A New Method for the Objective Qualification of Rooms

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Summary

The goal in room acoustical design is always to reach a given sound quality by tuning different features of the room. In the beginning of the design it would be a great help to know, what acoustical quality a given room shape can offer. In other words, there should be a tool for doing an objective comparison. The inverse approach in geometrical acoustics and the extensive use of energy decay curves can be used for this purpose. In this paper a short introduction of the method, and some examples are presented to demonstrate the possibilities.

1. Introduction

When designing room acoustics, one has to specify the required perceptual quality by some objective (i.e. measurable) parameters quantitatively first. Unfortunately, this very first step is still a hard task in itself, since there are too many factors that can influence the acoustical impression of a room. Nevertheless, for very simple reasons, only the acoustics of concert halls and theatres is studied thoroughly enough to enable such a specification [1, 2, 3, 4, 5]. In addition, once defining a possible set of room acoustical parameters, it would be useful to have a method that enables the designer to compare the possibilities of different room acoustical situations objectively and quantitatively at the same time.

Different rooms can provide different values for the same parameter types, therefore looking at the possible value ranges of given parameters may help to compare those different situations. Based on this approach, a simple comparison method is presented after a short overview of the conventional objective evaluation methods. Also, some application examples are presented in the last part.

2. Overview

Impulse responses contain all information about time invariant and linear systems. Assuming the acoustics of a room as such, the measurement of impulse responses is the usual way of studying the properties of the sound field. To have a more clear picture or an "essence" however, only selected features of the impulse responses are used for the characterisation.

Measurements evaluating two or more impulse responses are better for the description of spaciousness, but because of the approach discussed later, we focus on one channel measurements only from now on.

The different types of parameters may be classified into several groups and are more or less in direct connection with the energy decay curve (EDC). The EDC is actually the backward integrated energetic impulse response introduced by Schroeder [6]:

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

where $p(\tau)$ is the pressure response at the receiver. The frequency dependence of these parameters may be derived by band-limiting the impulse response before the calculation. It is still a question of what frequency resolution is needed to describe the subjective side well, and this should be the topic of experiments in the future. Nevertheless we assume here, that the impulse response is band-limited in our calculations already.

2.1. Parameters on the curve

The main parameter types characterise the absolute or relative position of one or more points on this decay curve, actually. This is shown in Figure 1.

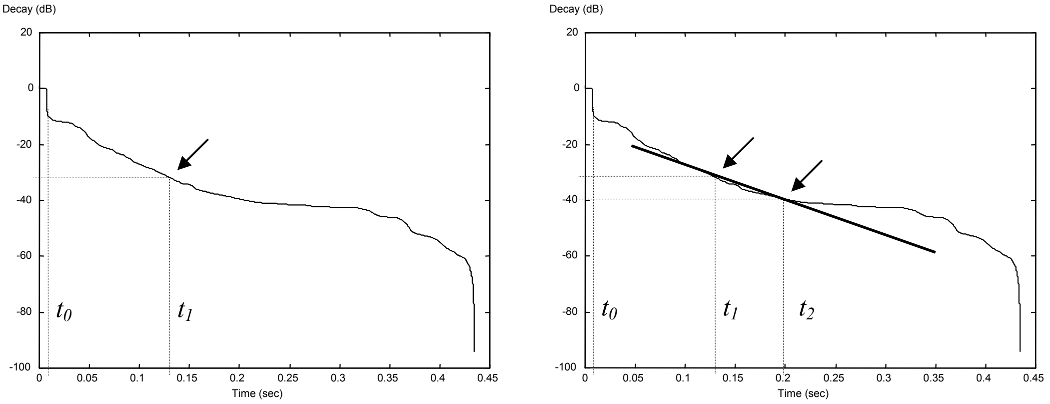


Figure 1. Different parameter types on the curve

The first group of parameters determines the absolute position of one point on the curve by the ratio of the received energy before and after a given time point, or the time needed to achieve the given received-to-remaining energy ratio.

