INVESTIGATION OF SPEECH PRIVACY IN BUILDINGS BY MEANS OF AURALISATION

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ABSTRACT
An algorithm for auralisation of sound insulation in buildings is introduced shortly and applied in listening tests of speech intelligibility in buildings. It is based on a physical prediction model in accordance with EN 12354 part1. The auralised sound gives a realistic binaural impression concerning relative loudness and coloration. With this tool listening tests on speech privacy were performed in a room-to room situation. As expected, significant differences were obtained in a comparison of situations with same single number rating but different frequency curves.

INTRODUCTION

A European standard describing a physical model of sound transmission in buildings based on the performance of building products and elements is almost ready to be harmonised and applied in building practice. The physical model behind the standard is a kind of first-order SEA (Statistical Energy Analysis) approach [1], 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 of the systems. The basic publication which was used for development of the harmonised standard is the paper by Gerretsen [2, 3]. For illustration, Fig. 1 shows the energy paths for a typical room to room situation and the corresponding transmission coefficients t.

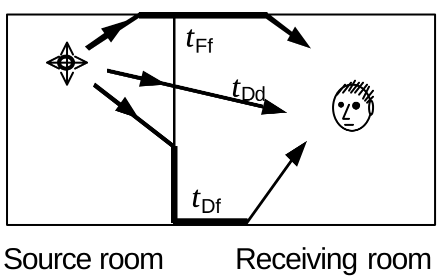


Fig. 1. Room to room situation with sound transmission over various paths denoted by indices with capital letters for the building element in the source room (Direct or Flanking) and with small letters for the building element in the receiving room (direct or flanking). For better visibility of the paths the path Fd is omitted.

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:

$$\boldsymbol{t}' = \sum_{i=1}^{N} \boldsymbol{t}_i \tag{1}$$

$$D_{\mathrm{nT}} = -10 \log \boldsymbol{t}' + 10 \log \frac{0{,}32\, V}{S} = -10 \log \boldsymbol{t}_{\mathrm{nT}} \tag{2}$$

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. 1 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.

This paper is focused on the brief description of a tool for auralisation of airborne sound insulation [4], which means that the one-third octave band data in terms of level differences and reverberation times are processed in a way that they can be convolved with sound signals and replayed with headphones. The tool is applied in listening tests where room-to-room situations are compared concerning the speech privacy in dwellings. Particularly different single number ratings were investigated and cross-linked with the results from the subjective tests. The work is motivated by the fact that is desirable to review and finally to harmonise the rating methods. For checking the quality and efficiency of the rating schemes according to ISO 717 [5], listening tests are performed for correlation of subjective impression with objective data. Instead of extensive tests in buildings or in laboratories, the investigation is made by using auralisation.

THE CONCEPT OF AURALISATION

In the meantime the term "auralisation" is well known in room acoustics [6], but so far not in building acoustics. When computer simulations are applied, auralisation is like the last step of the investigation, in which 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 description presented here is a brief version of a more detailed paper [4].

A sound signal is produced in the source room which radiates sound waves into the room volume and into the walls. Airborne sound is transformed into structural waves on the walls (particularly bending waves) which are transmitted through the building structure to the walls of the receiving room where the walls radiate airborne waves propagating to the receiver. Furthermore, in the receiving room reverberation is excited which contributes some sound energy to the sound signal at the receiver point. Basically, the same situation is present in a building acoustic measurement of the standardised sound level difference D_{nT} :

$$D_{\mathrm{nT}} = L_{\mathrm{S}} - L_{\mathrm{R}} + 10 \log \frac{T}{0{,}5\ \mathrm{s}} \tag{3}$$

with L_S denoting the average level in the source room, L_R the average level in the receiving room, and T the reverberation time in the receiving room. Eq. (3) can be written also in scale of squared sound pressures as :

$$\boldsymbol{t}_{\mathrm{nT}}^{-1} = 10^{D_{\mathrm{nT}}/10} = \frac{p_{\mathrm{S}}^2\, T}{p_{\mathrm{R}}^2\ 0{,}5\ \mathrm{s}} \tag{4}$$

with p_S and p_R the sound pressure in the source and the receiving room, respectively and $\boldsymbol{t}_{nT}$ denoting the (standardised) transmission coefficient. For the purpose of auralisation eq. (4) is re-arranged according to:

