In this contribution recent developments of auralisation in building acoustics are introduced and demonstrated in examples of basic research on acoustic comfort and annoyance in buildings. The term "auralisation" is well known in room acoustics, but so far not in building acoustics. The principle of auralisation is illustrated in Fig. 1. It shows the basic elements of sound generation, transmission, radiation and reproduction. From Fig. 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.

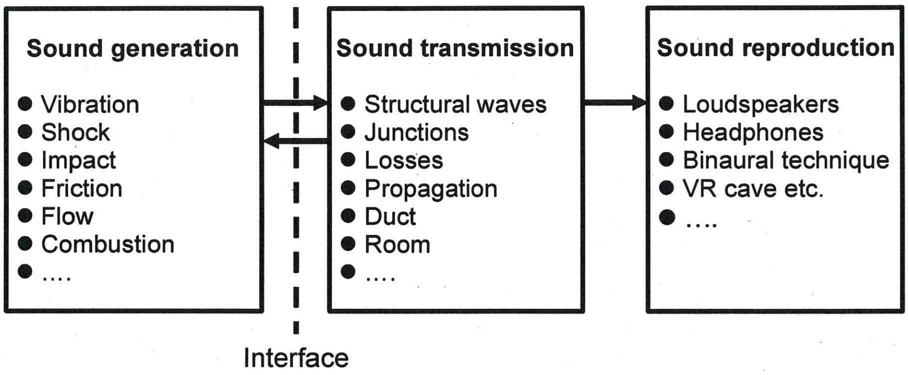

Fig. 1. Principle of Auralisation

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.

2 AIRBORNE SOUND INSULATION

The harmonised European standard EN 12354 [1], describing a physical model of sound transmission in buildings based on the performance of building products and elements, has been applied in building practice for several years now. 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 Gerretsen [2, 3]. His prediction model is equivalent to SEA.

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:

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

with V denoting the receiving room volume in m^3 and S the separating wall surface in m^2. Eq. (2) can also be expressed by using squared sound pressures:

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

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 Fig. 2 and eq. (2)).

In terms of sound pressure signals flowing through the building structure and rooms, the equation reads [4]:

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

with $f_{\tau,i}$ 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. $f_{rev,i}$ is the transfer function between the radiating wall i and the receiver. $f_{\tau,i}$ 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.

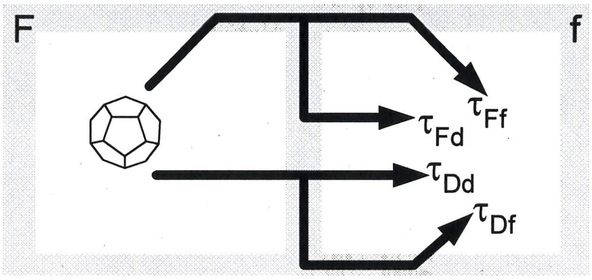

Fig. 2. Room to room situation with sound transmission over various paths denoted by indices with capital letters for the building element in the source room (Direct or Flanking) and with lower case letters for the building element in the receiving room (direct or flanking).

2.1 Verification and example application

The algorithm was tested in a “virtual measurement”. The level difference from the sound card output signals was measured in a source room and receiving room situation. The resulting standardised sound level difference, D_{nT}, in one-third octave bands was almost exactly identical to the input data (see [4]).

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 [5]. It could also be shown that the auralisation tool is very effective. The signals generated sound absolutely realistic regarding to coloration and level. An appropriate study in the future 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 the objective evaluation of speech transmission indices from the auralised signals, and on the multidimensional statistical evaluation of correlations between the single number ratings and the speech transmission index, 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 thus be replaced by computer simulation.

Furthermore, the 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 and Hellbrück [6]). 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), auralised 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, Thaden [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 under preparation at the time being.

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.

3 IMPACT SOUND INSULATION

Compared with what was described above, the auralisation of impact sound generated by walking on a floor is much more difficult. First, it must be noted that all data of impact noise levels of floors are measured by using the ISO tapping machine (ISO 140-6, -7). If one attempts to auralise the noise of a person walking on the floor above on the basis of standardised impact sound levels, the tapping machine excitation must be extracted from the measured data. This could be achieved by dividing the impact sound spectra by the force excitation by 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 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 solve, even in when dealing with linear transmission only [8].