In the first case the time point is called the *early time limit* (t_e). The absolute position of one point can be characterised by the ratio of energy before and after a given time limit:

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

or, by the ratio of the energy before the time limit and the total energy:

$$D(t_e) = \frac{\int_0^{t_e} p^2(t) dt}{\int_0^\infty p^2(t) dt}. \quad (3)$$

These two are related as:

$$D(t_e) = 1 - \frac{1}{10^{C(t_e)/10} + 1}. \quad (4)$$

Or, their connection with the EDC:

$$EDC(t_e) = 10 \cdot \log_{10}\left[1 - D(t_e)\right] = -10 \cdot \log_{10}\left[10^{C(t_e)/10} + 1\right] \tag{5}$$

Such parameters are for example Clarity and Definition where the early time limit is 50…80ms for relatively large spaces (e.g. concert halls, theatres, etc.). However, for smaller rooms, the early time limits of 15…25ms is recommended for the characterisation [7].

In the other case, where the time of a given decay is needed, the relation is fairly simple:

$$EDC(t_0 + t_A) = A. \tag{6}$$

where A is the given decay level, t_0 is the timing of the direct sound and t_A is the time required for the decay relative to t_0. This defines different decay rates or decay times, like the classical reverberation time for the -60dB decay level.

The second group of parameters determines the relative position of two points on the curve. These parameters characterise the ratio of the received energy between two time points relative to the total energy, or the time difference needed for a given decay.

A practical example is the M-factor for this. The M-factor was originally introduced in order to exclude the energy of the direct sound from the characterisation [7]:

$$M = C(20\text{ms}) - C(5\text{ms}) \tag{7}$$

where C(5ms) is assumed to describe the energy ratio of the direct sound.

Again, the time difference for a given decay level change describes decay rate, which is then used for the extrapolated reverberation times:

$$RT_{\Delta A} = \frac{-60\text{dB}}{\Delta A} \cdot \Delta t \tag{8}$$

where the total reverberation time is assumed to be at the -60dB decay level and ΔA is the decay level change in the Δt time interval. The early decay time (EDT_{10}) is derived from the -10dB decay level in this way, for example.

There are other parameters, like the centre time, that are related to the curve:

$$t_S = \frac{\int_0^\infty t \cdot p^2(t)dt}{\int_0^\infty p^2(t)dt}. \tag{9}$$

This relates to the total slope of the curve, because assuming an ideally exponential decay

$$p_{ideal}(t) = \varepsilon(t - t_0) \cdot e^{-\gamma(t - t_0)} \quad \Rightarrow \quad t_{S_{ideal}} = t_0 + \frac{1}{2\gamma} \tag{10}$$

where $\varepsilon(t)$ is the step function, t_0 is the timing of the direct sound, γ is the decay rate and $p_{ideal}(t)$ is the ideal pressure impulse response. From this, the ideal energy decay curve is

$$EDC_{ideal}(t) = 10 \cdot \log_{10}\left[e^{-2\gamma(t - t_0)}\right] \tag{11}$$

and therefore the decay time for a given decay level can be calculated by using the centre time:

$$T = \left(t_{S_{ideal}} - t_0\right) \cdot \left[-EDC_{ideal}(t) \cdot \frac{\ln 10}{10}\right] \tag{12}$$

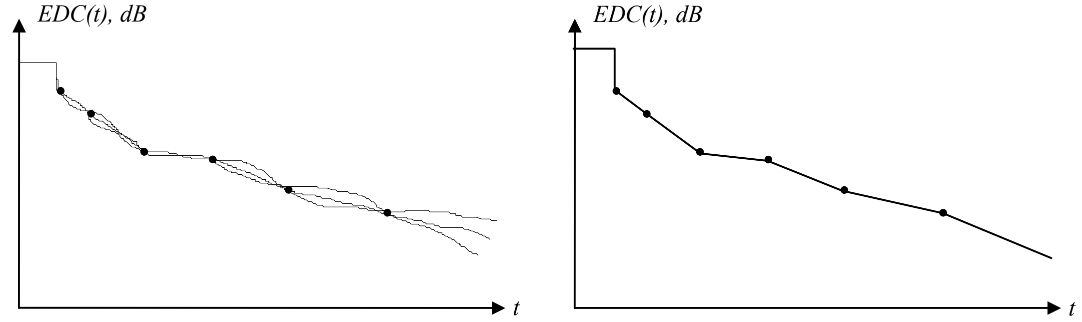
In practice, the differences of calculated and measured decay times describe how the measured impulse response deviates from the ideal one. The experiences show, that the values of t_S correlate to the values of EDT_{10} primarily [2].

