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Prediction tools in acoustics - Can we trust the PC?

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Prediction models and computer simulations are indispensable tools for design and consulting in various fields of acoustics such as architectural acoustics and sound design for vehicles or household appliances. The reliability of results from such computer tools depends on the quality of the algorithm which provides a best estimate of the sound and vibration data of interest. Also relevant is the quality of input data such as geometry or boundary conditions and, of course the skills of the operator. This presentation focuses on sources of uncertainties in computer models, on actual status in solving indoor acoustic problems as well as simulation of structural acoustics. Special emphasis is put on the relevance of uncertainties with respect to perception and just–noticeable differences.

1 Introduction

After introduction of the Personal Computer more than 30 year ago, computers are used in acoustic research, design and consulting in broad variety of applications. Some computer programs solve complex wave phenomena by using Finite Element or Boundary Element Methods (FEM, BEM), while others search for solutions for energy transport on geometrical paths (Ray Tracing, Image Sources) or between systems (Statistical Energy Analysis), just to list a few examples. An excellent overview on methods in computational acoustics was recently given by Botteldooren [1].

Uncertainties in acoustic prediction and simulations tools were studied only recently. One the one hand the reliability of results is often taken as granted, on the other computer simulation simulations are rejected due to severe doubts in their reliability. What is correct? Of course both.

In this discussion, however, uncertainties must be treated as object of scientific research on its own. It is not adequate to "calibrate" a computer model with adjustment of input data in a way that, for instance, reverberation times or other damping effects are matched to measurement results. The objective for computer simulation 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 then the correct data are used, there still remains the question of the correct model and the correct method appropriate for solving the acoustic problem. The latter aspect sets demands on the skills and experience of the operator. For this paper, we assume that the operator uses the software under good conditions of applicability to the acoustic problem. Then remain systematic and stochastic errors due to the algorithm itself.

In the analysis of uncertainties a very powerful tool can be applied which is related to uncertainties of measurements in general (ISO GUM). The principles suggested in this "ISO Guide to the expression of uncertainty in measurement" have not yet been considered in acoustics in a broad sense. And in computational acoustics there is hardly a 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).

In this contribution an attempt is made to discuss strategies for obtaining quantitative information on uncertainties of computer simulations. The sources of uncertainties discussed are related to material data, approximations in CAD models, and algorithmic details. The methods to obtain quantitative data on uncertainties are results from intercomparisons (so-called "round robins") and the statistical method of error propagation where independent variables are considered with mean and variance forming a final result such as reverberation time, sound level, clarity, etc.

2 How the check the correctness of computed results?

The obvious method to obtain information about the precision of computations is comparison with measured or analytic results. This is presumably done by every developer of algorithms. Analytic solutions exist for elementary cases of indoor or outdoor sound propagation or for structural acoustics. These reference results are very important since they deliver an unbiased judgment of the quality of numerical methods. And accordingly, many benchmark tests for numerical acoustics are available, for example ([2, 3, 4]). These benchmarks can proof that the numerical solution is adequate in principle. They do not necessarily proof, however, how the method applied behaves in general.

As soon as the problem becomes more realistic and, thus, more complex in boundary geometry and boundary conditions, measurements are the only way to define reference results. The interesting part begins when measurements are subject to uncertainty evaluation as well, in order to enable the congruence of data and the significance of their agreement or disagreement. In Figure 1, the two results of the measurement quantity *x* on the left cannot be interpreted if they agree or not, since no indication of variance or standard variation is given. In the middle they are considered not significantly different, whereas on the right they are statistically different. The tolerance used can be the simple standard deviation, σ, giving a statistical probability of 68% that the results are within the interval spanned by the mean $\pm\ \sigma$. If more safety is required, or more significance, 2σ corresponding to 95% probability that the true result is within the interval of the mean $\pm\ 2\sigma$. Details of uncertainty evaluation are more complex than that described here, but this short introduction may serve as tool for discussion of uncertainties of computational acoustics.

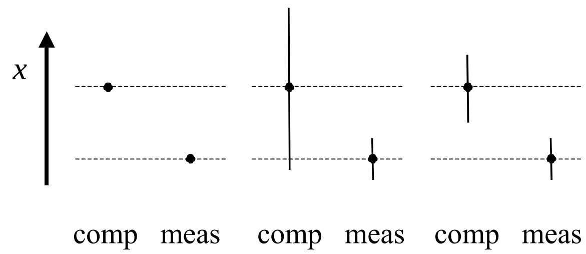


Figure 1: Statistical significance of difference between computed predictions and measurements. Left: no conclusion possible, middle: results are “the same”, right: results are significantly different.