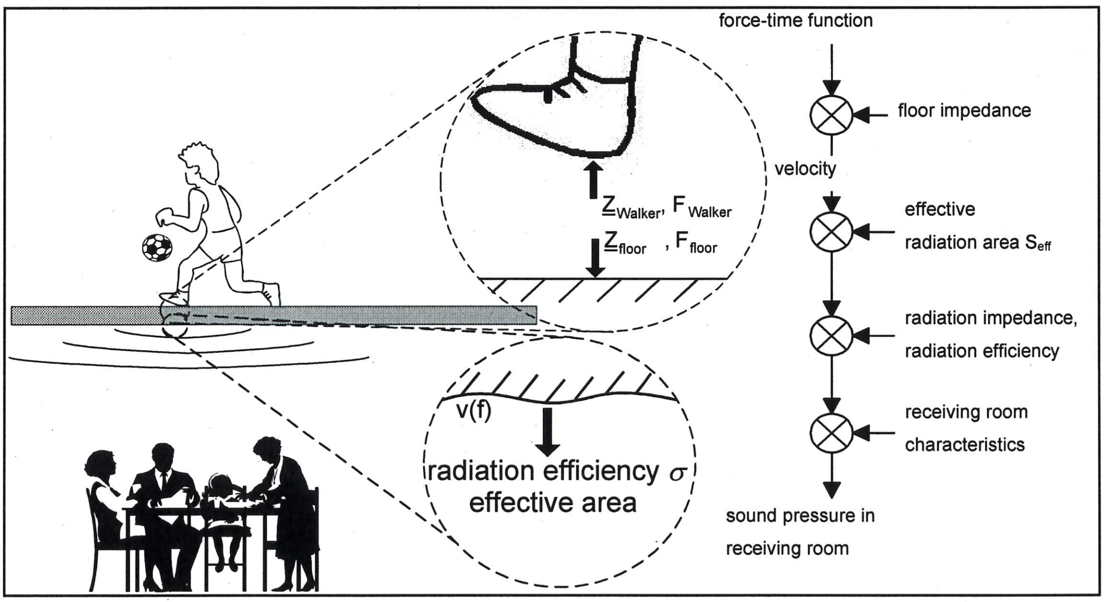

Fig. 3. Auralisation model for walking noise

Measurements of floor impedances and input forces and impedances of various excitations are still under evaluation. 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 above (airborne sound):

$$\begin{aligned} p_R(\omega) &= F_{0,\,\text{Walker}}(\omega)\frac{p_{\text{TM}}(\omega)}{F_{0,\,\text{TM}}(\omega)} \cdot \frac{Z_{\text{i, TM}}(\omega)+Z_{\text{a, Floor}}}{Z_{\text{i, Walker}}(\omega)+Z_{\text{a, Floor}}} \sum_{i=1}^{N} f_{\tau,i}(\omega) f_{\text{rev},i}(\omega) \\ &= F_{0,\,\text{Walker}}(\omega)\cdot H_{\text{Filter}}(\omega) \end{aligned} \tag{4}$$

with $Z_{a,Floor}$ denoting the point impedance of the floor construction, F_{walker} and $Z_{i,Walker}$ the spectrum of the force-time signal and the impedance of the actual excitation respectively, p_{TM} deduced from the normalised spectrum (L_n) of the tapping machine excitation, $F_{0,M}$ and $Z_{i,TM}$ the force spectrum and the impedance of the tapping machine, respectively. $f_{\tau,i}$ and $f_{rev,i}$ were defined above (eq. (3)).

The forces of the tapping machine, the modified tapping machine, and a rubber ball according to ISO DIS 140-11 were measured and force time signals were constructed. To obtain the tapping machine 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.

