New Approach to Design Control Rooms and Studios

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Abstract

It is possible to describe subjective quality in small and larger rooms with the same types of objective parameters. Most of these parameters characterize the early-to-late ratio of received energy at the listener position. By using a simple inverse procedure for the results of geometrical modeling algorithms, a method is presented to qualify different room shapes and source-receiver configurations by these parameters. The results and the method may help to design room acoustics in a more straightforward way.

0. Introduction

The aim of design is always to satisfy a given quality specified by some kinds of parameters and their values. This is the case in room acoustics also. However, the way of expressing perceptual quality by measurable parameters is still an open problem. The question is, what parameter types can describe what rooms, and how the values of these parameters relate to subjective features?

Transmission quality between a sound source and a receiver (listener) is derived usually from impulse responses. The most important objective parameters describe somehow the temporal distribution of received energy in the impulse response. Of the kinds are reverberation times, and early-to-late or early-to-total energy ratios at a given early time limit. A more general discussion of these features is possible using the energy decay curves.

To study room acoustical situations in general, usually computer models based on the assumptions of geometrical acoustics are used. The results are then monochromatic echograms. Modeled energy decay curves can be calculated from echograms easily.

Examining energy decay curves is advantageous from several aspects. Namely, they are in direct connection with objective parameters as mentioned above, on the other hand it is possible to compare real and modeled results more directly.

A novel way of inverse thinking allows to derive the amplitudes of each reflection from the slope of the energy decay curves [1]. Using the method, properties of different room geometries and source-receiver configurations can be analyzed and designed in more detail. In this paper after the short overview of the objective parameters and the energy decay curve, the method and an application example is presented to compare different room acoustical situations.

1. Objective parameters and the energy decay curve

Common room acoustical parameters describe the ratios of detected energies at receiver points at different time intervals. Usually the impulse response is divided into an early and a late part by the so called early time limit (t_e). Such parameters can be used to realize instructions, like "no strong reflections are preferred in the 20msec time interval after the direct sound" and so on.

The "Clarity" is the ratio of the early-to-late energies in dB:

$$C(t_e) = 10 \cdot \log_{10} \frac{E_0^{t_e}}{E_{t_e}^{\infty}} = 10 \cdot \log_{10} \frac{\int_0^{t_e} p^2(t)dt}{\int_{t_e}^{\infty} p^2(t)dt} \tag{1}$$

where $p(t)$ is the detected pressure at the receiver point. For larger halls, the t_e=80ms time-limit is applied usually. For smaller even t_e=15…25ms time-limit is used.

Similarly, one can express the early-to-total energy ratios in % to get the "Definition" or "Deutlichkeit":

$$D(t_e) = \frac{E_0^{t_e}}{E_0^{\infty}} = \frac{\int_0^{t_e} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}. \tag{2}$$

Larger halls are characterized using t_e=50ms time-limits for example. However, Definition and Clarity are not independent:

$$D_{t_e} = \frac{E_0^{t_e}}{E_0^{\infty}} = \frac{E_0^{t_e}}{E_0^{t_e} + E_{t_e}^{\infty}} = \frac{10^{C_{t_e}/10}}{10^{C_{t_e}/10} + 1}. \tag{3}$$

Excluding the direct sound, only the reverberant part is described using the M-factor. This uses two time-limits, where the first one is about 5ms assuming the direct sound to arrive and decay in that very first time interval.

$$M = C(20ms) - C(5ms). \tag{4}$$

As mentioned in the introduction, energy ratios can be characterized in a more general way using energy decay curves:

$$EDC(t) = 10 \cdot \log_{10}\left[1 - \frac{\int_0^t p^2(\tau)d\tau}{\int_0^\infty p^2(\tau)d\tau}\right]. \tag{5}$$

where instead of ∞ usually a finite time-limit (e.g. 1s) is needed because of the noise of the measurement. The energy decay curve is in direct connection with the parameters above:

$$EDC(t_e) = 10 \cdot \log_{10}\left(1 - D_{t_e}\right) = -10 \cdot \log_{10}\left(10^{C_{t_e}/10} + 1\right) \tag{6}$$

$$EDC(5ms) - EDC(20ms) = 10 \cdot \log_{10}\left(\frac{1 + 10^{C_{20ms}/10}}{1 + 10^{C_{5ms}/10}}\right) = 10 \cdot \log_{10}\left(\frac{1 + 10^{(C_{5ms}+M)/10}}{1 + 10^{C_{5ms}/10}}\right). \tag{7}$$

This is true for the reverberation time also:

$$EDC\left(RT_{60}\right) = -60dB. \tag{8}$$

As one can see, each of these parameters determine a point on the energy decay curve. An exception is the M-factor, because it specifies not the absolute position of two points, but their relative position.