In this respect, it is appropriate to define a scale of psychoacoustic relevance of differences and, thus, comparing differences between results or quantitative uncertainties addressed to simulations with the just audible differences (JND) of human hearing. In best case of listening environment in the laboratory by using headphones, for instance, the JND for reverberation time is about 5%, for strength (level) 1 dB and for definition 10% (after [5]). If uncertainties are smaller than these values, the simulation can be considered as sufficiently precise. For computer prediction and simulation including auralization, one could state the general rule of “don’t compute what you can’t hear”. This statement, however, is quite useless in other applications such as in discussing uncertainties in calibrations, for example.

2.1 Case studies and round robins in room acoustics

One of the first systematic investigations on reliability computer simulations, maybe the first in room acoustics, was presented in 1995 (Vorländer [5]) at the occasion of ICA Trondheim, 25 years after the publication on room acoustical ray tracing by Krokstad et al. In the first “round robin” data were collected from 17 participants in computer simulations and 7 in measurements. One result is shown in Figure 2. 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. Moreover it was significant 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 programs 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 (Bork 2000 [7], Bork 2005 [8]) who confirmed the results of the first project and who extended the scope and the interpretation towards new aspects. After all, one can state that computer simulations in room acoustics can handle room acoustic problems with similar uncertainty as measurements according to ISO 3382. Hence we can trust those results from geometrical acoustics (if the input data and algorithmic options are chosen properly)!

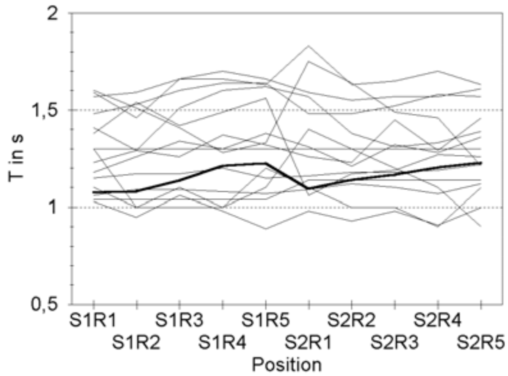


Figure 2: Results from the first round robin on room acoustical computer simulations (from [5]). Plot of reverberation times *T* predicted for the 1 kHz octave band in an auditorium. Thick line: average measurement result which has an uncertainty of 5% (± 0.05 s) (Lundeby et al 1995 [6]).

But it must be paid attention, because these room acoustic programs cannot handle problems with dominant effects of

- Diffraction
- Focusing
- Modes
- Pure tones

One or more of the points listed above exclude geometrical acoustics from the methods of choice. The errors are then systematic. They can be small or big, and it is impossible to predict the effect with any general conclusion, except that we can state that the software is wrongly used.

After all, the discussion on reliability of computer programs by using round robins is fine to obtain an overall impression. But it does not provide information about the reason of uncertainties. These are hidden in influences of the operator and in uncertainties of material properties, either in uncertainties of the product specification from standard measurements or by manufacturing variations of the products.

3 Sources of errors – material data

In the following we exclude influences of the operator, since this component is not predictable. Also, the model of the geometry, either as polygon model or as mesh, is for the moment considered as perfect. Basic rules such as the “six-nodes-per-wavelength” are very well investigated and usually can be applied without doubt. For constructing polygon models in geometrical acoustics similar guidelines exist, such as “walls-large-compared-with-wavelength”. In the latter case, however, the wide frequency range can hardly be covered by using only one polygon model. This aspect has not been tackled yet. For the following we neglect these uncertainties. Also neglected are uncertainties from too low computation time due to an insufficiently low number of rays, low reflection order etc.

The question is how accurate are acoustic results in best case?

3.1 Wave methods

In constructing models for FEM and BEM in practical applications we unavoidably come to the formulation of boundary conditions. Ideal conditions or surfaces including layered materials can be described by calculation, partly even analytic calculations (Mechel [9]) or fourpole and transmission line models. Boundary conditions of rather basic behavior can well be modeled, as illustrated in Figure 3, and the agreement between the simulation (FEM) and the measurement results is surely excellent (after Aretz [10]). But when it comes to real problems such as lightweight wall constructions (gypsum board screwed to studs) or seat in a car compartment, more severe problems of boundary conditions must be faced. Often data on the absorption coefficient can be found from which the magnitude of the reflection factor can be derived, but the phase information needs to be added by good guess or specific modeling. The differences shown in Figure 4 are an example for consequences of such phase uncertainties.

More detailed investigations are given by Aretz [11] and by Hirosawa et al [12], among others, who studied various concepts of getting complex material data of real-world problems such as car compartments and in the free field.

