Auralization examples to discuss the reverberation time as a standard for sports facilities

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Introduction

In the Netherlands and Belgium the standards for sports facilities are given as maximum values for the reverberation time. Since the dimensions of sports facilities may vary considerably (from 1000 to 100,000 m^3) and the reverberation time depends on the volume, they are given as increasing values with increasing dimensions. Actually the underlying idea is that the mean absorption coefficient should be about 25% for all dimensions [1], [2], [3].

In the design stage of a hall, calculations are made by summing the absorptive surfaces. In many cases Sabine's equation is used to calculate the reverberation time, but sports halls have usually non-cubic dimensions and absorbing materials are always inhomogeneously distributed, since the floor is non-absorbing and the ceiling is preferred for absorption. Hence the reverberation time may increase considerably compared to Sabine's. The international standard ISO 12354-6 [4] provides a method to calculate this effect.

If the reverberation time appears too long, it seems as if the effect of the absorption is lower than calculated in the design stage. However, adding absorption is not necessarily a solution; the distribution through the hall may be more important. In this paper three aspects will be discussed: the reverberation time, the sound pressure level and the occurrence of (flutter) echoes. Some architectural solutions will be given to overcome long reverberation times. It appears very instructive to listen to sound samples from auralizations in a virtual hall, so during the actual congress presentation some samples are presented. Audible sound is impossible for this paper, but a website is built containing both this text and some sound samples [5].

SPL, RT and (flutter) echoes

In a sports hall the sound pressure level plays an important role. The sound may come from a "wanted source" (speech for instance) or from other "noise sources" in the hall:

$$SPL = L_W + 10\lg\left(\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)}{A}\right). \qquad (1)$$

The value L_W represents the acoustic sound power level of the source. The source-receiver distance is given by r, while Q stands for the directivity of the source. For a human talker a value $Q = 2.5$ is often taken in front of the mouth (for A-weighted levels). A is the total absorbing surface and α represents the mean absorption coefficient when A is divided by the total geometrical surface. There are numerous books that give more details. Our own work is described in more detail in [6].

Eq. (1) predicts a constant value of SPL for big values of r. This contradicts experience, so Barron [7] developed an alternative, which in our case [8] is written as:

$$SPL_{bar} = L_W + 10\lg\left(\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)^{r/mfp}}{A}\right), \qquad (2)$$

with $mfp = 4V/S$, the mean free path. Equations (2) and (3) are equal if $r = mfp$.

In the design stage, A is calculated from the absorption coefficients of all materials. If the hall is finished, measuring the contributions of all surfaces separately is almost impossible and the total value A is measured instead from the reverberation time. In many cases Sabine's formula is used:

$$RT = \frac{0.16V}{A}, \qquad (3)$$

with V the room's volume.

Another characteristic determining the acoustical quality is the occurrence of "flutter echoes". In very reverberant halls they cannot be heard, but if all absorption is put on the ceiling echoes may be found along the length and width dimensions of the hall. They can be heard in practice and can be seen in plots of decay curves, but at present there is no method to quantify them. The phrase "flutter echoes should not be heard", as used in older standards is too informal for (legal) standards.

Sound decay in a sports hall, an example

A number of situations have been calculated in a ray-tracing model (Catt acoustic) of a big sports hall of 70 × 25 × 12 m^3. The floor plan is given in figure 1. The program produces many acoustical variables, but our focus is on the reverberation time (-5 to -35 dB) and the sound pressure level. Energy impulse responses from the program are used to study the echoes in the hall. Auralizations are made by convolution of the impulse responses from the program and "dry" sound samples.

A wanted source is at position A. It is represented by speech originally recorded in the anechoic rooms in Delft and Leuven. Noise signals are generated at position B. These signals are represented by four talkers or by impulsive sounds from a basketball dribble. Microphone positions are as indicated; one position (number 14) is at the mean free path distance mfp from the source, which is 14.5 in this hall. The source height is 1.5 m; microphone height is 1.2 m. In sports halls the reverberation time often depends on source and microphone height, since there is no influence of diffusing elements in the hall. These effects have been measured in real halls, but are also found in computer models.