These parameters are defined exactly in ISO3382 for different applications [8], and are used widely.

2.2. EDC specifications

As seen from the summary above, a room acoustical specification means the specification of the position of some points on the curve. In other words, fairly different energy decay curves can result the same values if they match at those points. At the same time, there is no exact specification between those points (

Figure 2). This explains also, why different rooms with the same measured values can sound very different.



a) b)

Figure 2. (a) Different curves for the same specification and (b) the "ideal" EDC

One can make the specification unambiguous by assuming exponential decays between the specified points (

Figure 2) and we may call this curve the "ideal EDC". A similar assumption can lead to the "ideal" values of Clarity and other parameters only by assuming an ideally exponential decay [1] for example.

3. The comparison method

As it was mentioned earlier, the performance of different rooms could be compared by the room acoustical value ranges they can produce. Furthermore, energy decay curves should be the tool for doing that comparison, since they are the connection between those parameters and the impulse responses.

The idea is to synthesise ideal energy decay curves based on the required parameter values for different room acoustical situations, and see if these situations are able to produce those curves. This procedure results in different value ranges for the different rooms.

To decide whether a situation can produce the prescribed results or not, a simple method called "energy decay curve fitting" is utilised. The goal with the EDC fitting procedure is to calculate the amplitudes of each reflection from a given EDC. The idea of EDC fitting comes from the inverse application of geometrical acoustics [9], and this way allows to analyse the behaviour of the room in a more straightforward way and in more detail. Here we are using this method only for the decision outlined above.

3.1. EDC fitting

To model room acoustical properties, methods utilising the assumptions of geometrical acoustics are used almost exclusively. These models calculate the predicted energy decay curves by a numerical integration from the echograms.

$$EDC_f^*(t_n) = 10 \cdot \log_{10}\left[1 - \frac{\sum_{i=0}^{n} p^{*2}_f(t_i)}{\sum_{i=0}^{N} p^{*2}_f(t_i)}\right] = 10 \cdot \log_{10}\left[1 - \sum_{i=0}^{N} E_f^*(t_i)\right], \tag{13}$$

where $p_f(t_n)$ is the reflected pressure at t_n time and $E_f(t_n)$ is the energy normalised to the total received energy (i.e. of the echogram). All these results are monochromatic (or narrow band limited) at the frequency of f, and the asterisk denotes that these are predicted results. One can recognise, that if the energy decay curves is known at t_n time points, the values of $E_f^*(t_n)$ can be derived simply. To do this, the prescribed (original) EDC should be "sampled" at the timings of the modelled reflections in the first step:

$$EDC_f^*(t_n) = EDC_f(t_n), \tag{14}$$

Then, by using a numerical differentiation, the amplitudes are derived as:

$$\begin{aligned} \overline{E}_f^*(t_0) &= D(t_0), \\ \overline{E}_f^*(t_n) &= \sum_{i=0}^{n} \overline{E}_f^*(t_i) - \sum_{i=0}^{n-1} \overline{E}_f^*(t_i) = \left[1 - 10^{EDC_f^{**}(t_n)/10}\right] - \left[1 - 10^{EDC_f^{**}(t_{n-1})/10}\right] \end{aligned} \tag{15}$$

where n=1, 2, …N.

This procedure is called EDC fitting, because the amplitudes of the resulting echogram provide a predicted EDC that fits the original one (Figure 3).

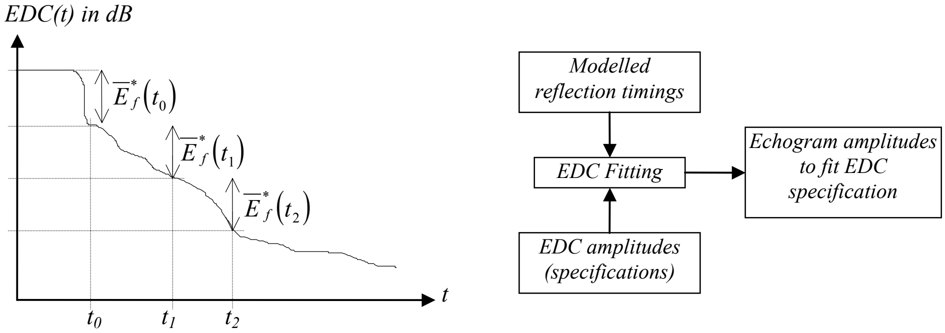


Figure 3. The EDC fitting procedure, where the energy decays are assumed to represent the energy ratio between each reflection (see eq. 15)