These relations are summarized in Figure 1.

2. Theory of a simple inverse method

In general, the inverse approach means, that assuming the accuracy of the model of a system, input parameters are derived from the output parameters. In our case this means that modeling parameters of the room are calculated from the parameters at the receiver point.

In order to apply the inverse approach, we assume the accuracy of the geometrical modeling method. For the procedure we make use of the energy decay curves. These can be calculated from the modeled echograms:

$$EDC_f^*\left(t_n\right) = 10 \cdot \log_{10}\left[1 - \frac{\sum_{i=0}^{n} p^{*2}_{f}\left(t_i\right)}{\sum_{i=0}^{N} p^{*2}_{f}\left(t_i\right)}\right], \tag{9}$$

where f denotes that this EDC is monochromatic, i.e. valid only at a given frequency, and the asterisk denotes that the curve is the result of the model. Also, t_n denotes the timings of the received echoes, where t_0 is the timing of the direct sound. The temporal distribution is determined by the shape and size of the room, and the position of the source and the receiver inside.

As one can see, due to the simple relationship between the curve and the amplitude of the echoes, the calculation can be inverted by a numerical differentiation. The whole procedure is called the “EDC fitting”. A known continuous $EDC(t)$ can be approximated with $EDC^{*}(t_n)$ by a simple “sampling” at the t_n moments:

$$EDC^{*}_{f}\left(t_n\right) = EDC_{f}\left(t_n\right). \tag{10}$$

At the same time one should take the relative amplitudes, i.e. where the amplitudes of the echoes in the modeled echogram are normalized to the total energy in the response

$$EDC^{*}_{f}\left(t_n\right) = 10 \cdot \log_{10}\left[1 - \sum_{i=0}^{n} E^{*2}_{f}\left(t_i\right)\right]. \tag{11}$$

Finally, the amplitudes of the echoes can be calculated with the finally recursive procedure:

$$\begin{aligned} E^{*}_{f}\left(t_0\right) &= \frac{E\left(t_0\right)}{E_0^{\infty}}, \\ E^{*}_{f}\left(t_n\right) &= \sum_{i=0}^{n} E^{*}_{f}\left(t_i\right) - \sum_{i=0}^{n-1} E^{*}_{f}\left(t_i\right) = \left[1 - 10^{EDC^{*}_{f}\left(t_n\right)/10}\right] - \left[1 - 10^{EDC^{*}_{f}\left(t_{n-1}\right)/10}\right], \end{aligned} \tag{12}$$

where n=1,2,3…N.

The amplitudes contain the attenuation due to the propagation and air absorption. If these are corrected, one gets a raw series of amplitudes that are determined only by the directional characteristics of the source and the receiver, and the absorptive features of the reflecting surfaces. Let us denote this data as the “raw echogram”. The procedure does not exclude non-specular phenomena, however for the sake of simplicity only the specular part is handled here.

3. Designing with the inverse method

The goal when designing room acoustics is to determine the surface properties of the walls and the configuration of sources and receivers to achieve the specified objective parameter specifications. In the common practice this means a trial-and-error process, where intuitively changed situations are tested by using different prediction methods.

Since the input parameters of the model are the properties of the sources, receivers and the surfaces, practically speaking the inverse method means a straightforward way of design. Accordingly, this approach makes the design more evident, simple, and allows the study of given room acoustical situations more analytically.

One can obtain automated and optimized solutions to fulfill the required quality by using simple stochastic methods also. In this case, errors are interpreted as the deviations at given points on the modeled energy decay curves. In the course of the optimization, random vectors in the parameter space are used to search in order to decrease the error. However, with this approach it is not possible to study the room acoustical problem analytically. That is, what are the most critical parameters (directional characteristics, absorption coefficients, etc.) that could make the results better or make the specifications impossible to match?