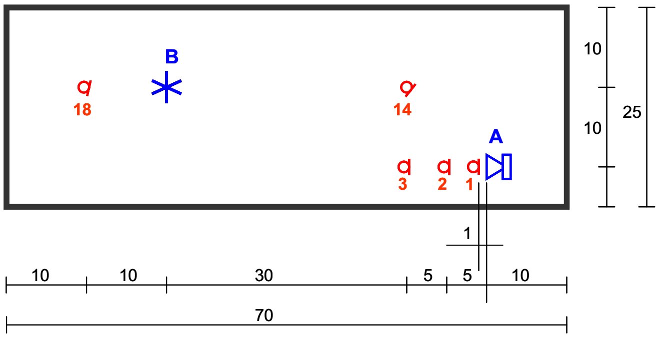

Figure 1: A sports facility used for ray-tracing simulations plus auralizations. The main source is at position A. If noise is added it is generated at position B. For microphone position 14, the source-receiver distance equals 14.1 m, which is almost equal to the mfp-value. All scattering coefficients are 10%.

The first computer runs were made to show the effect of the amount of absorption plus the distribution along the surfaces. Situation **(a)** is when floor, ceiling and walls all have a 7% absorption coefficient. The same is done for situation **(b)** but now all absorption coefficients equal 28%. In situation **(c)** the mean absorption coefficient is again 28% but the floor and four walls have 10% absorption and all the other absorption is on the ceiling with 70% absorption. Situation **(d)** is more a hypothetical case. It has the lowest absorption (18%) on ceiling and floor, a medium value (34%) on the side walls and the highest value (68%) on the two smallest surfaces. Now, the mean absorption is 28% again, but the decay times are equal in all three directions. This leads to the minimum reverberation that is possible [9].

The upper figure 2 gives the response to an energy pulse as calculated in the ray tracing model for microphone 14. The lower figure 2 shows the Schroeder curves as derived from the upper curve by backward integration. These are the curves that should be used to derive the reverberation times by curve fitting along the four slopes. The differences are immense; *RT*-values are 6.90, 4.55, 2.71 and 1.66 s. A complicating factor is that curves (a) and (d) are straight lines, but curves (b) and (c) are concave.

The *SPL*-levels can be derived from the Schroeder values at *t* = 0. In case (a) this level is 47.8 dB; for case (b) we find 42.4 dB, cases (c) and (d) differ only by a few tenths of a decibel from case (b). This is a remarkable result. If *A* is calculated from the RT-values (reversing Eq. 3) and input in Eq. (2), the *SPL*-values would differ considerably. The reason is that *RT* is found from the curves after 0.3 s, while the *SPL* values are mainly determined by the early reflections before 0.3 s. As can be seen in the upper figure there are only minor differences for cases (b), (c) and (d) before 0.6 s.

Figure 3 gives the same results of *SPL* and *RT* for the four situations (a) to (d), but now combined in one *SPL-RT*-graph, which is very instructive to compare measured and calculated microphone positions in a room. The four microphone positions 1, 2, 3 and 18 (from figure 1) are added to microphone position 14.

Figure 3 also shows two theoretical curves where equations (2) and (3) are calculated for mean absorption coefficients of 7 % and 28 %. The value of *RT* is found as one value for all receiver positions (*RT* is 6.9 and 2.0 s respectively), since there is no influence of the distance in Eq. (3).