3.2. Validity of an EDC

We call an EDC "valid" if the room can produce that. On the other hand, an EDC is "invalid" if the room is not able to produce that. The validity criteria is, that assuming an omnidirectional sound source in the room, and that all reflecting surfaces are planar, detected reflections at the receiver point must have a lower amplitude than that of the direct sound. This is easy to check by using the EDC fitting method, actually. It should be noted, that non-omnidirectional sources can be used in the method also, because their directional behaviour can be corrected for by a simple directional weighting.

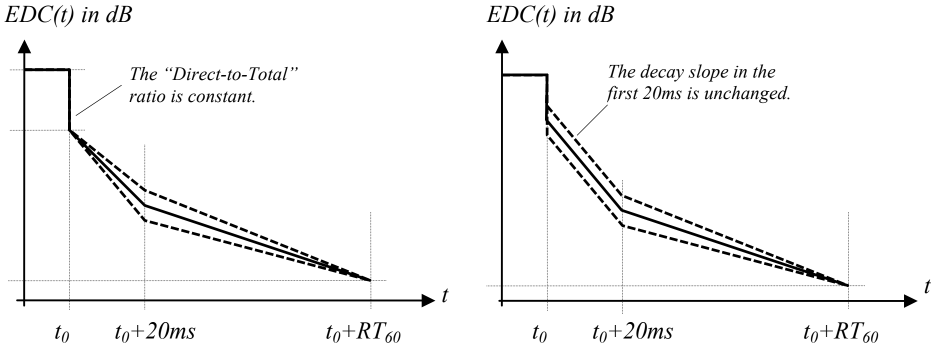
In other words, if a reflection has a higher amplitude than that of the direct sound, then it is evident, that the room is unable to produce the required EDC correctly. Of course, to check the real amplitudes of reflections, one has to correct the resulting echogram by the absorption of air and the attenuation due to propagation first. This correction results in a "raw echogram".

3.3. Getting the valid room acoustical parameter values

To get a whole view of the possibilities of a room acoustical situation, different combinations of the values of selected parameters are examined systematically.

In our application example below, the valid value combinations of clarity at 20ms and the M-factor are looked for at a given reverberation time RT_{60}. This selection of the parameter types is reasonable, since the C(5ms) in the formula of the M-factor is the direct-to-reflected energy ratio in fact. And, in the ideal world of a geometrical model (i.e. assuming a very narrow direct sound impulse), the

$C(5\mathrm{ms})\approx C(+0)$. Figure 4 shows some of the synthesised EDCs under these circumstances. Note, that the M-factor cannot be lower than 0dB, since the EDC must have a decaying slope, of course.



When changing only the C(20ms) value. *When changing only the C(+0ms) value.*

Figure 4. Ideal EDCs when changing the C(+0ms) and C(20ms) for a given RT$_{60}$.

3.4. Plotting the results

The results of the systematic search can be summarised in one plot. An example with the explanation of each section is in Figure 5.