Inverse methods, however, make possible to examine problematic points of the room and the configuration. Therefore, in this paper different room acoustical situations are compared with this method to demonstrate its application.

3.1. EDC template and ideal EDC

Because the study is based on the parameters described in the previous section, one has to assume that those parameters are related to the subjective impression of acoustical quality.

Each parameter determines an exact point or their relative position on this curve, so one may introduce the term "EDC template". This means, that if the acoustical quality is expressed by such parameters, several energy decay curves can match this specification. Of course, their slope between the determining points may be different (Fig. 2). These are the features that the aforementioned parameters cannot characterize.

To make the specification unambiguous, one can introduce also the term "ideal EDC". In this case the curve specifies an exponential decay between the points, i.e. in a logarithmic presentation, lines connect the points.

Note, that special attention is needed with the direct-to-reverberant ratio, which is included in the M-factor (Eq. 4) and in the recursive calculation (Eq. 12), because it is a special point on the curve. The direct sound is infinitely narrow in the echogram, so the ideal EDC should look like in Figure 3.

3.2. Criteria of the comparison

The EDC fitting procedure indicates, that significantly different reflection patterns can have almost the same energy decay curve slope and can result in the same objective parameter values. In our theoretical experiment the goal is to examine, what are the possible acoustical qualities a given room acoustical situation can offer.

Reflecting surfaces can only *absorb* energy, therefore reflected energy is always smaller than incident energy. If looking at the picture of a raw echogram, the amplitude of a detected reflection can be higher than the direct sound only if the directional pattern of the source and the receiver are such or if the reflecting surfaces are strongly curved (focusing).

Assuming omnidirectional characteristics of the source and the receiver, and that the room has only plane surfaces, in a valid "raw echogram" the direct sound should have the highest amplitude, and every echo should have a positive amplitude. If this criterion is not fulfilled, it indicates that the room is not able to satisfy the required objective parameters under the assumptions outlined above. In such a case one can see the critical points on the reflecting surfaces along the path of all echoes, that have invalid amplitudes.

3.3. Procedure of the comparison

In the first step, 3 different room shapes each having 2 different source-receiver configurations are modeled. The rooms and the situations are shown in Figure 4. These are typical, recommended room shapes and sizes for studios and reference listening rooms. During the modeling, detection timings and paths of the beams are recorded. Then, by using ideal energy decay curves, the amplitudes of each echo is calculated (Eq. 10-12).

In the experiment 3 parameters are affected. Reverberation times are kown from the recommendations [2,3,4]. To make calculation and modeling times shorter, only 400msec long echograms are considered. The M-factor and Clarity are the other two parameters.

According to the criteria of validity, minimal and maximal valid values of Clarity are taken as the function of direct-to-reverberant ratio. Then, the minimal and maximal values of the M-factor is calculated for these cases as well. Also, to show an analytical result, the surfaces that make the situations invalid, are counted for. These may be called the “critical surfaces”.

Such an application of the simple inverse method is rather theoretical, since it assumes that every surface can be divided into arbitrary small pieces having arbitrary absorption properties between 0 and 1. Also, this approach does not take the symmetry of absorption coefficients on the surfaces of the room into consideration, which is an evident requirement for the accurate stereo listening condition.

4. Results

The calculation results parameter values, that the rooms are able to produce, and which surfaces cause invalid situations. Considering the assumptions, invalid situations can be resolved only by changing the directivity of the source and the receiver or by changing the geometry.

There are two illustrations about the results. The first one shows the minimal and maximal valid values of C(20msec) (solid lines) and the M-factor (dotted lines) as the function of the direct-to-reverberant ratio, which changes from 0 to 1. For a more detailed look, only the reasonable range of values are shown (the M-factor cannot be lower than 0dB).

The C(20ms) is derived from the values of the resulting M-factor and the direct-to-reflected ratio, because actually the latter one determines the C(5ms) value here (Eq. 3). It explains also, why the M-factor is equal to C(20ms) when the direct-to-reverberant ratio is 0.5 (or D(50ms)=50%). Also, this is why the M-factor is also higher when the direct-to-reverberant ratio is lower than 0.5, and lower otherwise. As the direct sound gets dominant, the M-factor values trend to the anechoic case.

