



AURALISATION OF AIRBORNE AND IMPACT SOUND INSULATION

Michael Vorländer, Rainer Thaden

Institute of Technical Acoustics, RWTH Aachen University
e-mail: mvo@akustik.rwth-aachen.de; rth@akustik.rwth-aachen.de

SUMMARY

An algorithm for auralisation of sound insulation in buildings is introduced shortly and applied in tests of annoyance in buildings. It is based on a physical prediction model in accordance with EN 12354 parts 1, 2 and 3. The auralised sound gives a realistic binaural impression concerning relative loudness and coloration. In this contribution, the basic techniques for simulation of airborne and impact sound generation and transmission are discussed. In examples, strategies for transition of numerical results from prediction models into digital filters are explained. These examples cover the disciplines of noise control in buildings and in basic research of noise control.

1. INTRODUCTION

The term “auralisation” is well known in room acoustics, but so far not in building acoustics. When computer simulations are applied, auralisation is like the last step of the investigation where the pure numbers of the computed results are transformed into an audible demonstration of the sound field. Auralisation usually is based on convolution of mono sound signals with binaural impulse responses.

The concept of auralisation was first introduced in relation to acoustic modelling of sound fields in rooms. Already in 1929 in Munich, Spandöck and colleagues tried to process signals from measurements in model scale in a way that one could listen to the acoustics of a room in spite of the fact that the “room” was just a scale model. The idea was formulated quickly but at that time it was extremely difficult to realize it with acceptable quality. Twenty years later, in 1949, magnetic tape recorders were available. Spandöck et al. finally presented their system based on ultrasonic signals, scale models and a tape recorder working at several speeds [1, 2]. This kind of technique can be regarded as analogue computer. The basic elements were already present in this approach: Sound field modelling, convolution with any sound signal and sound reproduction. The results at that time do not meet our expectations of audio quality today. Background noise and low bandwidth were limiting the listening experience but nevertheless these experiments must be considered as first auralisation.

With the dramatic development of computers, the concept of simulation and auralisation was re-invented in the beginning of the 1960's by Schroeder et al [3]. In 1968, the first room acoustic simulation software was developed by Krokstad et al [4] and applied in sound field analysis in rooms. Finally, in the beginning of the 90's, processor speed, memory space, and convolution machines were sufficiently powerful to allow room acoustic computer

simulation and auralisation on a standard personal computer or relatively small workstations. Since then, several improvements in modelling algorithms, in binaural processing and in reproduction technique were made. For more detailed information, overviews on room acoustical auralisation by Kleiner et al [5] can be recommended.

Today, commercial software for room acoustical simulation is not considered to be complete without an option for auralisation through the sound card of the computer. This contribution summarizes the principle of auralisation in a general view. An extension of the principle away from room acoustics and towards noise control is presented and illustrated in examples.

2. GOAL AND PRINCIPLE OF AURALISATION

Imagine you have to explain a painting to a person who does not see it. The verbal characterization will be based on descriptors like size, colour, brightness, maybe on objects, or on resolution of details. A painting reproduced according to this description will be never exactly like the original. It will contain a lot of subjective interpretations, even if the descriptors are “objective parameters”. How much easier and unambiguous would it be if we just looked at the painting instead of discussing its parameters!

Just the same argument is valid for considering sounds interpreted by using some data or, better, by listening to auralised signals. Any sound, noise, music, in general: A signal generated, transmitted, radiated and perceived can more precisely be interpreted and compared by people if it is made audible instead of discussing “levels in frequency bands”, “single number quantities”, or “dB(A)”.

Of course, the whole field of psychoacoustics and sound design with well-known quantities is available for a significant characterization of sounds. Professionals in acoustics analyse sounds with excellent precision and they recommend excellent solutions to acoustical problems. But there are fields of acoustics where predictions can hardly be evaluated based on numbers. There are fields in acoustic engineering where non-experienced clients must be persuaded to invest for a better acoustic environment. And there are fields of acoustic research where the process of a particular auditory perception is not finally understood. Noise control is one of these fields.