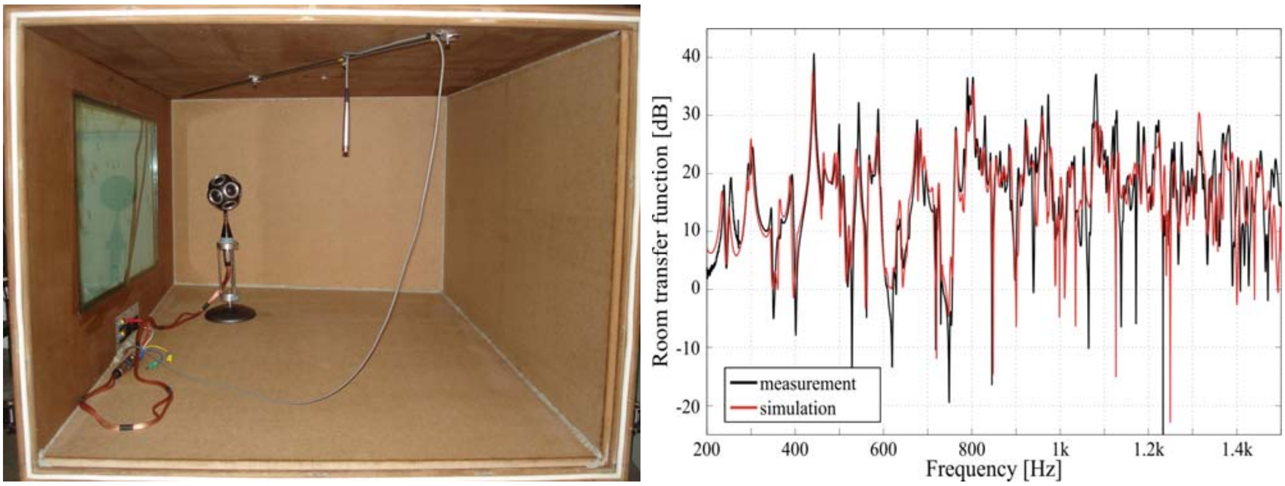


Figure 3: Scale model room (left) with a volume of V =0.74m^3 and FEM result compared with measurement result (right), after Aretz [10].

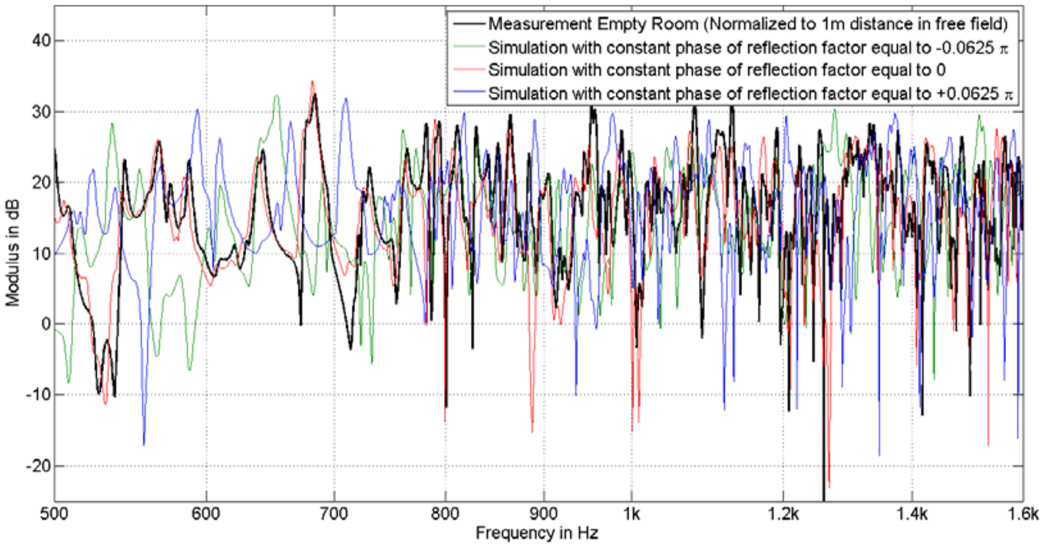


Figure 4: Room transfer functions (examples) for small phase variations of the reflection factor.

At the moment, however, there is no systematic approach for getting quantitative results of uncertainties in FEM, BEM and similar numerical methods, based on uncertainties of magnitude and phase of boundary conditions.

3.2 Geometrical methods

Also for geometrical acoustics there exist 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. The question concerning simulation software is here focused on the implementation. Should α be modeled angle-dependent or just be constant (random incidence)?

