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Performance of computer simulations for architectural acoustics

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ABSTRACT

Room acoustic simulation and auralization are tools for daily work in room acoustic research and consulting. In some cases, the performance of such software was proven to be excellent, in other examples severe errors occurred. In order to check the reliability or programmes verification tests and comparisons between simulated and measured results were performed. The first round robin on room acoustics computer software was presented on the occasion of ICA in Trondheim 1995. The results showed that geometrical methods work well, Scattering effects are, however, of great importance and were therefore implemented in later software versions. Since then we have seen significant progress in prediction and simulation tools in architectural acoustics. Ray-, Beam- and Cone-Tracing hybrid models of geometrical acoustics can be found in several programmes. These deliver user-friendly results in color-mapping and in auralizations. The question, however, is whether we can complete rely on these results. The reliability of results from such computer tools depends at least partly on the quality of the numerical solver for geometrical models. The quality of input data such as geometry or boundary conditions and, of course, the skills of the operator are relevant as well. This presentation summarizes the current state of in computer simulations, and it focuses on sources of uncertainties in computer models, on the actual status of current problems in the field of indoor acoustics and on approaches for quantitative error propagation of uncertainties of input data.

INTRODUCTION

Computer modelling of room acoustics was proposed in the 1960's by Schroeder [1] and first used in practice by Krokstad et al. [2]. The algorithms of typical programmes are based on geometrical acoustics. In geometrical acoustics, interference effects are neglected. The description of the sound field is reduced to energy, transition time and direction of rays. This approach is correct as long as the dimensions of the room are large compared with wavelengths and as long as broadband signals are considered. These approximations are valid with sufficient accuracy in large rooms intended for speech and music above Schroeder frequency.

Uncertainties in acoustic prediction and simulations tools were studied only recently. The reliability of results is often taken for granted, but computer simulations are also rejected due to severe doubts about their reliability.

This article is an attempt to discuss strategies to obtain quantitative information on uncertainties of computer simulations. The uncertainties that will be discussed stem from material data, approximations in CAD models, and algorithmic details. There are two methods to obtain quantitative data on uncertainties. First of all, results from intercomparisons (so-called "round robins") can be analysed, or the statistical method of error propagation can be applied. For the latter, independent variables are considered with their mean and variance forming a final result such as reverberation time, sound level, clarity, etc.

Geometrical acoustics: Ray Tracing and Image Sources

In geometrical acoustics two basic models of geometrical sound propagation are used, ray tracing and image sources. Often, however, these two approaches are mixed up or even confused and the physical meaning is distorted. It is important to highlight the different physical meaning of both methods: ray tracing describes a stochastic process of particle radiation and detection. Image sources are geometrically constructed sources which correspond to specular paths of sound rays. Often, image sources are constructed by using rays, beams or cones, which resembles the ray tracing algorithm. Nevertheless, they still remain "image source models". The fundamental difference between image sources and ray tracing is the way contributions in impulse responses are calculated. Ray tracing only yields impulse response low-resolution data like envelopes in spectral and time domains. Image sources (classical or via tracing rays, beams, cones, etc. [3, 4, 5]) may be used for exact constructions of amplitude and delay of reflections which narrow-band resolution depending on the filter specifications for wall reflection factors, for instance.

Hybrid models

Due to the contradictory advantages and disadvantages of ray tracing and image sources an attempt was made to combine the advantages in order to achieve high-precision results without spending too much complexity or computation time. Either ray tracing or radiosity algorithms were used to overcome the extremely high calculation time inherent in the image source model for simulation of the late part of the impulse response (adding a reverberation tail), or ray tracing was used to detect audible image sources in a kind of „forward audibility test“. The idea behind this approach is that a ray, beam, or cone detected by a receiver can be associated with an audible image source. The order, the indices and the position of this image source can be reconstructed from the ray's history by storing the walls hit and the total free path. Hence, the total travel time, the direction and the chain of image sources involved can be attributed to the image source. Almost all other algorithms used in commercial software are kind of dialects of the algorithms described above, and they differ in terms of how the specular with the scattered component is mixed. The specific choice of dialect depends on the type of results, particularly on the accuracy, spatial and temporal resolution.