The other illustration shows, how critical each surface is. There are two bars for each surface. The solid bar on the left shows, how critical the surface is with respect to the minimal C(20ms) value. The empty bar on the right shows, how critical the surface is with respect to the maximal C(20ms) value. These results characterize, which surfaces need special care when designing for the C(20ms) or M-factor values. In other words, if one is to design for a higher reflected energy in the early part, the surfaces with empty bars are important. Or, if one is to design for a lower reflected energy in the early part, the surfaces with solid bars are important, or “critical”.

Note, that the results are frequency dependent due to the air absorption. However, it seemed, that there are no significant differences between the results at 1kHz and 10kHz. Hence, the illustrations show only the results calculated at 1kHz.

4.1. Example 1

The results for the shoebox-type room are shown in Figure 5 and Figure 6.

Here, the side walls and the front wall is divided into 3-3 equal sized parts in order to introduce more degrees of freedom, and to have detailed results. The surface numbers are identified as in Figure 4.

As one can see, the direct part cannot be smaller than 20% of the whole response. From that point, in both cases, the range of available C(20ms) and M-factor values increase rapidly. However, the values can be significantly lower when the speaker is further away from the walls.

At the same time, the critical surface values show no significant differences for the minimal values. Typically the floor and the ceiling, and the front corners are more important from this point of view. Nevertheless, much more difference is observed for the maximal values, as the center part of the front wall is the only to limit the maximal values.

4.2. Example 2

The results for the trapezoid-shape room are shown in Figure 7 and Figure 8.

In this example, much greater change is expected, because the speaker is flush mounted in the wall in the first version, and in front of the wall in the other. Indeed, the valid value ranges do differ very much. It seems, that the flush mounted speaker can produce a more direct sound, but more early reflections only at the same time. For interpreting the critical surface illustrations, the surface numbers are shown in Figure 4.

Again, there is no significant change in the critical surface illustration between the two versions even for the maximal values. However, the importance of the wall no. 4 is evident in the case, when the speakers are in front of the wall, and that is what Fig. 8 shows.

4.3. Example 3

The results for the specially shaped “reflection-free” room are shown in Figure 9 and Figure 10.

This room shows the benefits of the special shape, because in both cases the advantages are more notable in the critical surface illustration. The surface numbers are shown in Figure 4.

An important advantage is, that surface no. 3 is not critical, any the less this surface is usually the window to a studio. Also, the importance of the back walls (no. 7 and no. 8) is high, which makes the room acoustical treatment easier in practice. Again, surface no. 4 becomes critical in the version, where the speaker is in front of the wall.

5. Summary

Based on well-known objective parameter types, several aspects of rooms can be deducted by utilizing simple relations. One of this is the fact, that most of the objective parameters correspond to points on the energy decay curves. Since modeled and real energy decay curves are more practical to compare, it is possible to calculate modeling parameters like absorption coefficients or directivity from the required objective parameters. This means a more straightforward design approach.

In this paper, only the first step of the inverse process is demonstrated. Here, by using the "EDC fitting" procedure, different room shapes and source-receiver configurations were compared. Assuming the validity of the geometrical modeling method and that the source and the receiver is omnidirectional, one can decide whether a room is able to produce a given EDC or not. Based on this criterion, ranges of possible values of the C(20ms) and M-factor were calculated as the function of the direct-to-reflected ratio. This theoretical calculation can help to qualify different rooms by the given objective parameters in the future.

In our further work, the practicability of such methods, the objective qualification of rooms, the objective and subjective effect of different sizes, shapes and early-time limits need to be tested. Also, the very important question of what other parameters of these types can characterize and how they characterize the subjective impression of a sound field in the room.

References

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[2] EBU Tech 3276: "Listening conditions for the assessment of sound programme material: monophonic and two-channel stereophonic", 2th Edition, 1997

[3] ISO /DIS 3382: "Acoustics - Measurement of the reverberation time of rooms with reference to other acoustical parameters", 1996

[4] ITU-R Recommendation BS.1116: "Methods for Subjective Evaluation of Small Impairments in audio systems including multichannel sound systems", 2nd Edition, 1997