Another question is related to scattering coefficients, *s*. There are no tables available in depth, except one first attempt in [13]. And also here: Should scattering be implemented in the software with angle dependence or just for the random-incidence average?

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 for sure sufficient. In non-mixing geometries such as corridors or flat halls, this effect may not be taken as granted, and instead of the average, specific angles of incidence dominate the losses.

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.

4 Error propagation

In measurements in physics and in particular in application of the ISO GUM [14], uncertainties are treated as object of calculation and prediction. Usually a result of an investigation (measurement, simulation) is based on one or more input parameter, which can be characterized by their specific uncertainties. The question is how these input uncertainties affect the uncertainty of the result in the end.

4.1 Concepts of error propagation

Consider a functional relationship *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 rms sound pressure, *p*, in a reverberation chamber and the reverberation time, *T*. *f*(*x*,*y*) in this case has the structure P = const · 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 What is the uncertainty of the final result, the sound power? It's obtained by using Equation (1).

In general, very basic calculation using an expansion in Taylor series gives:

$$\sigma_f^2 \approx \left(\frac{\partial f}{\partial x}\sigma_x\right)^2 + \left(\frac{\partial f}{\partial y}\sigma_y\right)^2 \tag{1}$$

If we now apply this concept to room acoustical simulation, we need equations for estimation the final result 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 in three examples. Also appropriate is a Monte-Carlo investigation with varied input parameters and statistical analysis of output quantities, see below.

4.2 Reverberation time

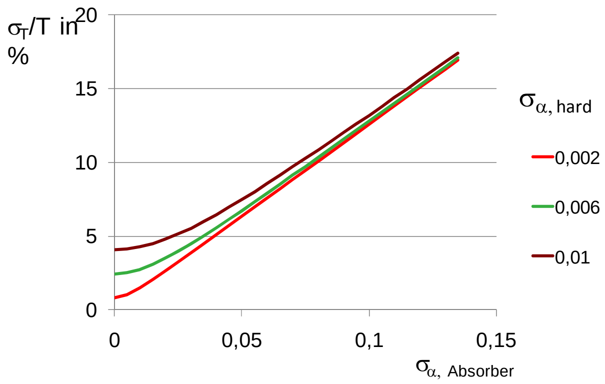
In a diffuse sound field, Sabine's equation

$$T = 0.16\frac{V}{\sum_i S_i\alpha_i}, \text{ with } \alpha_i \pm \sigma_{\alpha_i} \tag{2}$$

is a very precise tool for calculation of the reverberation time. Applying Equation (1) with uncertainties in the absorption coefficients yields

$$\frac{\sigma_T}{T} = \frac{\sigma_A}{A} = \frac{\sqrt{\sum_i S_i^2\sigma_{\alpha_i}^2}}{\sum_i S_i\alpha_i} \tag{3}$$

with *T* and *A* the reverberation time and equivalent absorption area, respectively. α_i and S_i are the absorption coefficients and the surface areas of the *i* room boundaries. Applied to a hall (V = 11000 m^3, S = 3400 m^2, T = 2.9 s, A = 700 m^2) yields the result plotted in Figure 5 (left). Two boundary materials are considered, one absorbing with α_1 = 0.7 ("audience", S_1 = 800 m^2) and one reflecting with α_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 5 (right) that a reverberation time with uncertainty below 5% (JND) can only be reached if $\sigma_{audience}$ is below 0.04 (which means $\alpha_1 = 0.7 \pm 0.04$). This result is confirmed by Monte Carlo simulation with normally distributed variation of input data.



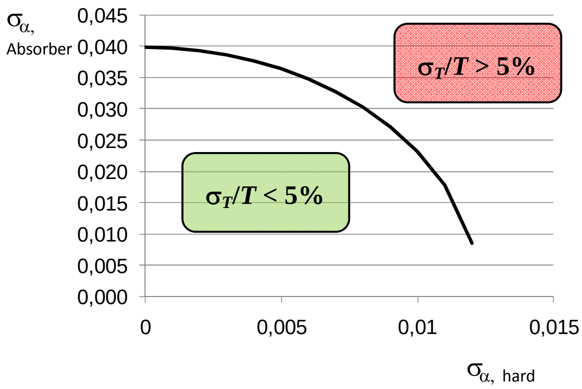


Figure 5: Relative uncertainty of the reverberation time (left) as function of the uncertainty of an absorber (curve parameter uncertainty of low-absorbing walls). Limen of maximum uncertainty of 5% (right). To obtain uncertainty of *T* below 5%: keep left of the line.