VERIFICATION TESTS

The computational performance and the accuracy of computer simulations can only be checked by modelling existing rooms and comparing the results with measurement results. This procedure was used for a lecture hall when a first intercomparison was carried out in Brunswick, Germany, in 1993 and 1994. The first results were partly disappointing [6]. Data were collected from 17 participants in computer simulations and 7 in measurements. One result is shown in Figure 1. It contains the prediction of reverberation time based on visual inspection of the test room and individual choice of absorption coefficients. The results of this phase showed a surprisingly large scatter with a strong tendency to underestimate the absorption coefficients and thus to overestimate the reverberation time.

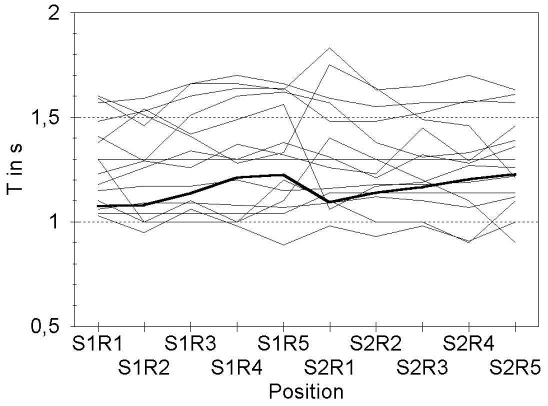

Figure 1. Results from the first round robin on room acoustical computer simulations (from [6]). Plot of reverberation times *T* predicted for the 1 kHz octave band in an auditorium. Thick line: average measurement result which has an uncertainty of 5% (± 0.05 s) (Lundeby et al 1995 [7]).

In some cases the differences exceeded 50%. Even simple quantities such as the sound level (strength) were predicted with up to ± 5 dB maximum deviation. In an overall accuracy rating, however, only a few programmes were deemed reliable. Moreover, it was obvious that algorithms with purely specular reflection modelling are not sufficient which was supported by the results of the second phase where the input data were fixed for all participants. Still the programmes which only used specular reflections overestimated the reverberation time systematically. Today it is common knowledge that in typical rooms after reflection order three or four, the main energy propagation goes through diffuse (scattered) sound.

In the following years two more round robins were created by Bork in 2000 [8] and in 2005 [9]). He confirmed the results of the first project and extended the scope and the interpretation towards new aspects.

Listening tests with recordings in the original room can be used to analyse auralizations of rooms. This round robin project, however, is still to be planned and started.

SOURCES AND CONSEQUENCES OF UNCERTAINTIES

In the following section the sources of uncertainties and their impact on the results are analyzed. In this discussion, an uncertainty must be treated as object of scientific research on its own. It is not adequate to “calibrate” a computer model by adjusting input data so that, for instance, reverberation times or other damping effects are matched to measurement results. The objective for computer simulations should be to be independent of adjustment factors. It should be purely based on physical data and corresponding databases of input data (typically material properties).

If correct data are used, the question whether the correct model and the correct method suitable for solving the acoustic problem are used, still remains. Therefore a skilled and experienced operator is needed. For this paper, we assume that the operator uses the software under appropriate conditions of applicability to the acoustic problem. Systematic and stochastic errors due to the algorithm itself may still occur.

In the analysis of stochastic uncertainties, a very powerful tool can be used which is related to uncertainties of measurements (ISO GUM). The principles suggested in this “ISO Guide to the expression of uncertainty in measurement” have not yet been considered in computational acoustics. In computational acoustics there is hardly any systematic approach to tackle the problem of uncertainties with a comparable insight which is available for some acoustic measurements (typically high-precision calibration techniques where uncertainties must be stated as part of the result).