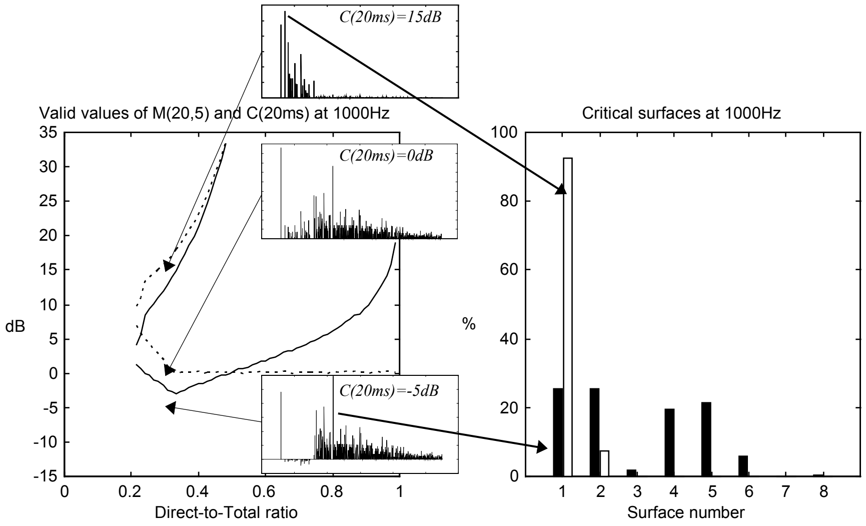


Figure 5. An example of the results showing the available limit values of the chosen parameters, and the distribution, showing how critical each surface type is with respect to those parameters

Here the valid combinations of the values of the C(20ms) and the M-factor are drawn by their maximal and minimal valid limit values as the function of the direct-to-total energy ratio. Note, that the direct-to-total energy ratio or D(+0ms) can be calculated from the direct-to-reflected ratio (Eq. 4). As a consequence, the C(20ms) can be calculated from the M-factor and the direct-to-total ratio:

$$C(20\mathrm{ms}) = M + 10\cdot\log_{10}\left[\frac{D(+0\mathrm{ms})}{1-D(+0\mathrm{ms})}\right]. \tag{16}$$

A value of 0 for the direct-to-total ratio means a pure reverberant sound, while the value of 1 means a pure direct sound. Again, because of the relations, if the direct-to-total ratio is 0,5 (or 50%), the M-factor is equal to C(20ms), because in this case the C(+0ms) is 0dB (i.e. the energy of the direct sound is equal to the energy of all the reflections).

It is also interesting to see, what the absolute minimal values can be. Since the value of the M-factor cannot be lower than 0dB, the slope of the curve of the *C*(20ms) minimal values turns positive at the point where the M-factor reaches 0dB. In other words, the lowest value of *C*(20ms) is at that point.

A second graph on the right is intended to show, how much each surface does limit the values of *C*(20ms) and the M-factor. The distribution bar graph of the “critical” surfaces is calculated as follows. Where the *C*(20ms) value becomes valid from invalid (i.e. at the minimal values), those surfaces are recorded, which contribute to the reflections that limit the validity. These are then summed through the whole procedure, and plotted with the solid bars. The same procedure is carried out where the *C*(20ms) value becomes invalid from valid (i.e. at the maximal values), but is plotted with the empty bars.

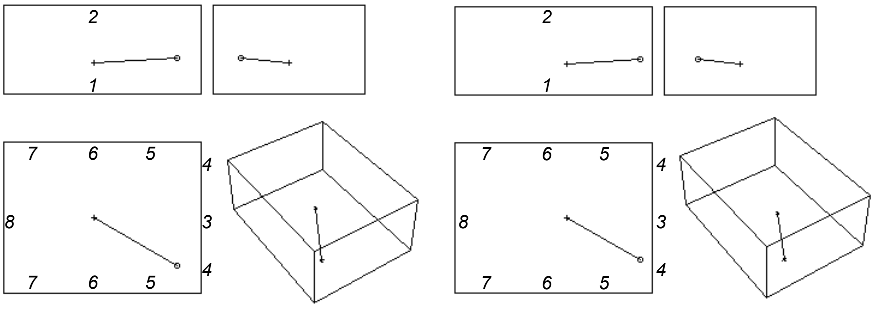
To put it in an other way, the surfaces with the solid bars need greater attention when designing for low reflected energy in the early part, while the surfaces with the empty bars need greater attention when designing for high reflected energy in the early part. The results are expressed in %, and the higher the participation of a surface is, the more it is important to treat those surface according the required results.

4. Application examples

In this part of the paper some application examples are presented to demonstrate the procedure outlined above. There are 3 different studio rooms each with 2 different situations (i.e. source-receiver configurations). The geometries and source-receiver configurations are shown later in Figure 6, Figure 8 and Figure 10. These geometries are recommended room shapes for studios and reference listening rooms. Although the effect of the furniture and the equipment is not negligible in practical cases, for the sake of simplicity, none of the rooms contain any furniture here. The prescribed reverberation time is RT_{60}=350ms in all cases.

