The young architect's guide to room acoustics

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The Young Architect's Guide to Room Acoustics

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Abstract: Most students in architecture are unable to design a concert hall from the acoustic textbooks, especially if the hall's volume is much less than used for symphony orchestras. Therefore a method is proposed to read the reverberation time and loudness from a simple G-RT-diagram as a function of volume and mean absorption coefficient. An "ideal curve" is proposed as "target values" in the first stages of the design process. They are also used to interpret the numbers generated by computer models in order to readjust the shape of the hall and the materials used.

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1. Introduction

At the Faculty of Architecture of our University, students develop (virtual) plans for concert halls of different sizes. They start with reading elementary books and lecture notes. For those who want to dig into the theory more profoundly, Kuttruff's book on acoustics [1] appears very adequate.

The next step is to use this knowledge for the first draft of a concert hall. Three books, commonly preferred in this stage, are Barron's, Beranek's and Lord's (in alphabetical order) [2, 3, 4]. However, these books seem to be written for the acoustic consultant or the architect having some experience in the field of room acoustics. One extra problem of Beranek's book is that it deals with big halls only, while in many student plans the focus is on a hall with 100 to 800 seats.

In the next stage students use simulation computer programs. It appears easy to input a hall into the computer, but then: how should the calculated values for the reverberation time, loudness, clarity, etc. be interpreted? What are the "ideal values"? It is the aim of the research described here, to help architectural students with these early steps in the design process.

The present paper was originally intended as a subject for discussion with the attendants of the RADS-conference in Awaji, Hyogo [5]. Comments were given at the conference itself, but before and after the conference itself more profound contributions were made[1]. These comments had a rather big influence on the present text.

2. Theory

There is a big variety of acoustical values; Beranek's book [3] gives an overview. However, the present method is meant for students, so the theory is kept elementary. Two values are presented here for the first stages of the design process: the reverberation time *RT* and the loudness *G* (strength). A third parameter (the clarity C_{80}) appeared very useful as well, but it is left out of this paper.

On the other side are the building parameters (shape, number of seats, materials, etc.) from which three have a leading role: the volume *V*, the total surface *S* and the mean absorption coefficient α.

The start is with Sabine's formula for the reverberation time, given as:

$$RT = 0.161 \frac{V}{\alpha S} \tag{1}$$

The loudness is calculated as:

[1] The authors want to thank R. Metkemeijer and M. Barron for their contributions.

$$G(r) = 10\log\left(\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)}{\alpha S}\right) - 10\log\left(\frac{1}{4\pi 10^2}\right) \quad (2)$$

where Q is the directivity of the source. The distance between source and receiver is given as r. For most positions in a hall the first term within the brackets can be neglected and hence equation (2) turns into:

$$G = 31 + 10\log\left(\frac{4(1-\alpha)}{\alpha S}\right) \quad (3)$$

Equations (1) and (3) are valid under the assumption that the sound field within the concert hall is diffuse; then equation (3) does not depend on r. In practice, however, G tends to decrease with r, but it can be proved that Eq. (3) is valid when $r = 4V/S$, which is the mean free path [3, 6]. At the early stage of the design process, Eq. (3) gives a sufficient indication of the total hall. In a later stage of the design process, computer models will automatically produce the different G-values through the hall.

3. The *G-RT*-diagram

To combine the two acoustical values with the three building parameters, we developed a "*G-RT*-diagram". Examples are given in [6], where the method is explained in somewhat more detail. However, in one graph only two building parameters can be presented, so the surface S is expressed in the volume by assuming a shoebox shape where length : width : height = 1.4 : 1.0 : 0.7. Fortunately the method appears surprisingly insensitive for other values. Only when a cube is used or an extremely long hall, significant differences are found and the following diagrams need to be readjusted.

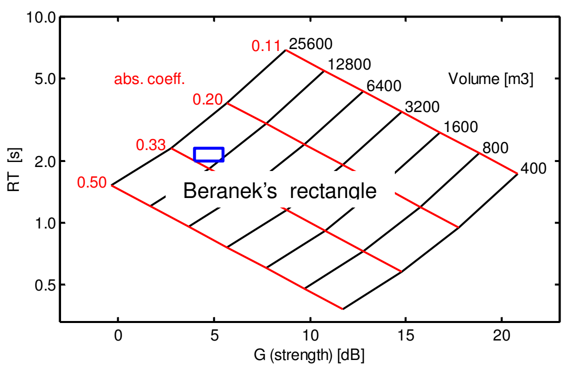

Fig. 1 Reverberation time and strength for a series of hall volumes and absorption coefficients.