The principle of auralisation is illustrated in Fig. 1. It shows the basic elements of sound generation, transmission, radiation and reproduction.

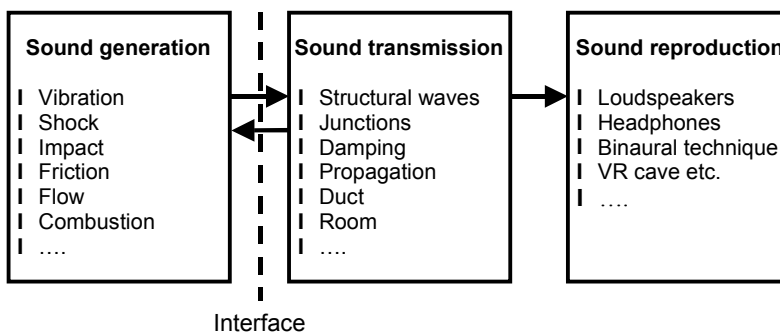


Fig. 1: Principle of auralisation in noise control

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 structural acoustics, 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. Please note the back arrow in Fig. 1.

As soon as the interface between source signal and the transmitting system (with feedback if necessary) is defined clearly and the transmission element is known, the acoustic situation can be projected into a model of signal flow. Signal theory itself can also be expanded without or with feedback. In the latter case, the signal will run through a two-port describing the transmitting element, for instance (see below). With a basic excitation signal in the transmitting element, the signal interface point can be fixed. This point is also a useful reference point for source characterization and calibration and for definition of a transfer function of the transmitting system to the receiver.

Provided, the transfer functions of the elements are known by calculation or measurements, the signal transmitted in the structure, duct, or room is processed by convolution. The transfer function is accordingly the transfer function of a “filter”. This looks simple at first sight, but the task is the creation of a filter representing as many as possible features of the real signal path or multiple paths. To illustrate this task further, some examples are given in the next sections. But it is clear that the requirements on the signal representation (bandwidth and sampling rate, for instance), on the accuracy of the data given on the transmitting system and on the quality of the sound reproduction system might be quite specific.

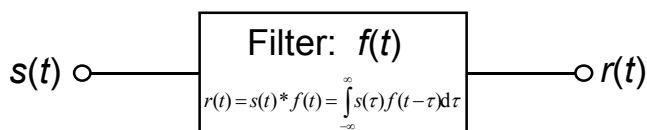


Fig. 2: Convolution of signal $s(t)$ with filter impulse response $f(t)$

Perception of sound signals has multiple dimensions, some of which are listed here: Kind of sound generation, direction of the event, movement of the source, own movement, environment (room: kind, shape and size). The auralisation filter must cover all relevant aspects of the specific case. A further problem is the identification of relevant signal paths, the degrees of freedom of motion in structural paths, and the definition of interface lines or planes between distributed velocity/pressure coupling.

3. AIRBORNE SOUND INSULATION

The European standard EN 12354 [6], describing a physical model of sound transmission in buildings based on the performance of building products and elements, was harmonised and applied in building practice. The physical model behind the standard is a kind of first-order SEA (Statistical Energy Analysis) approach [7] which means that the sound energy is considered, its magnitude and its flow through the building elements, the energy exchange between adjacent building elements, and the energy losses. The most important prerequisite for this approach is the existence of coupled modal systems with high modal densities.

“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 requires just knowledge of the mean energy, the mean losses, and the coupling mechanisms between the systems. The basic publications which were used for development of the harmonised standard are papers by Gerretsen [8, 9]. For illustration, Fig. 3 shows the energy paths for a typical room to room situation and the corresponding transmission coefficients τ .