4.1. Shoebox listening room

The geometry of the room situations is shown in Figure 6. The two situations differ in the way of the source and the receiver (d_{SR}) are positioned. The results are shown in Figure 7.



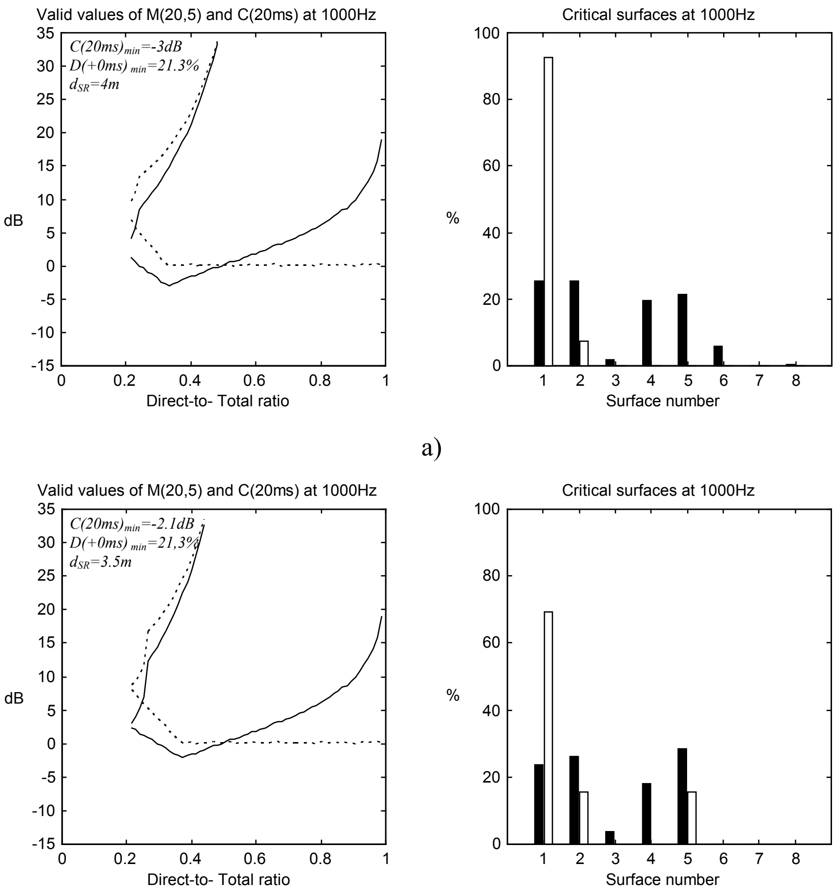
(size: 8.2m×6.3m×3.7m; d_{SR}=4m)

a)

(size: 8.2m×6.3m×3.7m; d_{SR}=3.5m)

b)

Figure 6. The shoebox room geometry and surface ID numbers



a)

b)

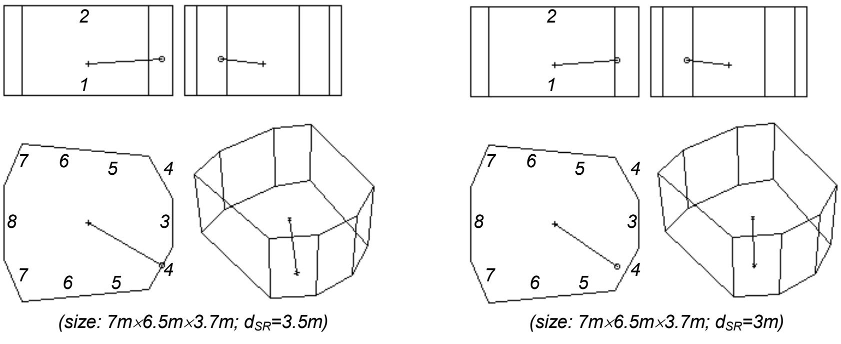
Figure 7. The results of the shoebox room.

The valid range of C(20ms) and M-factor are fairly wide. As expected, the configuration, where the source is further apart from the side walls and the receiver, can reach a lower C(20ms) minimum. Also it is clear, that the maximal values can be higher if the source is nearer to the side walls. Both versions cannot produce lower D(+0ms) values than 21%.

The critical surface distribution confirms also the facts, that the nearest corner is critical. However, it is interesting to see, that the ceiling and the floor are equally important, although they have significantly greater surface areas, and are responsible for the very first reflections.