In figure 1 Eqs. (1) and (3) are plotted with the hall volume and the absorption coefficient as parameters, where the room volumes range from 400 to 25600 m^3 a. The values for α (0.11, 0.20, 0.33, 0.50) are chosen to get 3 dB steps in Eq. (3). *RT* is given along a logarithmic scale, because *RT* should be considered as a *relative* factor.

Figure 1 also contains "Beranek's rectangle". In Beranek's book [3] values can be found for the mid frequencies of the "ideal" concert hall for symphonic music: *RT* should be between 2 and 2.3 seconds, while *G* should be between 4.0 and 5.5 dB for the "European" hall. If these values are applied, the ideal halls lie within a rectangle, as shown in figure 2.

Of the three variables *RT*, *G* and *V*, only two can be chosen independently. So only one volume (≈16,000 m^3) can be found if *RT* = 2.15 and *G* = 4.75 are chosen as ideal values. On many occasions, this conclusion is a shock to architectural students. Many students of our faculty want to have Mahler's 8th symphony played in a local gymnasium with a 3200 m^3 volume by choosing a 2.1 seconds reverberation time. Figure 1 shows them why this sounds like an inferno: it is much too loud. Smaller halls are meant for smaller orchestras and if a large orchestra has to play in a small hall, both *RT* and *G* must be decreased to find a compromise. Figure 1 also explains to students why some modern halls have sophisticated technical means to change the volume considerably depending on the type of music to be played.

4. Ideal values for smaller halls

It is the aim of the present work to find the "ideal" acoustics (if any) for halls smaller than those described by Beranek and to draw an "ideal curve" from Beranek's rectangle through the *G-RT*-diagram.

Barron deals with halls for chamber music ([2], chapter 6) and he gives an "ideal curve" which is based on the work by Cremer and Müller [7]. It is written as:

$$\log RT = 0.138\log V - 0.306 \quad (4a)$$

This resulting curve is drawn in figure 2. Barron compared this curve with results from some existing halls and found a good agreement. Yet we prefer a slightly different curve, defined as:

$$\log RT = 0.21\log V - 0.55 \quad (4b)$$

which is also drawn in figure 2.

The reason to deviate slightly from the Cremer-Müller-curve is twofold:

1. The curve from Cremer and Müller does not run through Beranek's rectangle. It doesn't need to, since the Cremer-Müller-curve is made for chamber music and if this is performed in big halls, a slightly lower *RT* may be preferable. Yet, we think, students should

depart from Beranek's Rectangle.
2. All rooms given by Barron are between 2,000 and 20,000 m³. If the curve is extrapolated to halls in the order of 400 m³ the mean absorption coefficient is so low that only small audiences are allowed.

Table 1 gives the same results. It has been used by students and was found very useful for the establishment of "target values" when using computer programs. This will be illustrated in a following section.

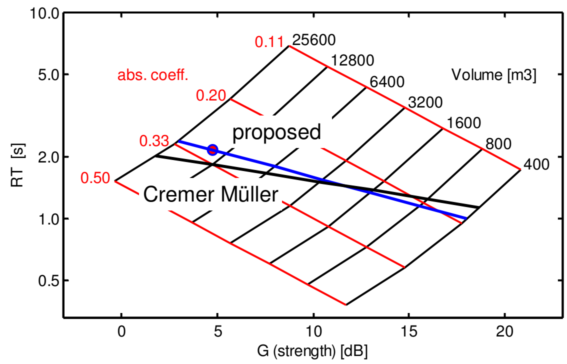

Fig. 2 Ideal curves drawn in the *G*-*RT*-diagram.

Table 1 The values of RT and G from the lower curve in figure 4. C_{80} and α are added.

Volume [m³]	400	800	1600	3200	6400	12800	25600
RT [s]	1.00	1.15	1.32	1.53	1.77	2.06	2.39
G [dB]	18.0	15.5	13.0	10.5	8.0	5.5	3.0
C_{80} [dB]	3.1	2.1	1.2	0.3	-0.6	-1.5	-2.3
α [-]	0.19	0.21	0.23	0.25	0.27	0.29	0.32

Table 2 Audience size as a function of hall volume for two mean absorption coefficients for non-audience surfaces .

