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The combination of absorbing materials and room shapes to reduce noise levels

Lau Nijs, Pernette Versteeg, Marinus van der Voorden.

Delft University of Technology, Faculty of Architecture, Delft, Netherlands
L.Nijs@bk.tudelft.nl

Abstract

Common equations for sound level predictions in diffuse rooms are too pessimistic about the possibilities for noise reduction when adding absorption. Barron's equation appears more appropriate in "shoe boxes", but ray tracing models predict even more decrease when L- and U- shaped rooms are used, since the corners within these rooms cause an extra reduction. However, room shape as a building design parameter is only effective in combination with relatively high absorption coefficients.

1. Introduction

The goal of our investigations is to reduce noise in (public) spaces. The spaces under investigation are for instance sports facilities, but also work and living spaces for mentally challenged people, where many (sometimes quite noisy) people try to work and live together [1]. The findings from our work have to be used by architects and acoustic consultants and therefore we concentrate on the impact of room shape, absorption and shielding elements on noise reduction. This paper focuses on the combination of on room shape and absorption.

2. Theory

2.1. Relevant acoustical quantities

The reverberation time is the acoustical quantity most widely used by architects. However, for our purposes this quantity has some drawbacks: it depends too much on the room volume and the results from ray tracing methods depend too much on the diffusion factor. The proof is beyond the scope of the present paper, but in our opinion a better quantity to quantify a noisy environment is the sound pressure level (L_p) or the related "strength" (G).

The quantities L_p and G also play a big role when more sophisticated quantities for speech intelligibility like STI (speech transmission index) or C_{50} are used. We found that STI and C_{50} give little indication about the

acoustical quality in the rooms investigated. STI and C_{50} make more sense if they are used in conjunction with the background noise in a room. Hence, " STI in noise" or U_{50} (instead of C_{50}) are much better predictors and then the values of L_p and/or G are also needed. Therefore the emphasis within this paper is on the strength G .

2.2. Equations used in this paper

The two equations for the reverberation time (denoted by RT) used for our research are Sabine's and Eyring's equation, given respectively as:

$$RT = \frac{0.161 V}{S_{tot} \alpha} \quad (1a)$$

$$RT = \frac{-0.161 V}{S_{tot} \ln(1 - \alpha)} \quad (1b)$$

V stands for the volume of the room; S_{tot} is found by summation of all surfaces (S_i) through the room. All of these surfaces have their own absorption coefficient (α_i) and so the total absorbing surface is found as:

$$A_{tot} = \sum \alpha_i S_i \quad (2a)$$

The mean value of the absorption coefficient over the total space is found from:

$$\bar{\alpha} = A_{tot} / S_{tot} \quad (2b)$$

The sound pressure level $L_p(r)$ in a room is given by:

$$L_p(r) = L_W + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4(1-\bar{\alpha})}{A_{tot}} \right) \quad (3a)$$

where r stands for the distance between sound source and receiver. L_W is the sound power level of the source and Q is the directivity factor of the source.

To eliminate the sound power of the source, L_p is compared with the sound pressure level from an omni directional sound source (so $Q = 1$) with the same acoustic power, measured in the free field when $r = 10$ m. The result is denoted by G (strength) and is calculated as:

$$G_{sab} = 31 + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4(1-\bar{\alpha})}{A_{tot}} \right) \quad (3b)$$

The index *sab* is used to denote that this equation is valid for diffuse fields where all directions are evenly distributed (see, for instance, Pierce [2]).

In the front rows of a concert hall the first term within the brackets is bigger than the second. However, for bigger distances (which is for the majority of seats) the first term can be neglected. In this case Eq. (3b) predicts a constant strength for a large part of the hall. This conclusion contradicts with the results of measurements in concert halls and therefore, Peutz [3] suggested an extra sound level decrease which is constant per doubling of the distance through the hall. Later, Barron proposed a sound level reduction that is proportional to the distance itself [4]. It appears somewhat more accurate and it is written as:

$$G_{brn} = 31 + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{\exp(-0.04r/RT)}{A_{tot}} \right) \quad (4)$$

At one specific distance Eqs (3b) and (4) are equal. If Eq. (1b) is used for RT , this distance is found as:

$$r_{mfp} = 4V/S_{tot} \quad (5)$$

which is nothing else than the mean free path. It can also be demonstrated that, at this distance, the first term can be neglected.