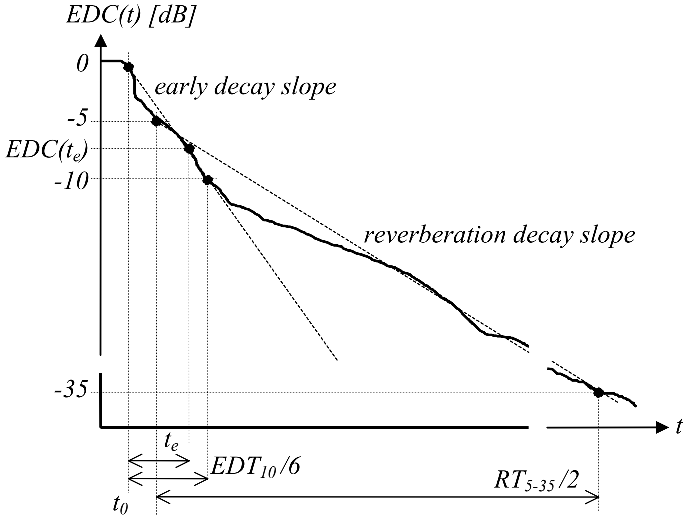


Figure 1. Relationship of objective parameters and the EDC

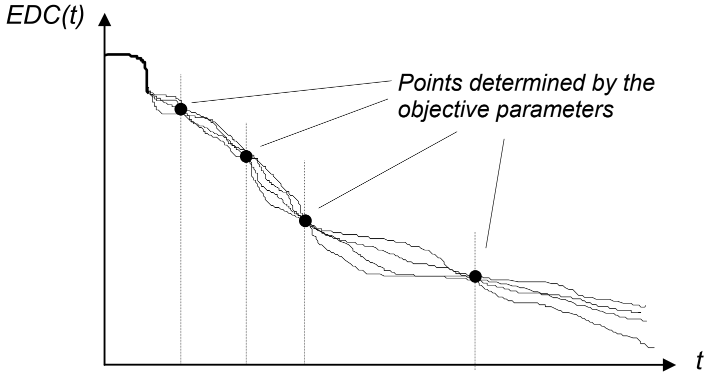


Figure 2. Different EDCs matching the specification

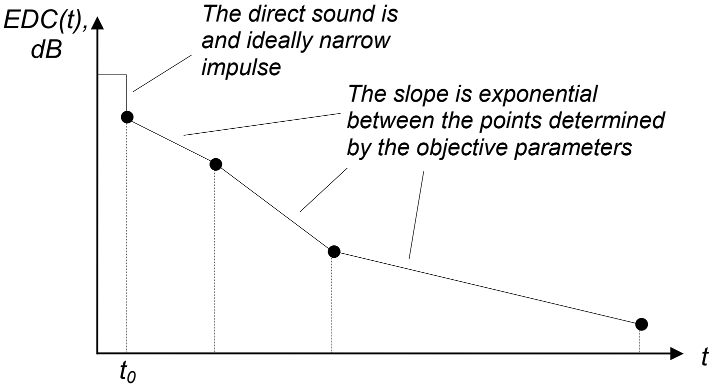
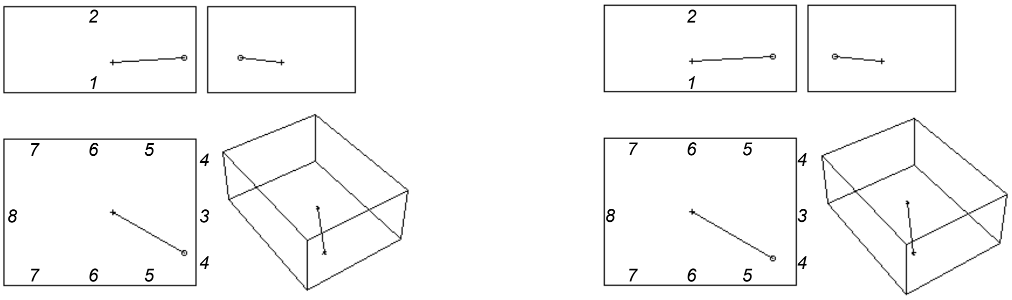