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

It should be noted that t_{nT} , like t', is composed of the sum of all transmission paths (see Fig. 1 and eq. (1)). In terms of sound pressure signals flowing through an acoustic linear and time-invariant system in the entire frequency range , the equation reads:

$$p_{\mathrm{R}}(\omega) = p_{\mathrm{S}}(\omega) \sum_{i=1}^{N} f_{\tau,i}(\omega)\, f_{\mathrm{rev},i}(\omega) \tag{6}$$

with $f_{\tau,i}$ denoting filters related to the transfer functions between the source room and the radiating walls in the receiving room. $f_{\mathrm{rev},i}$ is the transfer function between the radiating wall and the receiver. This equation is at least correct for certain simplifications (see below). Except for the phases, the filters can be identified unambiguously. $f_{\tau,i}$ must have exactly the same one-third octave band spectrum as the corresponding path transmission coefficient, and $f_{\mathrm{rev},i}$ is a classical room transfer function derived from the impulse response between the wall and the receiver.

The equations above represent, however, the sound transmission in a simplified way. Transfer functions are properly defined just for point sources, so the vibrating walls are considered as point sources instead of bending wave patterns. These simplifications are necessary to keep the problem feasible, but they must be justified. It should be kept in mind that it is not intended to model and to evaluate specific psychoacoustic effects. It is aimed at a realistic sound signal with correct coloration and level. The direct sound(s) radiated from the walls, however, are modelled by using correct binaural filters. Thus the wall with the strongest sound transmission may even be localised. Furthermore, in a strict sound field simulation the reverberation tail must be modelled by ray tracing or similar techniques. Also here, to achieve a feasible solution, the receiving room can just be chosen from the list of nine example rooms, the reverberation tails of which are measured and simply added to the direct sound(s).

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 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.

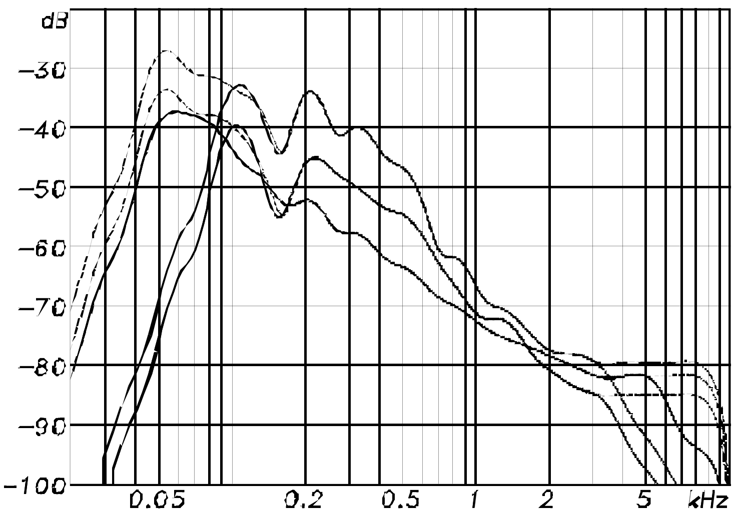


Fig. 2. Frequency curves of t_{nT} for different transmission paths with extrapolation (dashed lines) and without extrapolation (solid lines)

The complete impulse response (Fig. 3) describes the transmission from the source room to the receiving room and can be used for a convolution of any mono-signal to obtain the signal as perceived by a listener in the receiving room. Starting from the one-third octave band data and the chosen receiving room example, its generation requires just 10 seconds even on an older Pentium II PC with 233 MHz clock frequency.