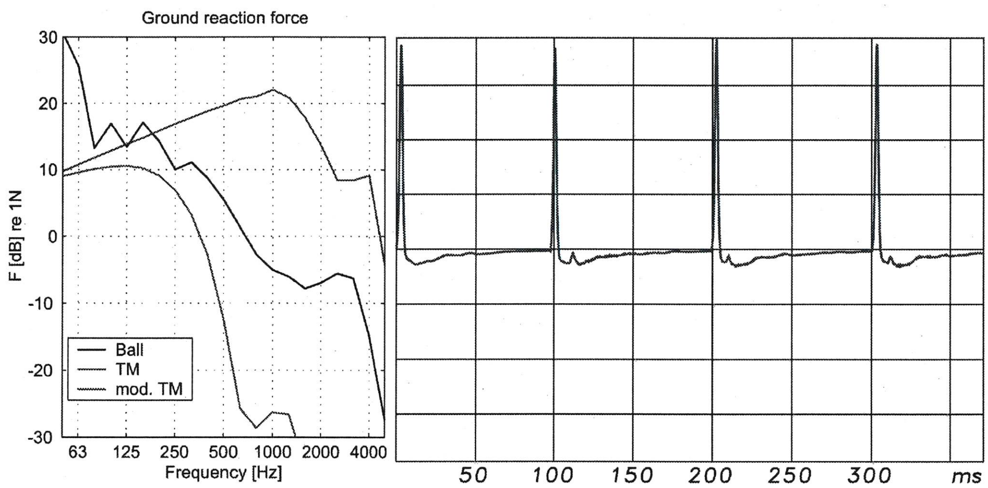

Fig. 4. Left: Force spectra of the tapping machine, the modified tapping machine and a rubber ball according to ISO DIS 140-11. Right: Force-time signal of the tapping machine.

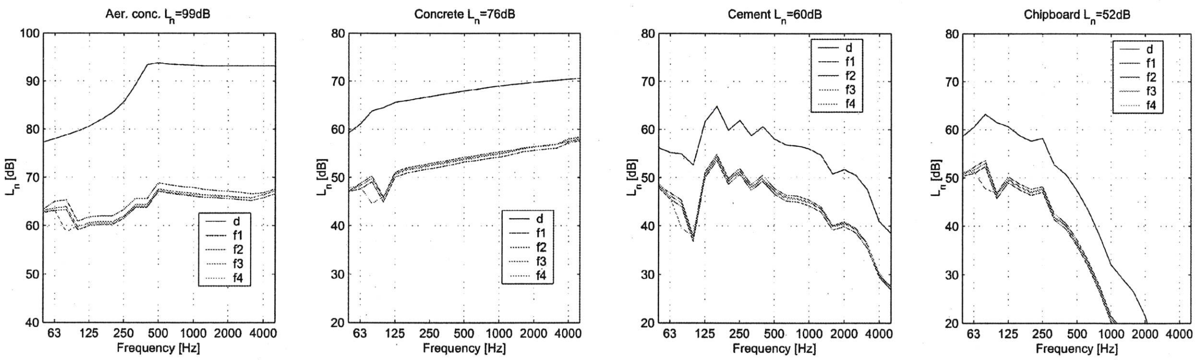

Fig. 5. Normalised impact sound pressure levels modelled according to EN 12354, left to right: bare aerated concrete, bare concrete, concrete floating floor, wooden floating floor.

In the first approach, four different room situations were auralised and analysed regarding their sound pressure levels. It is assumed that the floor impedance is very high compared with the source impedance. With this prerequisite, 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 Fig. 4 and the room impulse response as described above. Tab. 1 shows a comparison between $L_{n,w}$, $L_{n,w+Ci}$, and the levels of the auralised signals for the tapping machine (TM) and the modified tapping machine (modified TM: with rubber layer, ISO 140-11).

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

Tab. 1. Impact sound levels and levels of auralised signals.

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 as well for the floors with additional layers. The modified tapping machine generates rather different results which correspond better to $L_{n,w+Ci}$. This can be explained by the forces of the two sources. Whereas the tapping machine produces a rather broad force spectrum, the modified tapping machine only contributes energy up to, say, 400 Hz (see Fig. 4). $L_{n,w+Ci}$ focuses more on lower frequencies, so this seems to be a reasonable result.