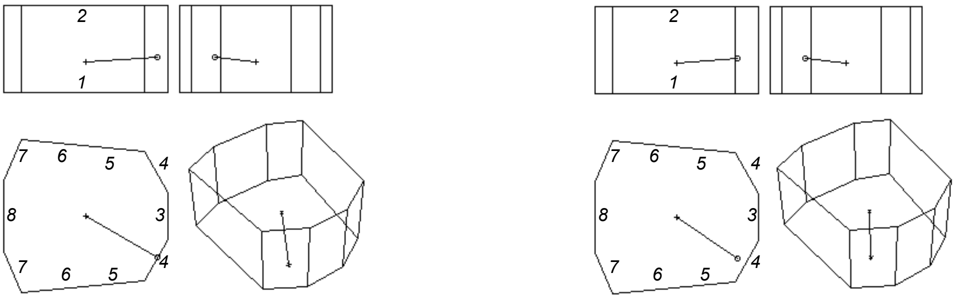
Figure 3. The ideal EDC assumes exponential decay

Example 1. Shoebox-type



(size: 8.2m×6.3m×3.7m; d_{SR}=3.5m) (size: 8.2m×6.3m×3.7m; d_{SR}=4m)

Example 2. Trapezoid-like type



(size: 7m×6.5m×3.7m; d_{SR}=3.5m) (size: 7m×6.5m×3.7m; d_{SR}=3m)

Example 3. "Reflection-free" type (5.6m×6m×3.7m)

(size: 5.6m×6m×3.7m; d_{SR}=3m) (size: 5.6m×6m×3.7m; d_{SR}=2.5m)

Figure 4. Room acoustical situations in the experiment

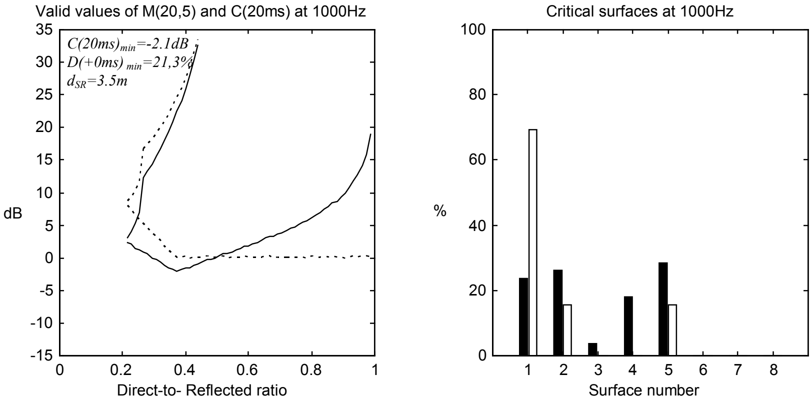


Figure 5. Results for the room Example 1 when speaker distance is 3.5m.

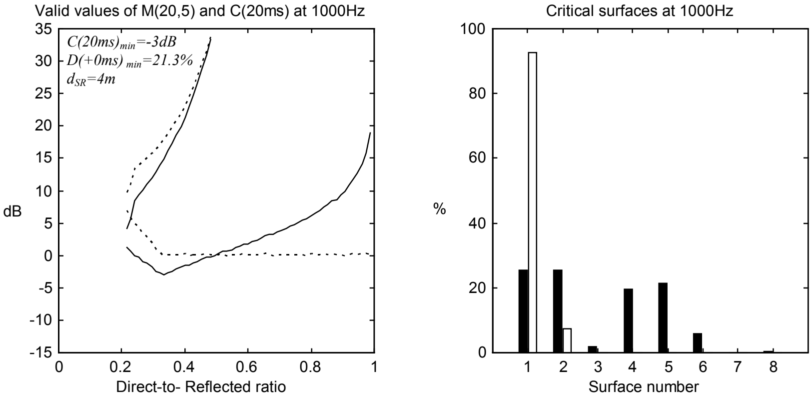


Figure 6. Results for the room Example 1 when speaker distance is 4m.