4.2. Trapezoid room

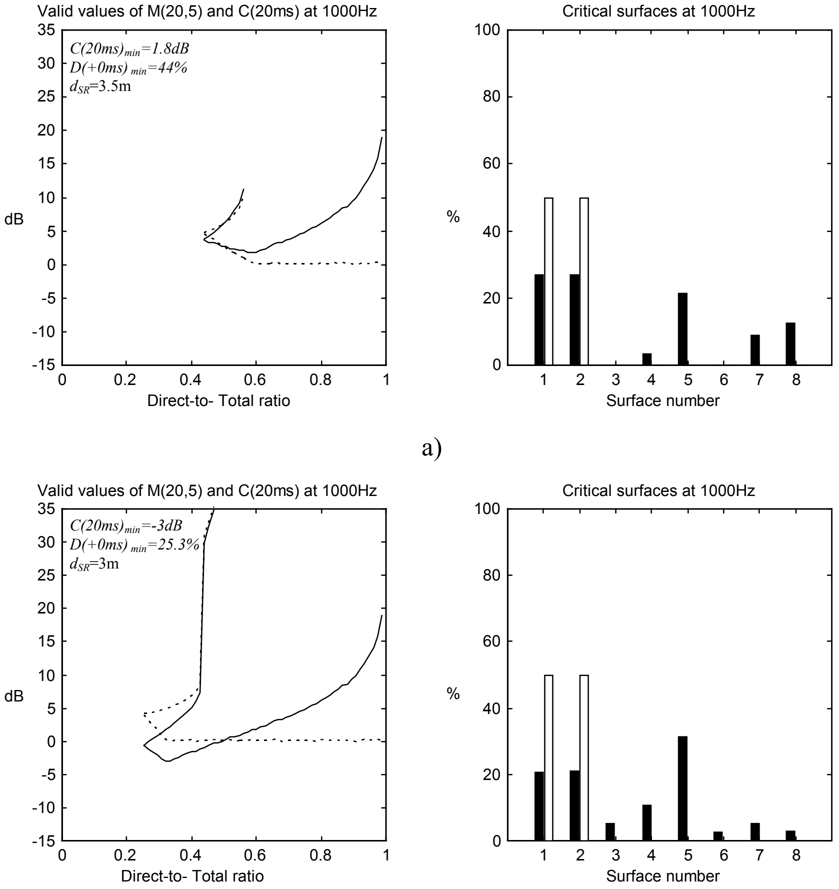
The geometry of the room is shown in Figure 8. In case a) the source is wall mounted (d_{SR}=3.5m), and in case b) the source is in front of the wall (d_{SR}=3m). The results are shown in Figure 9.



a)

b)

Figure 8. The trapezoid room geometry and surface ID numbers



a)

b)

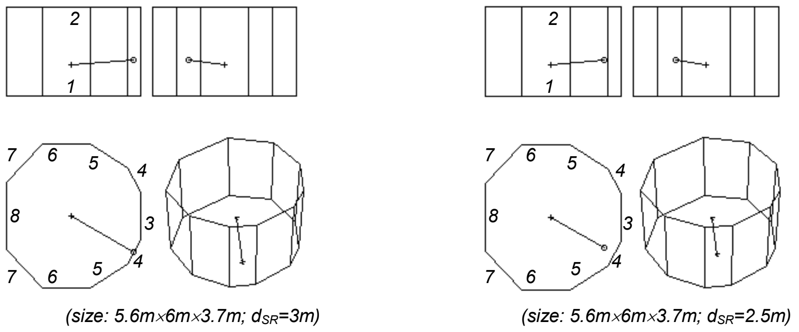
Figure 9. The results of the trapezoid room shape

A valid range of values of C(20ms) and M-factor are more narrow and show great differences in the two cases. The difference is due to the minimum of D(+0ms). It seems, that the trapezoid room with wall-mounted sources can produce much higher direct-to-total energy ratios only. This means also, that in case a) the minimum of C(20ms) is significantly higher than in case b).

The critical surface distribution confirms the differences due to the fact, that the source is wall-mounted in case a). As expected, the role of the surface behind the source (surface no. 4) increases when taking the source out of the wall. Again, the importance of the walls near the source are the most dominant here.