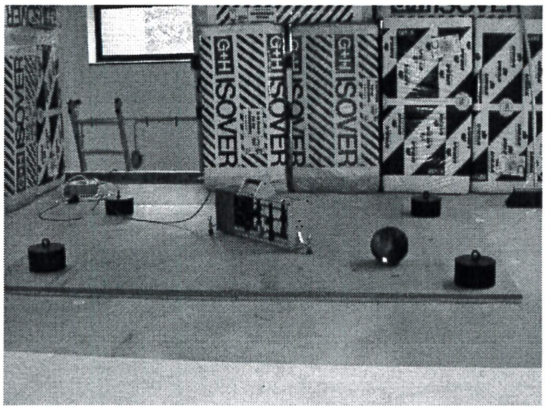

Fig. 6. Impact sources: representation of impact excitation by standard sources

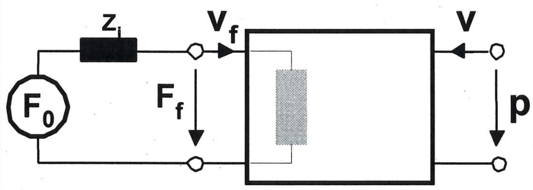

Fig. 7. Two-port model of impact sound

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, see eq (4). In a first try, the static impedance under the foot of a person is measured using a shaker, a force, and a velocity transducer. Results are published in [8]. They show clear effects of the relative dynamic mass of the leg and the stiffness of the foot or shoe.

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. This is explained in more detail in [9]. If the floor impedance is known, the actual force injected into the floor can be calculated. Specific aspects are still under investigation and will be published in the near future, as well as results from subjective tests with various kinds if impact noise.

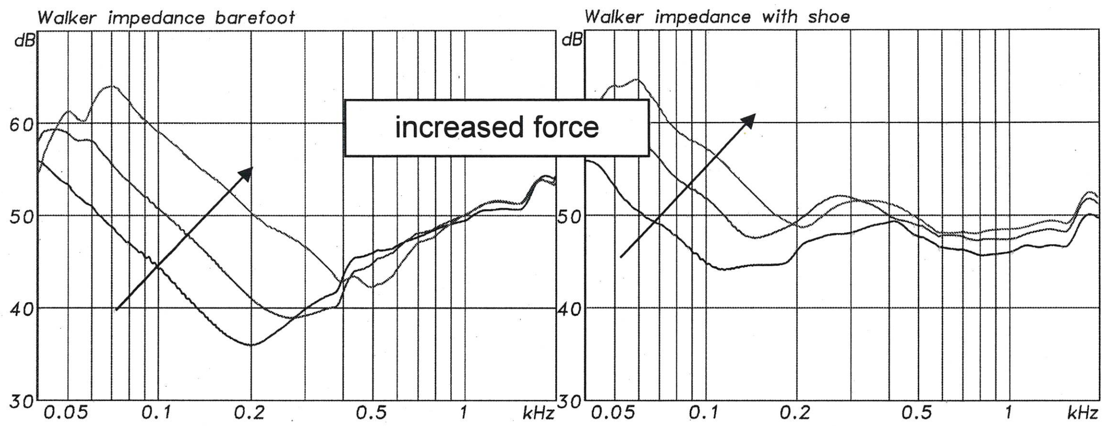

Fig. 8. Source impedances for impact sound excitation with variation of the static force

4 DO WE NEED NEW SINGLE NUMBER QUANTITIES?

As described above, the technique of auralisation can help in studying specific features of the construction concerning airborne and impact sound insulation. Thus not only can the single numbers standardised in national and international documents be used to characterise 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.

Furthermore, as recently discussed by Rasmussen [10], 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", 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.

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, the acoustic expert can reach the community and the authorities who decide on investment in noise control.

5 CONCLUSION

Auralisation of sounds in buildings is possible on the basis of standardised input data from prediction models. 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 much easier than with recordings or measurements from real buildings.

Special signal processor (DSP) systems are no longer required to solve simulation and auralisation tasks. Standard PCs can be used to create auralisation filters and to process input signals with these filters. The applications of auralisation, 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. Auralisation can hence be expected to remain a growing field of acoustics not only in room acoustics and car industry, but also in building acoustics.

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 auralisation will lead to more cooperation between acoustic engineering and annoyance research on a national and international level.

The auralisation tool described here is implemented as an option in prediction software [11]. Sound examples can also be found on the Internet [12].

6 ACKNOWLEDGEMENTS

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