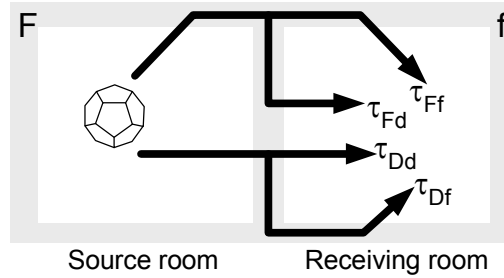


Fig. 3: Room to room situation with sound transmission over various paths denoted by indices with capital letters for the building element in the source room (Direct or Flanking) and with small letters for the building element in the receiving room (direct or flanking).

Now, the total sound level difference in terms of D_{nT} , for instance, can be calculated by adding all energy contributions, provided, the sound signals are incoherent:

$$\tau' = \sum_{i=1}^N \tau_i \quad (1)$$

$$D_{nT} = -10 \log \tau' + 10 \log \frac{0,32 V}{S} = -10 \log \tau_{nT} \quad (2)$$

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

The equations for prediction of the global sound insulation illustrated in Fig. 3 are basic but complicated in grand total as they form a set of numerous variations of materials, junctions, room dimensions etc. The results of these programmes are sound insulation quantities like the sound reduction index, the standardised or normalised sound level difference in one-third octave bands. Starting with these data, the auralisation technique comes into play.

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 a kind of first-order SEA (Statistical Energy Analysis) approach.

Eq. (2) can be written also in scale of squared sound pressures as:

$$p_R^2 = p_S^2 \frac{\tau_{nT} T}{0,5 s} \quad (3)$$

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 [10]. It should be noted that τ_{nT} , like τ' , is composed of the sum of all transmission paths (see Fig. 3 and eq. (2)). In terms of sound pressure signals flowing through the building structure and rooms, the equation reads:

$$p_R(\omega) = p_S(\omega) \sum_{i=1}^N f_{\tau,i}(\omega) e^{-j\omega \Delta t_i} f_{rev,i}(\omega) \quad (4)$$

with $f_{\tau,i}$ denoting interpolated filters related to the transfer functions between the source room and the radiating walls and Δt_i the relative delays in the receiving room. $f_{\text{rev},i}$ is the transfer function between the radiating wall and the receiver. Except for the phases, the filters can be identified unambiguously.

Input data for the wall filters are given at most from 50 Hz to 5 kHz. But usually, the data are just available between 100 Hz and 3.15 kHz. Considerable hearing impressions, however, are excited in a wider range. Therefore, the frequency range must be extended by extrapolation. This is performed according to physically reasonable assumptions. If data below 100 Hz are missing, the sound insulation curve between 50 Hz and 100 Hz is extended according to the 6 dB/octave rule (mass law) and towards higher frequencies above 3.15 kHz or 5 kHz the extrapolated sound insulation curve is considered constant until 10 kHz. Outside the transmission range of 50 Hz to 10 kHz, the signals are cut down by 36 dB/octave.

$f_{\tau,i}$ must have exactly the same one-third octave band spectrum as the corresponding path transmission coefficient, and $f_{\text{rev},i}$ is a classical room transfer function derived from the impulse response between the wall and the receiver.

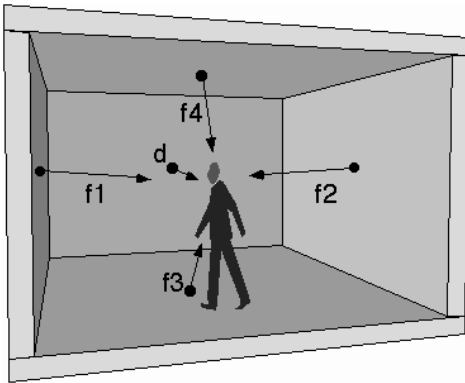


Fig. 4: Situation in receiving room

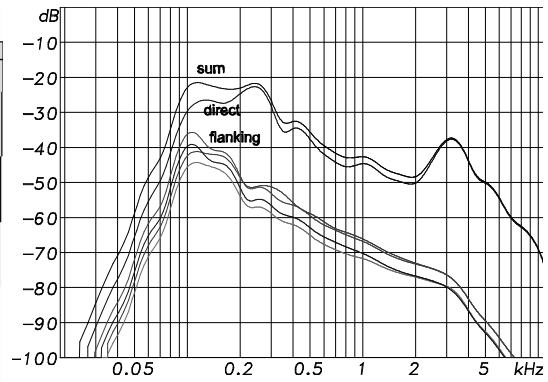


Fig. 5: Auralisation filter frequency curves (monaural part) of τ_{RT} for direct and flanking transmission [10].