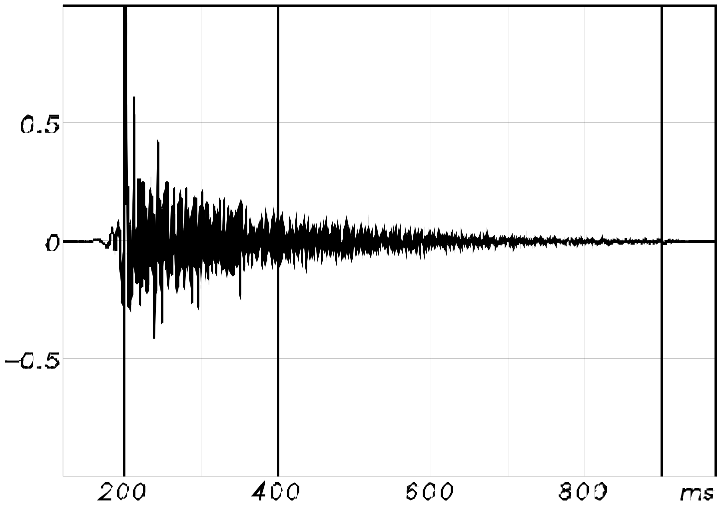


Fig. 3. Impulse response of transmission from source to receiving room (example: right ear, left ear similarly).

CASE STUDIES

The main question is whether building technology today is still compatible with the standardised rating scheme using shifted reference curves. Another point and a general problem is that the weighted or dB(A) single number rating can hardly provide any information about the cause of possibly insufficient sound insulation. Below 100 Hz and above 3150 Hz no data are influencing the single number rating, which is problematic for low frequency of traffic noise components particularly. Alternatives involving the recently introduced spectrum adaptation terms (e.g. $C_{50\text{-}5000}$) were not yet investigated sufficiently.

For the listening tests, in total six situations were modelled, consisting of three pairs of identical single number ratings and sound insulation classes ("Schallschutzstufen" SSt) according to the German VDI directive 4100 [7]. Fig. 4 - 6 show the standardised sound level differences of the three pairs. The table to the right shows the corresponding numerical data.

Room situation	R'_w	R'_w+C
SSt 1 A	53,0	51,0
SSt 1 B	52,9	50,9
SSt 2 A	55,9	52,9
SSt 2 B	56,0	51,0
SSt 3 A	59,6	57,6
SSt 3 B	59,6	57,6

Table 1: six room-to-room situations.

The sound insulation classes are defined as follows: SSt 1: speech can be understood , SSt2: speech can fairly be understood and SSt 3: speech can be noticed but cannot be understood. SSt 3 means that speech has half subjective loudness than for SSt 2.

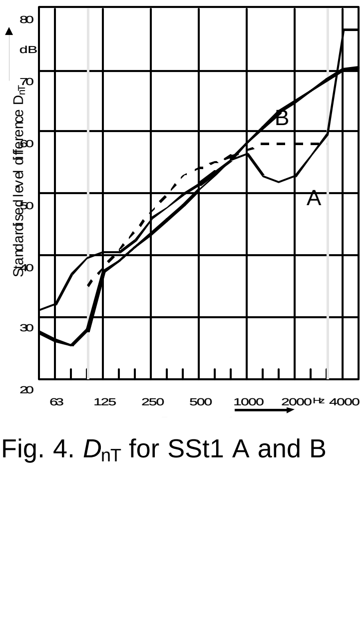


Fig. 4. D_{nT} for SSt1 A and B

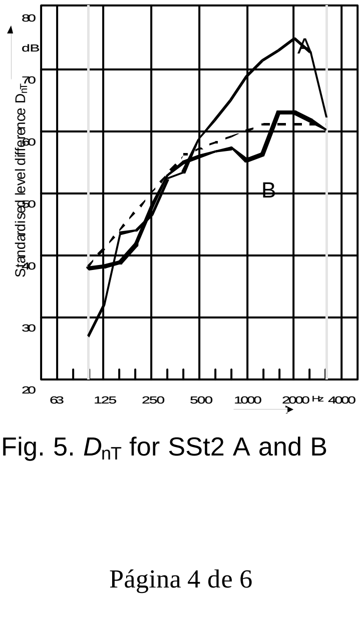


Fig. 5. D_{nT} for SSt2 A and B

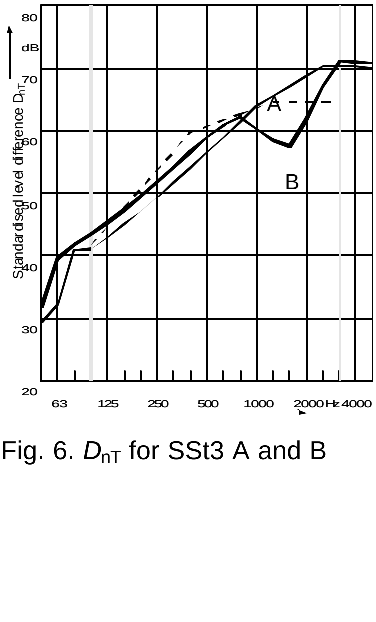


Fig. 6. D_{nT} for SSt3 A and B

LISTENING TESTS

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 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.