For concert halls the outcome of Barron's equation is considered as a drawback; a constant strength through a hall is preferred. We will, however, demonstrate that these results turn into an *advantage* when the acoustical quality in noisy environments must be improved.

3. The impact of absorption

3.1. Results from theory

Results from the previous equations (3b) and (4) are given in figure 1. To emphasize the differences, the room dimensions are chosen a bit extreme: $20 \times 5 \times 2.5$ m. Hence the volume V equals 250 m^3 and the total surface S_{tot} equals 325 m^2 . The mean absorption value is used as parameter.

The curves show rather small differences between Eqs (3b) and (4) for the 10% absorption coefficient. For 50% absorption, however, differences are no less than 12 dB.

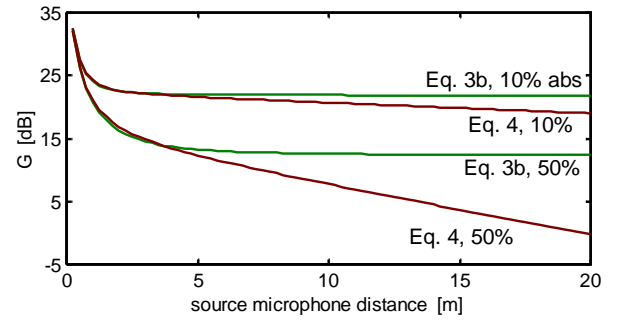


Figure 1: The strength G from Eqs. (3b) and (4) as a function of r for two values of the absorption coefficient. Source is omni directional, so $Q = 1$.

3.2. Results from ray tracing

In our work a ray tracing model is used to compare different room shapes. Therefore a comparison was made between Eq. (4) and the results from CATT acoustic (V8.0) in the same room as used for figure 1. The results are given in figure 2.

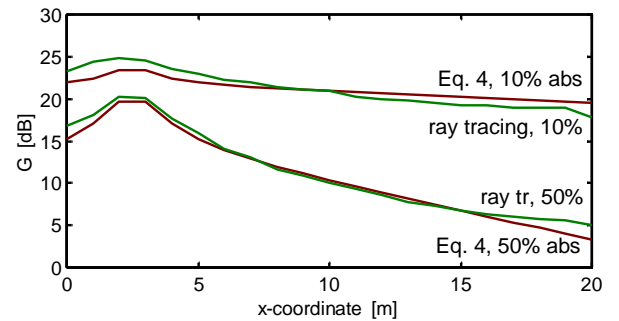


Figure 2: Barron's curve compared with results from a ray tracing model. Absorption is equally distributed. Room is $20 \times 5 \times 2.5$ m; source is in the axis at 2.5 m from the front wall. A row of microphones (at 1 m intervals) is along the length axis. Shortest distance to the source is 1.12 m.

A few remarks have to be made:

- In ray tracing programs a source position is needed; in figure 1 it is not. Therefore figures 1 and 2 show somewhat different curves.
- Results from CATT depend on the diffusion coefficient of the walls. The chosen value is 30%. We have done quite some work on this subject but those results will not be given here.
- For microphone positions close to the source, Eq. (4) predicts a higher G -value than Eq (3b). This increase is even higher in the ray tracing model. We trust the ray tracing model somewhat more, since we are not certain that Eq. (4) fully fulfils the law of conservation of energy in the room.

All in all, the agreement is well enough to use the results from the computer model to instruct architects about absorption and room shape.

3.3. Measurement results in the G - RT -diagram

As said earlier, the results from Barron's curves are a blessing for the acoustic consultant abating high noise levels. If the absorption coefficient in the room of figure 1 is increased from 10% to 50%, Eq. (3b) predicts a 9.5 dB improvement at 20 m, whereas Eq. (4) predicts twice that value. We found similar effects in results from measurements in a restaurant. The restaurant was built about thirty years ago with an absorptive ceiling, but a few years ago the classical error was made when the ceiling was painted. To retain the acoustical quality, new ceiling materials were attached recently, giving us the opportunity to perform before and after measurements. Measurements of all common acoustical values were done at 15 microphone positions with distances to the source ranging from 1 m to about 16 m. The results are given in figure 3. They are presented as value pairs for every microphone position in a G - RT -diagram.