It is sensible to define a scale of psychoacoustic relevance of differences and, thus, comparing differences between results or quantitative uncertainties of simulations with the just audible differences (JND) of human hearing. The best listening environment in a laboratory using headphones meets the following criteria: the JND for reverberation time is about 5%, for strength (level) 1 dB and for definition 10% (after [6]). If uncertainties are smaller than these values, the simulation can be considered sufficiently precise. For computer predictions and simulations including auralization, one could formulate the golden rule“don’t compute what you can’t hear”. This statement, however, is quite useless when it comes to discussing uncertainties in calibrations, for example.

SYSTEMATIC UNCERTAINTIES

The reasons for deviations between simulations and measurements are shortcomings in the algorithms and the modelling approach. As described before, ray tracing (or similar) and the image model are the basis for all simulations. In the following section, some examples are discussed where the physics of wave propagation is only roughly approximated. Errors may possibly occur, and the question is whether they affect parameters like reverberation time or clarity and whether the approximations are audible.

Level of detail in the CAD model

A proper CAD model is essential for room acoustic simulations. The surface elements, usually polygons, must be large compared with wavelengths in three decades, in order to cover the audio frequency range. This is virtually impossible. Compromise solutions without any theoretical foundation are, thus used for engineering applications. The results may be wrong due to an unfortunate choice of the level of detail. A high level of detail will lead to unnecessary long computation times as well. Accordingly a large potential is identified in the acceleration of algorithms at low frequencies at low spatial resolution in the CAD model, and at late times in the impulse response, where the late decay is built by scattering rather than by deterministic specular reflections in a detailed CAD model. An ongoing project currently deals with the question which criteria can be used for choosing an appropriate level of detail in CAD models [10] (see Figure 2). These findings will also be relevant for simulations of large volumes such as cathedrals, stadiums, airports and trains stations with reasonable computation times.

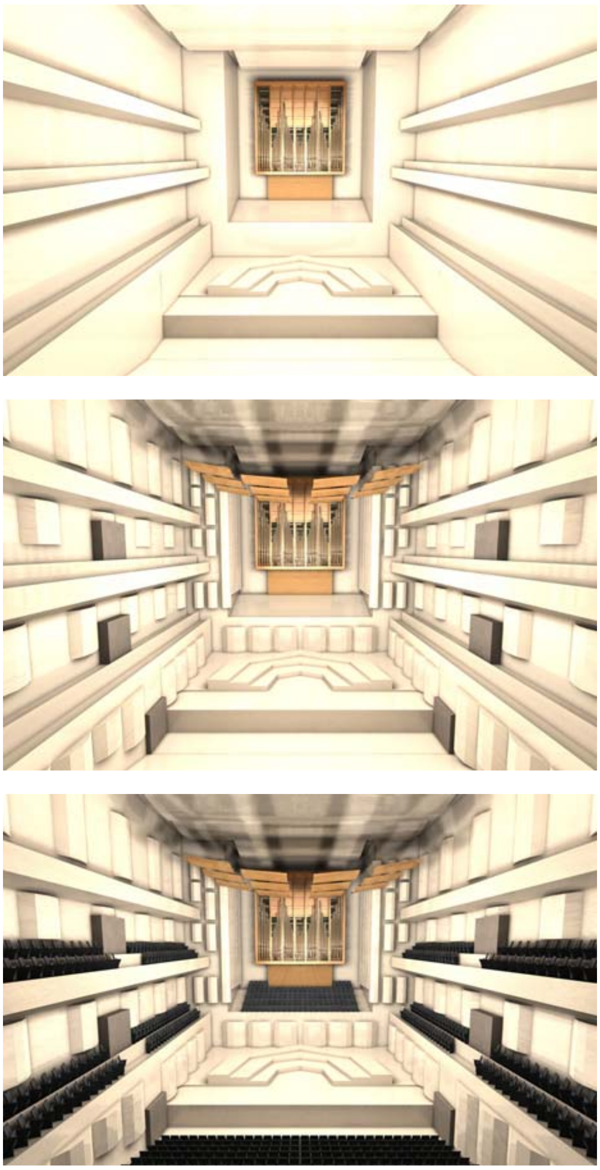

Figure 2. Level of detail in a CAD model of a concert hall illustrated for (top to bottom) low, mid and high frequencies.