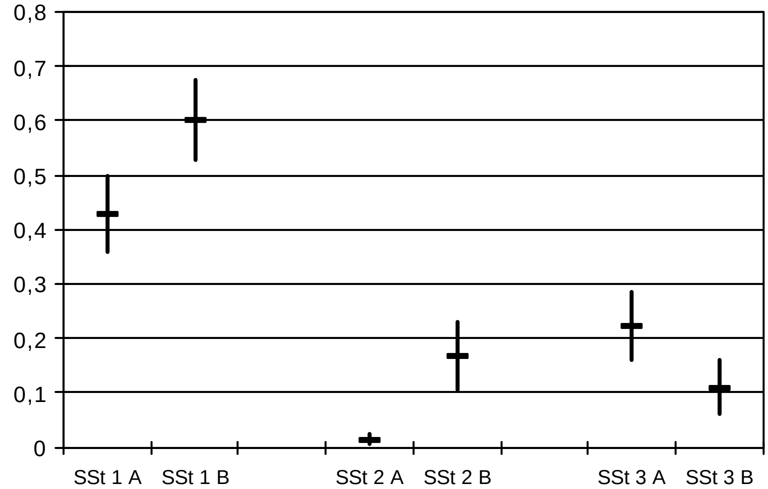
Of course, speech intelligibility depends not just on the absolute level, but on the signal-to-noise ratio, too. Therefore the consideration must include the background noise level and its spectrum, the absolute signal level and the sound insulation. In this study, the background noise was not varied but fixed by choosing steady state pink noise with absolute level of 20 dB(A). The level of the speech in the source room was chosen 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 auralised speech signals corresponding to the six cases (table 1) 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 word 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.

RESULTS

The results are shown in Fig. 7. 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.



	SSt 1 A	SSt 1 B	SSt 2 A	SSt 2 B	SSt 3 A	SSt 3 B
Rw	53.0	52.9	55.9	56.0	59.6	59.6
Rw+C	51.0	50.9	52.9	51.0	57.6	57.6

Fig. 7. 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.

CONCLUSION

An algorithm for auralisation of sound insulation in buildings was developed. It allows the influence of sound transmission paths through building structures and of the receiving room to be modelled. The auralisation tool is added to a PC programme for determination of the airborne sound insulation of buildings from the performance of building products in accordance with EN 12354 parts 1 and 3. Consequently the one-third octave band input data of the standardised prediction model are used as input data. Elementary data processing like filter theory, binaural technology and convolution with source signals are applied. The geometrical and absorptive characteristics of the specific receiving room was considered to have only secondary importance and was approximated. The auralisation tool is implemented as an option in the commercial software “BASTIAN®” [8].

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 STI 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.

REFERENCES

[1] Craik, R.J.M., Sound Transmission through Buildings using Statistical Energy Analysis. Gower Publishing Limited, England
[2] Gerretsen, E., Calculation of sound transmission between dwellings by partitions and flanking structures. Applied Acoustics 12 [1979], 413-433.
[3] Gerretsen, E., Calculation of airborne and impact sound insulation between dwellings. Applied Acoustics 19 [1986], 245-264.
[4] Vorländer, M., Thaden, R., Auralisation of Airborne Sound Insulation in Buildings. ACUSTICA / acta acustica 86 (1) [2000], p. 70-76.
[5] ISO 717, Acoustics - Rating of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation.
[6] Kleiner, M., Dalenbäck, B.-I., Svensson, P., Auralisation - An Overview. J. Audio Eng. Soc. 41 [1993], p. 861-875.
[7] VDI 4100, Schallschutz von Wohnungen – Kriterien für Planung und Beurteilung (Noise control in buildings – criteria for planning and assessment). VDI Directive 1994.
[8] BASTIAN® User Manual (see also http://www.gh-isover.de).