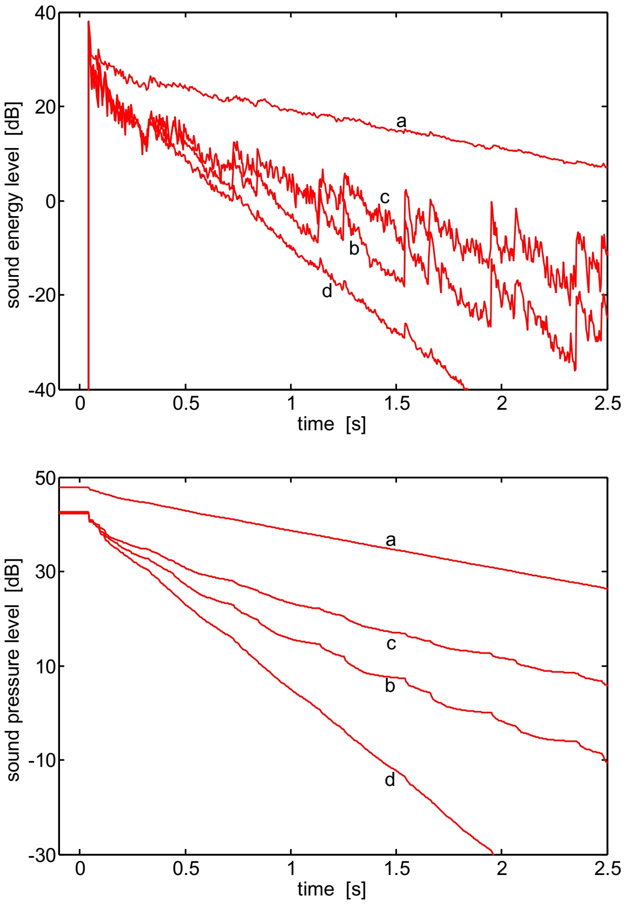

Figure 2: Echograms (top) and Schroeder curves (bottom) as calculated from the four cases as given in the text. Microphone position is number 14. Reference sound level is taken as 60 dB at 1 m in an anechoic chamber.

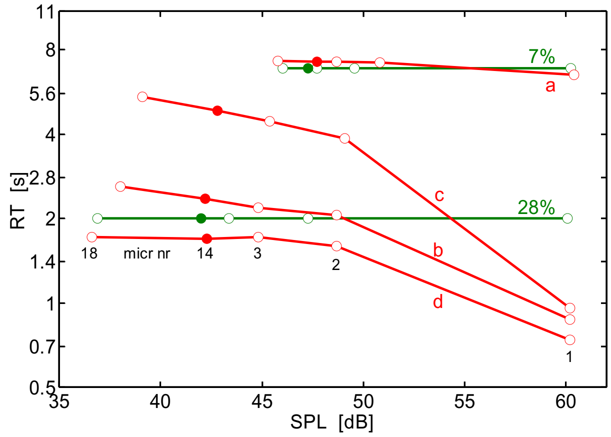

Figure 3: *SPL* and *RT* for the four cases explained in the text, for the five microphone numbers indicated in figure 1. Position 14 is given as full dots, the other four as open circles. Both horizontal lines are calculated with equations (2) and (3) using 7% and 28% mean absorption.

The results from figure 3 can be summarized as:

- The reference level is 60 dB at 1 m in the anechoic chamber. Levels at microphone position 1 are slightly higher due to the hall's reflections.
- Eq. (3) predicts a constant reverberation time through the entire hall. This is not the case in the ray-tracing results.
- Curve (a) and the 7% curve agree quite well. This is where Sabine's theory is most reliable, since reverberant situations lead to diffuse fields.
- All four curves (a) to (d) show a slight increase of *SPL* at the mfp distance. This is due to the non-cubic space as explained in [9].
- The reverberation times of curves (b), (c) and (d) appear to depend strongly on the distribution of absorbing materials. In the special case (d) the reverberation time is even below the one predicted by equation (3). Actually ray-tracing theory predict a minimum value equal to Eyring's reverberation time instead of Sabine's. Eyring's value is always lower.
- *RT* values at position 14 are: 7.3, 4.5, 2.7 and 1.7 s for situations a, c, b and d. The results from the standard 12354-6. are 7.60, 3.30, 2.90 and 2.12 s. The trend is the same but the mutual differences from the standard are less. It is difficult to say which value should be preferred; we are planning scale model measurements to investigate the effect. However, situation (d) should tend to Eyring's value, but the minimum value from standard 12354-6 is Sabine's. That is not very likely. Results from another ray-tracing program (Odeon) confirm the Catt-results.
- The striking result is that the values of *SPL* are almost equal for situations (b), (c) and (d) at microphone position 14 where $r = mfp$. Differences are greater at position 18. So *SPL* depends only marginally on the positioning of absorbing materials.
- In fact this last result means that the reverberation time is *not* a good predictor if we want to characterize the sound pressure level in a sports facility. Measuring *SPL* directly gives better information. This is not very difficult in practice under one condition: the noise source must be calibrated. Simple methods with exploding balloons etc. are useful to find *RT* but useless for *SPL*.