Curved surfaces

To the author’s knowledge, none of the simulations packages allows modelling of curved surfaces. Usually curved surfaces are approximated by a number of planes. Curved surfaces produce very special features like focal points or caustics. The questions is whether an approximation by planes produces a focus as well and whether the sound level in the focal region is correct ([11, 12]) It was shown that only deterministic approaches with coherent image source contributions can be used.

Recent work published by Vercammen [13, 14] clarified much more details concerning the problem of focusing. He provided mathematical formulations for sound reflections from concave spherical surfaces. Calculations of the sound pressure are given particularly for the region near the focus. For a hemisphere the energy is distributed over a circular area with a width of $\lambda/2$. For a small wavelength the focusing effect is therefore quite strong. Generally, a reduction of the extremely high pressure by absorbers or diffusers in the curved boundary is not enough to eliminate the focusing effect. Outside the focal a strong interfering sound field can be observed. Vercammen concludes that within reasonable accuracy the sound field outside the focus can be calculated with geometrical acoustics. Computer models based on image source methods, however, are not capable of describing the focal pressure.

Diffraction

Diffraction in room acoustics mainly occurs for two reasons: there might be obstacles in the room space (e.g. stage reflectors) or there might be edges at surroundings of finite room boundaries. In the latter case, either the boundary is forming an obstacle, such as columns or the edge of an orchestra pit, or the boundary is forming the edge between different materials with different impedances (and absorption). Since diffraction is a typical wave phenomenon, it is not accounted for by the basic simulation algorithms listed above. In the past attempt were made to include diffraction as a statistical feature into ray models. But the success was rather limited because the increase in calculation time turned out to be a severe problem. In optics and radiowave physics, ray tracing models were generalised into so-called UDT (uniform geometrical diffraction theory [15]). Other approaches were presented by Svensson [16], who applied the model by Biot and Tolstoy [17]. They are very useful when it comes to determining first-order diffractions. All methods of geometrical diffraction for simulation of a multiple-order diffraction and corresponding reverberation are, however, very time consuming.

Most recently, Svensson and Schröder implemented diffraction modules in simulation software for both stochastic ray tracing and deteministic image sources [18, 19]. Tests and comparions with experiments are subject to ongoing research work.

Spherical wave impedances

Scattering, diffraction etc. are examples of wave phenomena which are not covered by geometrical acoustics. Nevertheless it is sometimes assumed that image source algorithms including the possibility of complex wall reflections factors can yield “correct” modal sound fields in rooms. This is, however, a wrong assumption. The image source model is a correct solution of the wave equation for one rigid boundary. For one non-rigid boundary, it can be shown ([20, 21]) that the spherical wave solution based on complex impedance is a good approximation, if the position of source and receiver are located not too close (> one wavelength) to the wall. This is basically the content of the large room assumption. The relevant dimension compared with the wavelength is then not the room volume, but the smallest dimension, height or width. In flat rooms or in long rooms like corridors grazing incidence angles may occur quite often, so that the plane wave reflection is too rough an approximation at low frequencies.

Therefore, in all cases where room modes are to be calculated, in small rooms such as studio rooms, or living rooms, only wave-based models can be used, such as BEM or FEM or similar.

STOCHASTIC UNCERTAINTIES

Sources of stochastic uncertainties in simulations are usually introduced by uncertain input data, mainly by boundary conditions of absorption and scattering. These data are often taken from databases or textbooks, or is provided by software with integrated databases.