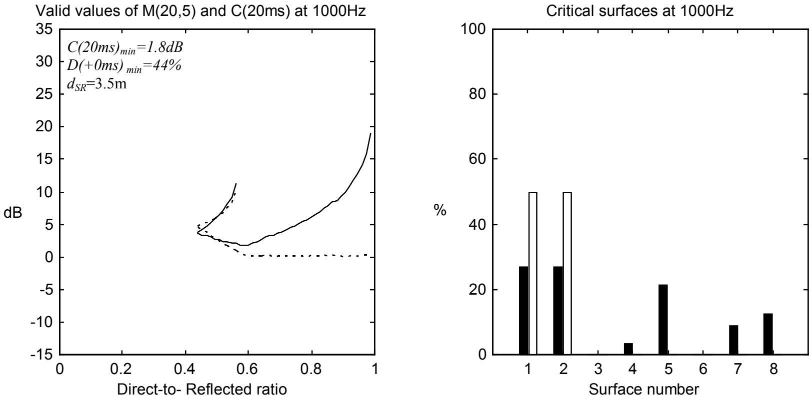


Figure 7. Results for the room Example 2 when speaker distance is 3.5m (in wall).

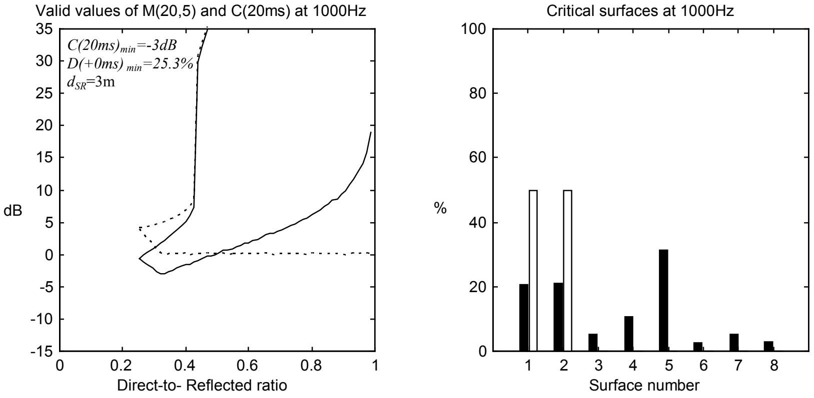


Figure 8. Results for the room Example 2 when speaker distance is 3m (in front of wall).

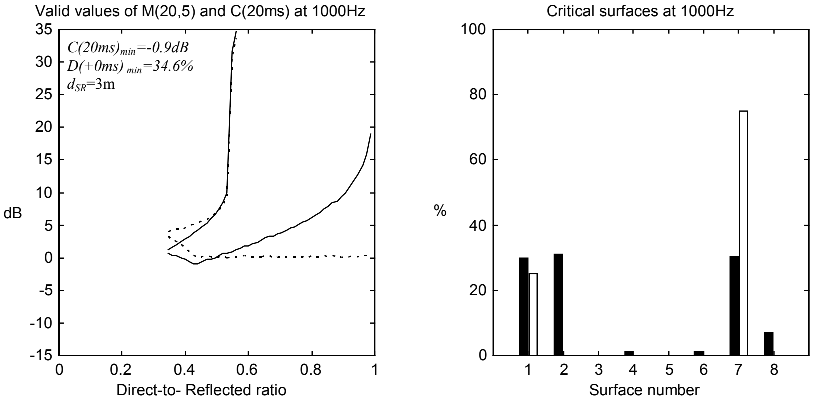


Figure 9. Results for the room Example 3 when speaker distance is 3m (in wall).

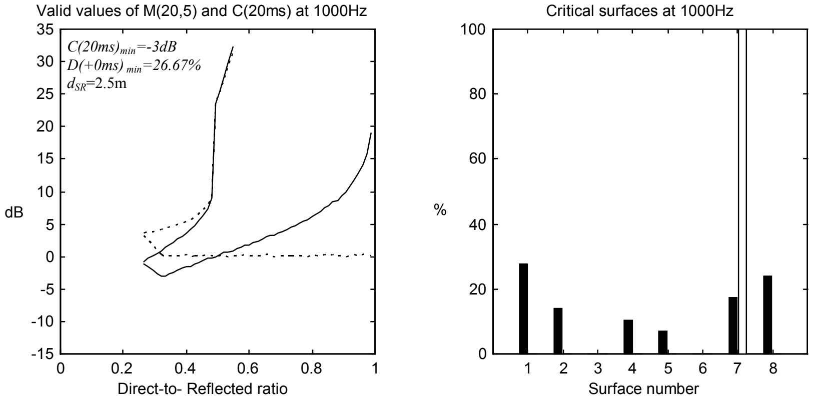


Figure 10. Results for the room Example 3 when speaker distance is 2.5m (in front of wall).