Auralizations to investigate echoes

The echograms of the upper part of figure 2, show strong differences in echo behavior. Sound samples have been made, with the aid of the auralization techniques of the ray-tracing program, to investigate the effect in more detail. Three cases are used; the homogeneous case with 28% absorption (b) has been left out.

When speech at a "normal" level is used as input signal, a strong difference in reverberation can be heard between case (a) at one side and cases (c) and (d) on the other. The difference between cases (c) and (d) are very small, since echoes are heard in both cases. An increase in the sound level (for instance with 12 dB) is needed to hear the differences more clearly. Differences are also more audible with the impulsive sound of a basketball. Multiple echoes are not really audible, not even if a true impulsive sound is used. Probably the present hall is too big to generate that rattling sound that is typical for flutter echoes.

Two signals are used for source B: speech from four people speaking simultaneously (at the same power level as the talker in A) or a basketball dribble (impulses at about two per second). Again the reverberant case (a) is much louder than the other two. There is an audible difference between cases (c) and (d), especially for the basketball dribble. The sound level is the same but echoes are less pronounced in case (d).

When the signals from sources A and B are combined, the speech intelligibility of case (a) is very bad. Differences between cases (c) and (d) almost vanish when speech is used as noise. Speech can be understood up to microphone position 3 at 10 m. Differences between cases (c) and (d) are much bigger for the basketball dribble, since in case (c) a much stronger echo is perceived.

Echoes, can they be avoided?

Situations (c) and (d) show an (audible) echo at about 400 ms, which originates along the long axis in the hall. Multiple repetitions (flutters) can be seen in curves (b) and (c) at about 800, 1200, 1600 ms etc. But case (d) is more or less a hypothetical case and so the question arises if the echoes can be avoided by architectural means.

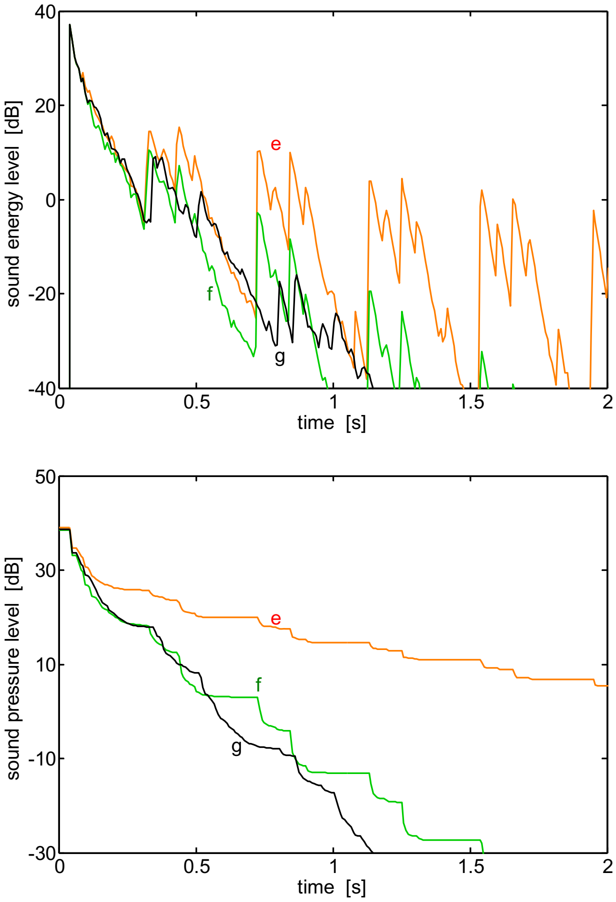

Figure 4: Echograms (top) and Schroeder curves for cases (e), (f) and (g) explained in the text. Curves are calculated at microphone position 14.