The stochastic uncertainties are casued by influences of the operator and by uncertainties of material properties due to either uncertainties in the product specification from standard measurements or by manufacturing variations of the products. In the following section we will not take the influences of the operator into account, since this component is not predictable. The geometrical model, known as "polygon model", serves our purpose perfectly. There are guidelines for constructing polygon models in geometrical acoustics, such as "walls-large-compared-with-wavelength". We will neglect these uncertainties. Uncertainties that stem from low computation time due to an insufficiently number of rays, low reflection order etc. will be neglected as well. We will only consider material input data.

Absorption coefficients

For geometrical acoustics there are a few preliminary studies of the influence of material data on the prediction results. In contrast to data of complex impedances or reflection factors, tables of absorption coefficients are widely available in textbooks and online. Most questions concerning simulation software focus on the implementation. Should α be modeled angle-dependent or just be constant (random incidence)?

ISO 354 provides a standard method for measuring random-incidence absorption coefficients in reverberation rooms. The uncertainty inherent in the method can be expressed as follows:

Table 1. Uncertainty of absorption coefficients (ISO 354)

Low α ($\approx$ 0.1)	0.1
Mid α ($\approx$ 0.4)	0.1
High α ($\approx$ 0.9)	0.2

Source: Data extracted and condensed from (ISO 354, 2003)

Scattering coefficients

Surface scattering occurs if wall surfaces are corrugated. The specific reflection pattern depends strongly on the frequency. However, with diffuse field conditions and the corresponding uniform sound incidence, not the detailed reflection characteristic is needed, but knowledge about a random-incidence scattering coefficient, *s*, which is defined as the ratio between the scattered sound energy and the totally reflected sound energy [22]. There are no detailed tables available, except for one attempt in [23]. Still the question remains: should scattering be implemented in the software with angle dependence or just for random incidence?

The question of angle dependence cannot be solved generally. If the sound field provides a good mixing and, thus, a good diffuse field approximation, the random-incidence data are surely sufficient. In non-mixing geometries such as corridors or flat halls, this effect may not be taken for granted, and instead, specific angles of incidence dominate the losses. For scattering walls it can be expected that differences are noticeable for vertical or horizontal orientation of 1D structures [24].

In the next chapter a first attempt is made to predict the uncertainty of room acoustic simulation, if the input data of absorption coefficients show typical uncertainties.

PROPAGATION OF UNCERTAINTY

For measurements in physics and particularly applications of ISO GUM [25], uncertainties are treated as object of calculation and prediction. Usually results of an experiment (measurement, simulation) are based on one or more input parameters, which can be characterized by their specific uncertainties. The question is how these input uncertainties affect the uncertainty of the result in the end.

Concepts of error propagation

Consider a function $f(x,y)$ which describes how the two input data x and y form the final result f. An example is the calculation of the sound power, P, by measuring the spatial average rms sound pressure, p, and the reverberation time, T, in a reverberation chamber. In this case, the function has the structure $P = \text{const} \cdot p^2/T$. Needless to explain that the room average of the sound pressure suffers from uncertainties, and the reverberation time as well. Those are characterized by the standard deviations, σ_p and σ_T, respectively. Now, what is the uncertainty of the final result, the sound power? It is obtained by using Equation (1).

$$\frac{\sigma_P}{P} \approx \frac{\sqrt{\left(\frac{\partial P}{\partial p}\right)^2 \sigma_p^2 + \left(\frac{\partial P}{\partial T}\right)^2 \sigma_T^2}}{P} = \sqrt{\left(2\frac{\sigma_p}{p}\right)^2 + \left(\frac{\sigma_T}{T}\right)^2} \qquad (1)$$

The relative uncertainty in measuring the sound pressure is, thus, more relevant than the relative uncertainty of the reverberation time.