The remaining question is how large the uncertainties of absorption coefficients are in practice. Here, ISO 354 gives the following information (Table 1).

Table 1: Typical uncertainties of absorption coefficients (ISO 354)

Absorption coefficient	Uncertainty
Low	0.1
Mid	0.1
High	0.2

Hence can be concluded that without specific adjustment or more precise measurement of absorption coefficients simulation results will not yield an accuracy better than the limit given by JND of 5%. Blind usage of data from textbooks or tables which are taken from ISO 354 measurements will create uncertainties larger than the JND for *T*!

4.3 Strength

For the sound level, or "Strength",

$$G = 37 - 10\log\sum_i S_i\alpha_i \,, \text{ with } \alpha_i \pm \sigma_{\alpha_i} \tag{4}$$

the uncertainty can be derived as well. The result is

$$\sigma_G = 4.34\frac{\sigma_T}{T} = 4.34\frac{\sigma_A}{A} = 4.34\frac{\sqrt{\sum_i S_i^2\sigma_{\alpha_i}^2}}{\sum_i S_i\alpha_i} \tag{5}$$

Further inspection shows that for obtaining a maximum level deviation of 1 dB (JND for sound level), the uncertainty of the absorption coefficient can be rather large (as expected). Uncertainties in $\alpha_{audience}$ between 0.15 and 0.18, as being typical values of uncertainties (Table 1) here are no problem indeed.

4.4 Clarity

Finally we 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 (Barron [15]).

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

Detailed calculation (Equation 1) with uncertainty of T (Equation 3) yields

$$\sigma_{C_{80}} \approx B \cdot \frac{\sigma_\alpha}{\alpha} \tag{7}$$

with a dimensionless room constant, B, of about 6. It depends on V, T and the source-to-receiver-distance, r. The variation of B between a classroom ($B = 5$) and a church ($B = 7$) is small.

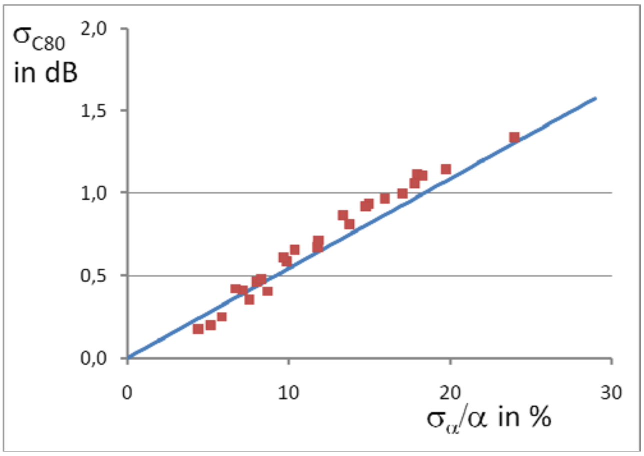


Figure 6: Uncertainty of the Clarity, C_{80}, as a function of the relative uncertainty of α. Continuous line: Prediction according to Equation (7). The red squares indicate results from Monte Carlo simulations using ray tracing with variation of absorption coefficients (normal distribution)

Figure 6 shows the uncertainty of C_{80} as function of the uncertainty of α. Good news is that the uncertainty is rather small compared with the JND for clarity (1 dB). In figure 6 also results from Monte-Carlo simulations are shown. The input data were varied around the nominal values of 0.7 and 0.03 with given standard deviation (normal distribution) The standard deviation of the clarity output was observed and added as red squares. The prediction from error propagation equation nicely fits the Monte-Carlo results.

The expression of results from simulations can only benefit from better accuracy and more information about uncertainties. For statistical energy analysis, SEA, for example, some studies were started which lead to insight into variances on input data [16]. And this is being integrated in user guidelines and output information in software. More investigations and implementations of this kind will surely follow.

5 Summary

Can we trust the PC? Yes, if

- we trust the operator to run the software with appropriate parameters,
- the software is applicable for solving the acoustical problem:
  □ wave effects (modes, diffraction, focuses) with wave methods
  □ others with geometrical methods (room acoustics, outdoor noise propagation)
- all runtime conditions are perfect AND the input data of geometry and boundary conditions are correct

The study of material parameters shows that more information and material databases are required for complex impedances or reflection factors. Furthermore, blindly used databases of absorption coefficients are not precise enough to get predictions of reverberation times as accurately as needed in design processes. In the same time, predictions of sound levels and clarity C_{80} are not causing similar problems. Future work should aim at more systematic investigation of sources of errors and error propagation. Like in measurements, results from computer models should contain also information about the uncertainty.

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