Volume [m³]	400	800	1600	3200	6400	12800	25600
S_{occ} at 10% [m²]	34	65	122	224	407	736	1311
m³ / pers at 10%	5.9	6.1	6.5	7.1	7.8	8.7	9.8
S_{occ} at 13% [m²]	24	49	97	185	348	642	1173
m³ / pers at 13 %	8.3	8.2	8.3	8.6	9.2	10.0	10.9

5. Audience size

RT and *G* are interesting values for the acoustician, but if a hall is in its first stage of design, the architect needs building parameters like dimensions, audience size and absorption coefficients.
In almost any case the audience and the orchestra are the main absorbing surfaces in a concert hall. Kosten [8] used the (big) concert halls given in Beranek's book to derive a relative factor (1.07) to calculate the reverberation time from the volume and the total occupied surface S_{occ}. This was a first attempt to combine acoustical values and building parameters, but Kosten's value 1.07 fails for smaller halls. Log-log-dependencies like given in equations (4) are more likely, but this is subject of further research.

Our somewhat different approach is found in table 2. The occupied surface is assumed as totally absorbing. For other surfaces a mean absorption factor is used. In the paper for the RADS-congress [5], this value was estimated as 10%, but in the before-mentioned discussions on that paper Dr. Metkemeijer commented that this value is too low. He did many measurements in halls when the chairs were removed and a value of 13% appears more likely. This value even tends to increase since nowadays halls are filled with ever increasing sets of lighting. Therefore the volume of modern halls tends to increase as well in order to keep the right reverberation time. Table 2 gives the results for 10 and 13%.

It is interesting to calculate the volume per person from S_{occ}. Table 2 gives these results if the number of seats is assumed as 2.0/m², which is a common value for older halls. Some modern halls have values as low as 1.6, but there is a tendency back to older values in recent years. Table 2 gives only a very rough estimation, because values in practice vary considerably. This is illustrated by the four examples given by Barron ([2], chapter 6): Wigmore Hall has a small stage and the audience surface is big. Hence it has only 5.3

m^3/person. The other three halls Barron deals with are more according to table 2 with values ranging from 8.3 to 9.2 m^3/person. Beranek's book shows (for big halls) values from 6 - 12 m^3/person, but all his "better" concert halls are in the order of 8-10 m^3/person.

6. An example: Young Architect at work

One student's project is given here as an example. The task was to convert a machine hall from the 19th century into a concert hall for chamber music. The given volume is 2400 m^3, so the size for audience plus orchestra as estimated (after interpolation) from table 2 is about 140 m^2 and the number of seats is 280. That does not fit on the floor surface of this particular hall, so the seat number was reduced to 260.

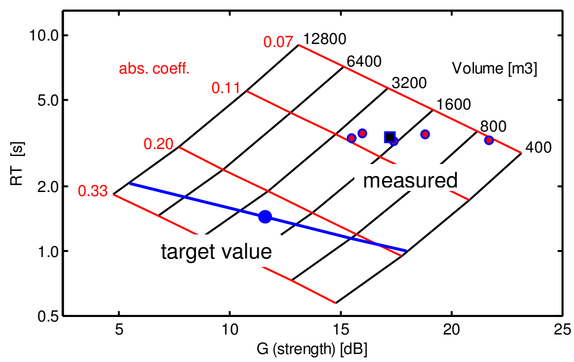

Fig. 3 Design scheme. The square dot from the measured values is at mean free path distance between source and receiver. The example is for 500 Hz; for other octave bands slightly different values are found.

Figure 3 shows the *G*-*RT*-diagram. It contains the "target value", which is on the intersection of the "ideal curve" and the curve for 2400 m^3. Also six measured values are given in the hall when it was completely empty. The six measured values show a rather small variation in *RT*-values; the variation in *G*-values is rather big because they are taken for different source-receiver distances. They agreed with the values predicted with Barron's method to calculate decreasing sound levels through the hall (see [6] for details about the method).

One specific measured value is denoted by a square dot. It is for the mean free path distance and it is the aim of our method to bring this value close to the target value of the hall when renovated. This is not always easy since from the three variables *RT*, *G* and *V*, only two can be chosen independently.

The next step was to build a computer model and to calculate *G* and *RT* for similar source and receiver positions. In this case, bringing the values at the mean free path distance close to the target value was not too difficult, since the extra audience plane appeared adequate.

A similar *G*-C_{80}-diagram can be made with C_{80} instead of *RT*. In theory this diagram gives no extra information. However, when interpreting computer output, it appeared useful as well. It is even possible to estimate the influence of sound reflectors etc.

Another task set for this particular student was to make a design for a theatre in this existing hall as well. At that stage we made a first attempt to develop an ideal curve for speech as well. It will be given in a future paper.

Designing a theatre with the method appeared not too difficult as well, but, as always, the biggest task was to design technical possibilities to change the theatre into a chamber music hall and vice versa.

Discussion

A simple scheme is possible in the first stages of the design process and we believe that the curves of figure 2 and the values in tables 1 and 2 are appropriate. It took some time for students to get familiar with the system, but it proved to be a useful instrument, especially for understanding the output of computer models.

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