If we now apply this concept to room acoustical simulation, we need equations to estimate the final results from certain input data with uncertainties. The latter are uncertainties absorption coefficients, and these are known from the uncertainties in reverberation room measurements (ISO 354). This procedure is now illustrated by three examples. Also appropriate is a Monte-Carlo investigation with varied input parameters and statistical analysis of output quantities, see [26], where parts of this work were published before.

Application to uncertainty of room acoustic data

The task is to find a model function which describes the expected dependence of room acoustic impulse responses on absorption coefficients. This function, however, is very well known. It is an exponential law of energy decay in a diffuse sound field. Statistical reverberation theory serves well as basis for the expectation value. This way, Sabine's equation is a very precise tool for calculation of the reverberation time in a diffuse sound field.

We now apply the error propagation with independent (uncorrelated) uncertainties of *i* absorption coefficients, $\sigma_{\alpha i}$, to the equivalent absorption area, *A*

$$\sigma_A^2 \approx \left(\frac{\partial A}{\partial \alpha_1}\sigma_{\alpha_1}\right)^2 + \left(\frac{\partial A}{\partial \alpha_2}\sigma_{\alpha_2}\right)^2 + \ldots \tag{2}$$

With

$$A = \sum_i S_i\alpha_i \quad T = 0.16\frac{V}{A} \tag{3}$$

yields

$$\sigma_A^2 = \sum_i \left(S_i\sigma_{\alpha_i}\right)^2 \quad , \text{ and} \tag{4}$$

$$\frac{\sigma_T}{T} = \frac{\sigma_A}{A} = \frac{\sigma_{\langle\alpha\rangle}}{\langle\alpha\rangle} = \frac{\sqrt{\sum_i \left(S_i\sigma_{\alpha_i}\right)^2}}{\sum_i S_i\alpha_i} \tag{5}$$

with *T* and *A* the reverberation time and equivalent absorption area, respectively. α_i and σ_i are the absorption coefficients and the surface areas of the room boundaries counted by *i*. Applied to a hall yields the result plotted in Figure 3. Two boundary materials are considered, one absorbing with $\alpha_1 = 0.7$ ("audience", $S_1 = 800$ m^2) and one reflecting with $\alpha_2 = 0.03$ ("hard", $S_2 = 2500$ m^2). The curves are plotted with the standard deviation of the hard surface as parameter. The abscissa is the standard deviation of the audience absorption. It is crucial to recognize in Figure 4 that a reverberation time with uncertainty below 5% (JND) can only be reached if σ_{audience} is below 0.04 (which means $\alpha_1 = 0.7 \pm 0.04$). This result is confirmed by Monte Carlo simulations with a normally distributed variation of input data.

Hence, it can be concluded that without specific adjustment or more precise measurement of absorption coefficients simulation results will not yield a accuracy better than the limit given by JND of 5% for reverberation time.

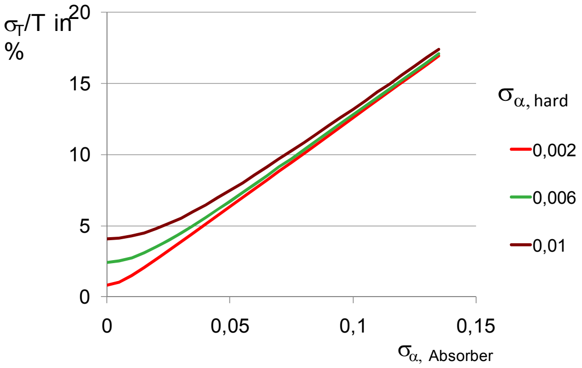

Figure 3. Relative uncertainty of the reverberation time as function of the uncertainty of an absorber (curve parameter uncertainty of low-absorbing walls) (from [26]).