4.3. Reflection-free room

The geometry of the room is shown in Figure 10. In case a) the source is wall mounted (d_{SR}=3m), and in case b) the source is in front of the wall (d_{SR}=2.5m). The results are shown in Figure 11.

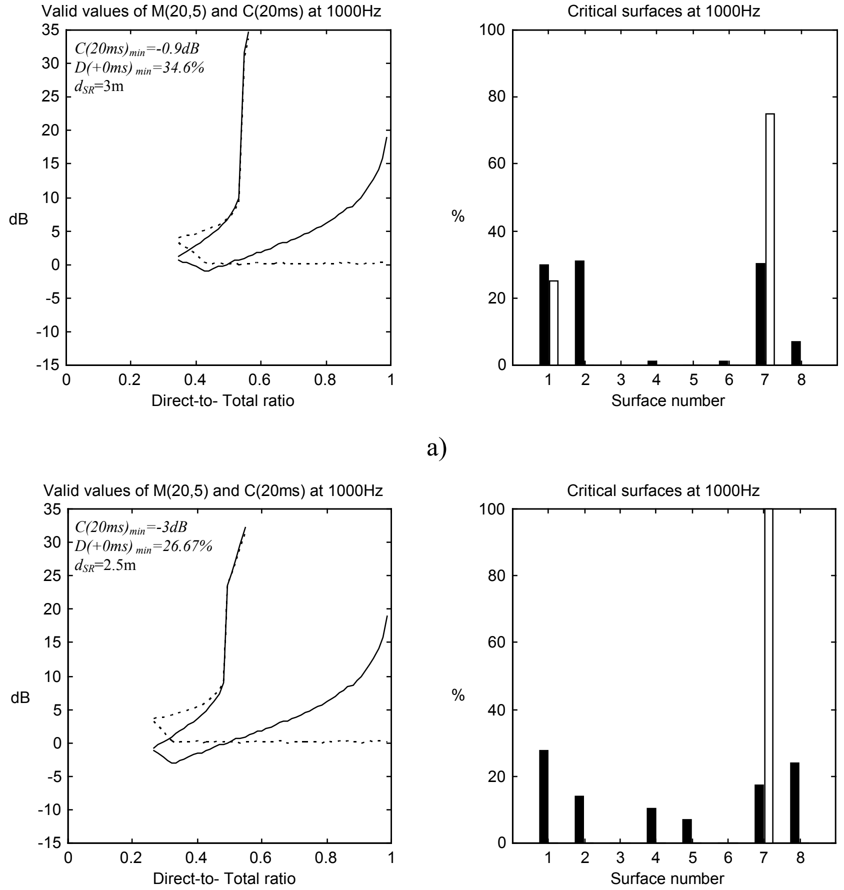


(size: 5.6m×6m×3.7m; d_{SR}=3m)

(size: 5.6m×6m×3.7m; d_{SR}=2.5m)

a) b)

Figure 10. The reflection-free room geometry and surface ID numbers



a)

b)

Figure 11. The results of the reflection-free design.

Due to the special shape, this room has a narrower valid range of the values of C(20ms) and M-factor than in the cases above. At the same time the change in the shape and the position of the curves is not as significant as in the case of the trapezoid room.

The real benefits of this special shape show up only in the distribution of critical surfaces. Considering their areas, the back walls (surface no. 7 and 8) are surprisingly important, and the nearest surfaces become important only when taking the source out of the front wall. In practice this feature of the room is important when treating surfaces, because the equipment or the furniture is typically not in front of the back walls.

5. Summary

Starting from a summary of the most usual parameter types the paper showed a method to compare and qualify different room acoustical situations objectively, utilising the inverse approach of geometrical acoustics.

It should be noted also, that the method uses several simplifications and approximations. Firs of all, non-specular reflection components were neglected. Then, while searching for the possible valid room acoustical parameter values, the method assumed, that each reflecting point on the surfaces could have any absorption coefficient. That is not true in practice, of course. Nevertheless, even having these simplifications, the application examples proved the potential of the method.

However there must be several verifications in the future, for example for theatres, concert halls, etc. Also it would be interesting to see, how this method could be used for multichannel characterisation methods.

6. References

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