Several computer runs have been made from which three situations are presented here. Like the previous situations, the cases **(e)**, **(f)** and **(g)** have a nearly reflecting floor surface and absorption on the ceiling. But now the long walls are absorbing as well (70%) to emphasize the sound transmission along the longest dimension reflecting against the two smallest walls. In case (e) these walls have a 7% absorption coefficient, which is increased to 70 % in case (f). In case (g) the small walls are non-absorbing but inclined, so the sound reflections are steered upwards to the absorbing ceiling. The length of the hall is 70 m along the floor and 78 m along the ceiling.

Results are given in figure 4. Situation (e) has a strong (flutter) echo. When listening to the auralized sound a single echo is perceived after 400 ms plus a "metallic" sounding reverberation. There is some difference in sound between cases (f) and (g), but they have no practical meaning for the architectural design process. Both cases (f) and (g) have an audible echo at 400 ms. The only way (we could find) to avoid the echo at 400 m is to use totally absorbing walls, which is not very realistic. All other cases (including a case with total diffusion using Lambert's law) show the echo.

The lower part of figure 4, shows that there is a big difference in reverberation times between case (e) at one side and cases (f) and (g) at the other. Case (e) has 3.8 s. The reverberation times of case (f) equals 1.1 s. It is interesting to see that case (g) has much less absorption on the two walls than case (f) and yet the reverberation time is even lower: *RT* = 1.0 s. These values look short in comparison with situations (a) ... (d), but that is due to the absorption on the long walls in the present case. Sabine's reverberation time in case (f) is 1.1 s as well. This means that the use of smart reflections and a lot of diffusion appears to be just as effective as absorption. There is even one Dutch sports facility where inclined advertising signs are used to avoid flutters.

In the previous section of this paper the reverberation time was called unfit to predict the amount of absorption and consequently the sound pressure levels in the hall. When it comes to flutter echoes, however, there is more correlation between the reverberation time and the existence of flutter echoes. In figure 3 the Schroeder curves also give information about the total energy in the (flutter) echoes, so the existence of flutter echoes leads to a higher reverberation time.

Conclusions

- The Dutch and Belgian standards give maximum values for the reverberation times in sports facilities. If that maximum value is exceeded it may be caused by a lack of absorbing surface and/or by the existence of (flutter) echoes.
- To investigate if the lack of absorption is the main drawback of a hall, measuring the *SPL* gives adequate information. Measuring *RT* may underestimate the absorption and hence overestimate the noise in a sports hall. Measuring *SPL* (or rather the loudness *G*) is not difficult but it requires a calibrated sound source. The combination of *SPL* and *RT* in one graph gives optimal information.
- If the amount of absorbing materials is sufficient to reduce noise levels, the reverberation time may still exceed the standard values if (flutter) echoes are present. However, there is no value to express the annoyance of flutter echoes in sports facilities in a numerical value.
- It is hard (if not impossible) to combat early echoes that reflect only once. Multiple echoes can be avoided by extra absorption, but diffusion and well chosen inclined surfaces are equally effective.
- Sabine's equation always underestimates the reverberation time in sports facilities, since they are always non-cubic with inhomogeneous absorption. Ray tracing methods and the standard EN-12354-6 both predict an increase of *RT*, but they do not agree completely. Ray-tracing models are able to predict the influence of inclined surfaces; EN 12354-6 fails in this respect.
- Auralizations are useful to demonstrate excessive noise and flutter echoes. Since it is not clear, if flutter echoes or high noise levels are most annoying, they will be used in future investigations.

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