3.1 Verification and example application

The algorithm was tested in a “virtual measurement”. The level difference from the sound card output signals was measured in source room and receiving room situation. The resulting standardised sound level difference was almost exactly identical to the input data.

In listening tests related to speech intelligibility in buildings, it could be shown that simple single number rating procedures are not generally correlated with speech privacy. It could also be shown that the auralisation tool is very effective. The signals generated sound absolutely realistic in respect of coloration and level. An appropriate study in future should 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.

At the Institute of Work, Environmental and Health Psychology at the Catholic University of Eichstaett-Ingolstadt together with the Institute of Technical Acoustics at RWTH Aachen University, the Irrelevant Speech Effect (ISE) was investigated. 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.

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 randomized order. In former 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 [11]).

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 55dB(A), auralised speech in the receiving room at 35dB(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 35dB(A) with good intelligibility (Schlittmeier, Thaden [12]). 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 in preparation at the time being.

4. IMPACT SOUND INSULATION

Compared with that described before, auralisation 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 auralise the noise of a person walking on the above floor 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 is the interface problem as illustrated in Fig. 1 above. This problem, however, is difficult to be solved, even if only linear transmission is considered [13].

Measurements of floor impedances and input forces of various excitations are still under investigation. 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):

$$p_R(\omega) = F_{\text{walker}}(\omega) \frac{p_{\text{TM}}(\omega)}{F_{\text{TM}}(\omega)} \sum_{i=1}^N f_{\tau,i}(\omega) f_{\text{rev},i}(\omega) \quad (5)$$

with F_{walker} denoting the spectrum of the force-time signal of the actual excitation, p_{TM} deduced from the normalized spectrum (L_n) of the tapping machine excitation, F_{TM} the force spectrum of the tapping machine.

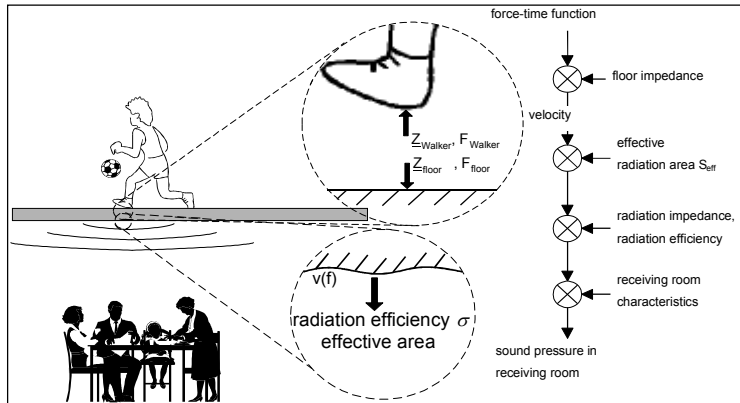


Fig. 6: Auralisation model for walking noise

In a first approach four different room situations were auralised and analysed 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 Fig.8 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 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.

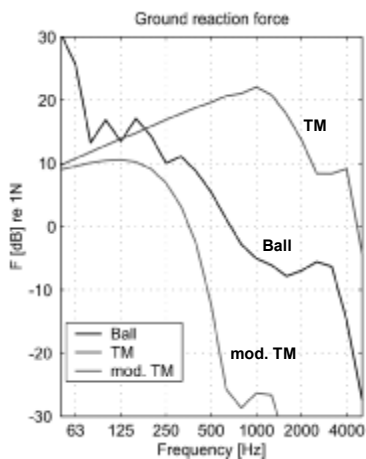


Fig. 7: Forces of the tapping machine, the modified tapping machine and a rubber ball according to ISO DIS 140-11.