For the sound level, or "Strength" the uncertainty can be derived as well. Further investigation shows that to obtain a maximum level deviation of 1 dB which is considered as JNDs for sound levels, the uncertainty of the absorption coefficient can be rather large. Uncertainties in α_{audience} between 0.15 and 0.18, being typical values of uncertainties (Table 1) there is indeed no problem.

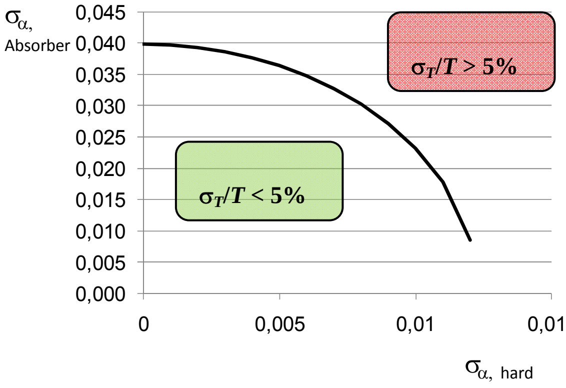

Figure 4. Limen of maximum uncertainty of 5% (right). To obtain an uncertainty of *T* below 5%: keep left of the line (from [26]).

We now calculate the error propagation for the parameter Clarity, C_{80}. It is based on the ratio between early and late reflections and can be estimated from statistical reverberation theory as well (based on Barron [27]).

$$C_{80} \approx 10\log\left[e^{\frac{1.104}{T}}\left(1+\frac{13.8V}{4\pi c r^2 T}\right)-1\right] \tag{6}$$

Detailed calculation based on the approach presented above (see example of Equation 1) with uncertainty of *T* (Equation 5) yields

$$\sigma_{C_{80}} \approx B\cdot\frac{\sigma_{\langle\alpha\rangle}}{\langle\alpha\rangle} = B\cdot\frac{\sigma_T}{T} \tag{7}$$

with a dimensionless room constant, *B*, of about 6 [26]. The variation of *B* between a classroom ($B = 5$) and a church ($B = 7$), however, is small.

With an uncertainty of *T* below 10% the uncertainty of C_{80} is rather small compared with the JND for clarity (1 dB). It is worth mentioning that the prediction from error propagation with Equation (7) fits results from repeated simulations with statistically varied input data nicely.

FINAL REMARKS AND CONCLUSION

The computation speed remains an interesting issue and is certainly worth mentioning. These days, this question is, however, no longer relevant, except for large-room simulation or, better to say, large polygon models (> 1,000 polygons). The computation times of usual programmes are in the order of magnitude of seconds to minutes at most. In real-time processing, we even obtain computation times of milliseconds for updating binaural room impulse responses in CAD models of 100 polygons [18].

Concerning uncertainties of input data, more research is required for the investigation of sources of uncertainties and their relevance for the results of room acoustic quantities. Independently, research is needed to obtain information about the JNDs of those perceptual dimensions. In particular, only little information about perception of scattering is available. It can be expected that the rather large uncertainties in measured random-incidence scattering coefficients play only a little role in the overall acoustic impression, but this assumption is not yet validated.

SUMMARY

This presentation concerns the state of the art in computer simulations, and it focuses on sources of uncertainties in computer models, on actual status in solving indoor acoustic problems and on approaches for quantitative error propagation of uncertainties of input data.

Simulations in architectural acoustics are powerful tools. Their reliability depends on the skills of the operator to create an adequate polygon model and to choose correct input data of absorption and scattering. Information on the uncertainty of such input data is hardly known, and the error propagation into final results of room acoustic parameters not yet studied sufficiently. It can be shown that prediction of reverberation times with better precision than the JND (5%) requires input data which are more accurate than data taken from ISO 354 measurements. For prediction of strength and clarity, there is no conflict when we compare the uncertainties with corresponding JNDs (1 dB).

Research on room acoustic simulation nowadays focuses on a better modelling of sound propagation effects such as diffraction, modes and spherical wave effects in small rooms, and scattering.

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