RT appears quite constant through the room. This has been found in almost all rooms we measured. Of course G has its maximum value close to the source (more than 25 dB at 1 m); it decreases with increasing distance.

Figure 3 also contains the theoretical curve from Eqs. (1a) and (3b) (denoted by "Sabine's curve"). If these equations were true in measuring practice, the curve would be the limiting value with increasing distance. That means, the 1m values would be the same but no dots would be found at the left side of the curve. Figure 3, however, shows dots on the left side. That is because Barron's equation (4) gives a much better agreement with measuring results.

The figure also illustrates why we call Barron's curve a blessing. Following Sabine's curve the improvement in the restaurant would be no more than about 3 dB. However, for the larger source to microphone distances (the leftmost dots) the improvements are 6 to 7 dB.

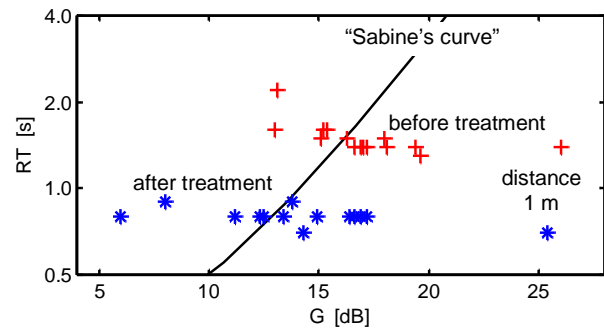


Figure 3: RT plotted versus G for a restaurant before and after adding an absorptive ceiling. Volume is 993 m^3 ; total surface is 878 m^2 .