To verify the algorithm, the sound pressure levels of the auralised signals were evaluated.

Tab. 1 shows a comparison between $L_{n,w}$, $L_{n,w}+C_i$, and the levels of the auralised signals for the tapping machine (TM) and the modified tapping machine (mod.TM).

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

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

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 gives rather different results which correspond better with $L_{n,w}+C_i$. 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, 400Hz. Since $L_{n,w}+C_i$ focuses more on lower frequencies, this seems to be a reasonable result.

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. Results can be seen in Fig.9.

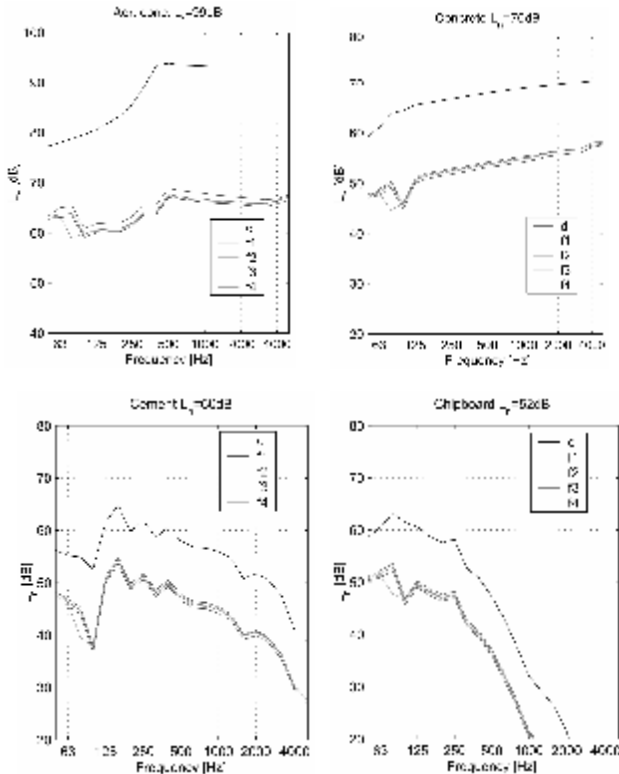


Fig. 8: Normalised impact sound pressure levels modelled according to EN 12354. left to right: bare aerated concrete, bare concrete, concrete floating floor, wooden floating floor.

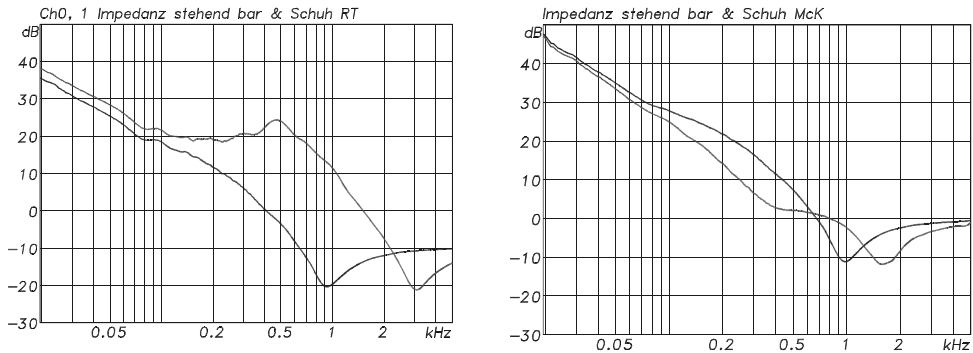


Fig. 9: Foot impedances, left: male, 80 kg, bare foot vs. leather sole, right: male, 70 kg, bare foot vs. rubber sole.

Since the measurements are carried out in a static condition, the results may differ from the actual impedance during walking. To measure this, a model is developed as seen in Fig. 10. The source (walker) is modelled as an ideal force source F_0 and an impedance $Z(f)$ (two-port) which can be simplified to a real force source F_0' with an inner impedance of $Z_s(f)$. By measuring the force and velocity at the output of the source with two different impedances connected (e.g. two different floors below the source), the open-circuit force F_0' and the inner impedance Z_s can be calculated. This is explained in more detail in [13]. If the floor impedance is known, the actual force injected into the floor can be calculated.



Fig. 8: Model of the interaction between source and floor.

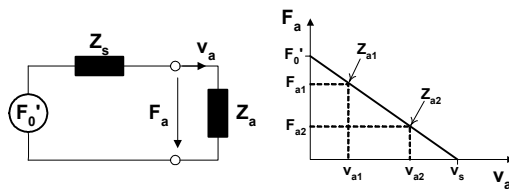


Fig. 9: Determination of open-circuit force and impedance by two measurements.

5. CONCLUSIONS

Auralisation has become an own discipline of acoustics. It was developed from room acoustical simulations by making use of the progress in computer technology for signal processing. Today, 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. It is an advantage in economic competition to illustrate the performance of a new sound insulating system, new material or a new design by an audio example. Marketing strategies are to almost hundred percent based on visual impressions and graphically optimised advertisements. But for acoustic products it is most obvious to extend this strategy by adding auralisation elements. 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 noise control.

The auralisation tool is implemented as an option in the commercial software “BASTIAN[®]” [14]. Sound examples can also be found in the Internet [15].

REFERENCES

- [1] F. Spandöck, Akustische Modellversuche. *Annalen der Physik V* 20, S. 345 (1934).
- [2] F. Spandöck Die Vorausbestimmung der Akustik eines Raumes mit Hilfe von Modellversuchen. *Proc. 5th ICA Vol II, Liège*, p. 313 (1965).
- [3] M.R. Schroeder, B.S. Atal, C. Bird, Digital Computers in room acoustics. *Proc. 4th ICA, Copenhagen*, p. M21 (1962).
- [4] A. Krokstad, S. Strøm, S. Sørsdal, Calculating the acoustical room response by the use of a ray tracing technique *J. Sound Vib.* 8, p. 118 (1968).
- [5] M. Kleiner, B.-I. Dalenbäck, P. Svensson. Auralisation – an Overview. *J. Audio Eng.* 41, p. 861 (1993).
- [6] EN 12354, Building Acoustics – Estimation of acoustic performance of buildings from the performance of products. 6 parts.
- [7] Craik, R.J.M., *Sound Transmission through Buildings using Statistical Energy Analysis*. Gower Publishing Limited, England.
- [8] Gerretsen, E., Calculation of sound transmission between dwellings by partitions and flanking structures. *Applied Acoustics* 12 [1979], 413-433.
- [9] Gerretsen, E., Calculation of airborne and impact sound insulation between dwellings. *Applied Acoustics* 19 [1986], p. 245-264.
- [10] M. Vorländer, R. Thaden, Auralisation of Airborne Sound Insulation in Buildings, *Acustica united with acta acustica* 86, p. 70 (2000).
- [11] Klatte, M., Hellbrück, J., “Der Irrelevant Speech Effect”: Wirkungen von Hintergrundschall auf das Arbeitsgedächtnis, *Zeitschrift für Lärmbekämpfung*, 40 (1993), p. 91-98
- [12] Schlittmeier, S.J., Thaden, R. (in prep.). Irrelevant background speech does disturb: The contribution of speech intelligibility and semantic content of low background speech to the Irrelevant Speech Effect.
- [13] Thaden, T. Brandner, Characterisation of floor impact sources. *Proc. InterNoise 2003 Jeju* (2003).
- [14] BASTIAN[®] User Manual (see also <http://www.datakustik.de>).
- [15] Sound examples: http://www.akustik.rwth-aachen.de/Forschung/Projekte/tritt_aura (english).