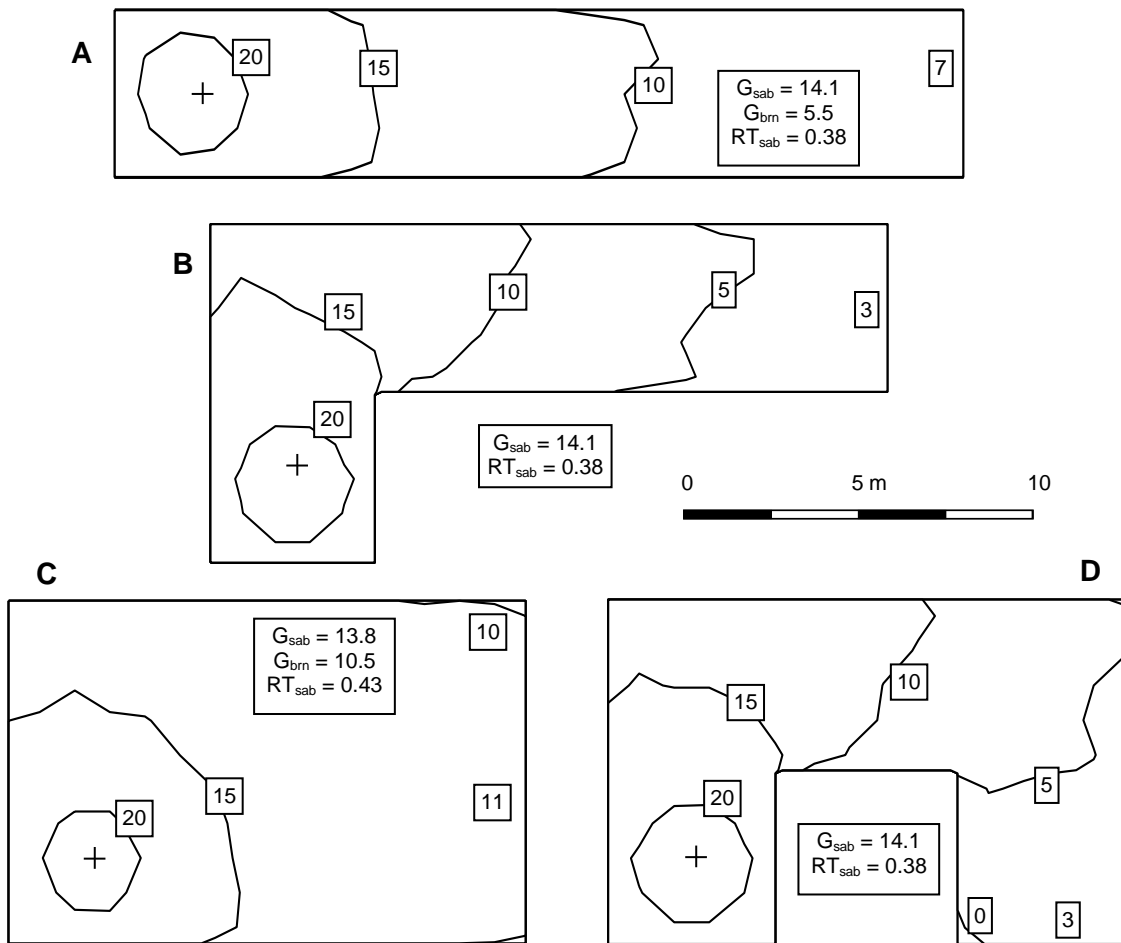


Figure 4: The strength G for four room configurations. Crosses indicate source positions. Mean absorption coefficient is 0.33 for all surfaces. The given values of G_{sab} , G_{brn} and RT_{sab} within rectangles are calculated with Eqs. (4), (3b) and (1a) respectively.

4 The impact of room shape

In the previous sections an indication was given about turning Barron's curves into an advantage for the architect. Now we will investigate if room shape may decrease noise levels even more.

Figure 4 gives computed G -values for four different room shapes. They are part of a more comprehensive "catalogue"; here the most striking results are given.

The long room shape (figure 4A) is 25 m long. In shapes B and D the distance between source and receiver is a bit ambiguous. Therefore the values of G_{brn} have been left out in figures B and D. It is found however that the total traveling distance of the sound is important, including the rounding of the corners. This distance is in the order of 25 m too. Room C is added to show the big difference to room D.

5 Conclusions

3.4. Conclusions from the acoustical viewpoint

From figure 4 conclusions can be drawn about absorption in combination with room shape. The following conclusions, however, are also based on additional investigations not shown in figure 4.

- Barron's equation works well for both *rectangular* rooms; differences with results from the ray tracing model are in the order of 1 dB.
- Corners introduce extra reductions in the order of 3 dB per corner. In fact the ideas about propagation through ventilation ducts are more appropriate than those of sound in diffuse rooms. This effect was verified in some measurements already carried out.
- The reverberation time shows some odd results. In case A, the calculated value is in the order of 0.55 s, while the Sabine value is 0.38. Although the diffusion coefficient in the ray tracing program is taken as high as 30%, flutter echoes appear, increasing the

reverberation time. In cases B and D, ray tracing and Sabine's RT 's do much more agree, because the room shape avoids the occurrence of flutter echoes.

- This effect is another reason why we prefer G above RT in predictions. Ray tracing models are based on the prediction of sound energy, so they are at their best for the prediction of G . We will try to show this in a future article.

3.5. Conclusions for Architects

- The differences between room C and room D are in the order of no less than 10 dB.
- The mutual differences in G -values between the four shapes are much less at low absorption coefficients. This is a similar effect as already shown in figure 1. It means that sound level reductions depend on the *combination* of room shape and absorption coefficients.
- One might expect that, in case D, absorption on the long wall is more effective than on the floor or on the ceiling. However, the position of the absorption plays only a minor role; the total amount of absorption is much more important.
- When the source is positioned as in figure 4B and 4D, it is a little bit advantageous to concentrate absorption material around the source. However, in multi-source environments without fixed source positions, this effect plays no role anymore. Still, for instance in living rooms for mentally challenged people, the effect can be used to design a separate television corner, etc.
- So far, nothing has been said about sound frequency. Common porous absorbing materials show increasing absorption with increasing frequency and hence noise levels will decrease. We found (in other research) that this is a design principle to aim at (more or less according to NR-curves). The high frequency absorption of many panel absorbers is too low and the resulting sound will be too penetrating.
- As also shown earlier [5], extra shielding elements in the rooms may locally decrease sound levels and can be used to decrease noise from particular sources. For the total room, again, the total amount of absorption plays the key role.

The most important conclusion for architects is:

- *An adequate design of room shape improves acoustical quality.*

So the next step for an architect is to combine these room shapes with architectural function. It is also a subject of our future research. Therefore room shape D was developed. It is, for instance, possible to use the "hole" within the U-shape as a kitchen space, separated from the U-shape itself with glass windows in order to give the staff in an institution

for mentally challenged people the possibility to keep an eye on their pupils.

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