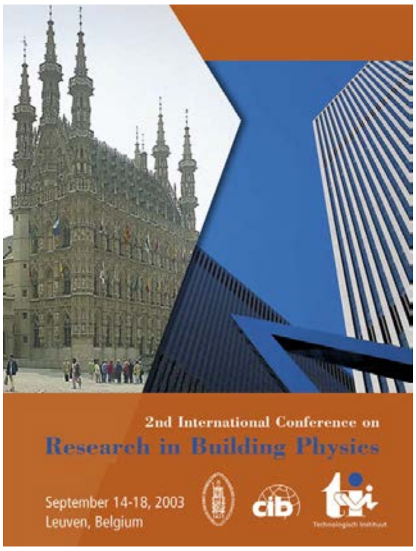

Expressing legal demands in acoustical quantities; is the reverberation time a good predictor for the speech intelligibility in a sports hall?

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ABSTRACT: The reverberation time is used in legal demands to provide for good acoustical quality in a sports hall. However, the reverberation time depends too much on the hall's volume, so the volume should be taken into account as well. There is a second drawback to the reverberation time: calculated and measured decay curves may be rather concave, especially in shoe box shapes and it is very hard to estimate the noise levels in a sports hall from the reverberation time. An alternative is possible by simple measurement of the strength of the diffuse sound field, but this method requires an extra indication about the characteristics of the loudspeaker used for the measurements

1 INTRODUCTION

1.1 *The reasons for investigating the reverberation time*

In the Netherlands a reverberation time of 1.8 seconds is used as a rule to provide for a good acoustical climate in a sports hall. Recently, however, problems occurred when a facility was built containing a track for athletics; it had a much bigger volume than usual. Both the architect and the acoustical consultant did their best, but even then they did not succeed to bring down the measured reverberation time below 2.3 seconds. The hall users did not complain about bad acoustics; they even said to like the acoustic climate. This is, in itself, not a reason to doubt the reverberation time as a predictor, but when we investigated the problem in more detail and calculated other acoustical quantities (expressing speech intelligibility) we found indeed that the new hall showed no real problems.

1.2 *Which quantities should be used for a sports hall?*

At the start of the twentieth century, Sabine introduced the reverberation time in room acoustics. Since then the reverberation time has been the major parameter in the "science and art of acoustics". For large concert halls values between 2.0 ad 2.5 seconds are considered as desired, while these values drop to 1.5 for smaller halls, 1.0 for classrooms and 0.5 for living rooms.

For music, the reverberation time is a very good quantity to start with, but other values (e.g. "loudness", "IACC", see Beranek, 1996) should not be neglected.

The question arises which quantities must be used in a sports facility. A lack of absorbing materials in a hall leads to very high noise levels when public attends the games in the hall. Another (more important?) reason to provide for good acoustics is the speech intelligibility; for instance for a coach talking to his/her pupils on a distance between 1 and 10 m. Since background noise and speech intelligibility are strongly related we decided to take the speech intelligibility in relation to the noise level as a starting point.

Speech intelligibility is determined by a few quantities:

1. the vocal strength of the talker
2. the reverberation of the talker's sound
3. the background noise produced by the other athletes and coaches in the hall
4. the background noise caused by spectators
5. the background noise of heating and cooling systems.

The first point determines the "acoustical signal", all the other sounds cause "noise" and it is the signal-to-noise-ratio that causes speech intelligibility.

2 THEORY

2.1 *Some basic equations*

A room is acoustically given by the dimensions of the surfaces surrounding the hall, the surfaces within the hall, and the acoustical properties of each surface, mainly expressed in terms of the energy absorption factor and the diffusion factor.

Sabine discovered a linear regression between the total amount of absorption (A_{tot}) in a room and the reverberation time T. In present ISO-standards this is written as:

$$T = \frac{55.3\,V}{c\;A_{tot}}\,, \tag{1a}$$

where V represents the volume of the room and c stands for the speed of sound.

Substituting c = 332 m/s leads to an equation, which is widely used in practice:

$$T = \frac{V}{6\,A_{tot}}\,. \tag{1b}$$

In Sabine's method the total amount of absorption in a room is given by the equation:

$$A_{tot} = \sum \alpha_i S_i\,, \tag{2a}$$

where S_i stands for each geometrical surface.

From this equation the mean value of the absorption coefficient is calculated as:

$$\bar{\alpha} = A_{tot} / S_{tot} \tag{2b}$$

There is one problem with equations (1) and (2). If: the mean absorption coefficients tend to one, the reverberation time should tend to zero. This is not the case.

Therefore the formula derived later by Eyring is more accurate in this respect. Equation (2a) must then be rewritten as:

$$A_{tot} = -\sum \ln(1-\alpha_i)S_i \qquad (2c)^1$$

Because of all the reflections in a room the sound power perceived by a listener increases when compared to the sound power found in an anechoic room. In acoustical textbooks (see for instance Pierce for an extensive explanation) the total sound pressure level is calculated as:

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

The distance between the source and the receiver is given by r; L_W is the acoustic power level, which is a characteristic for the sound source.

The first term within the brackets represents the direct sound from source to receiver. It decreases when a listener moves away from the source. The second term represents the reverberant sound field. It does not carry any information about the distance, so it is assumed constant through the room and hence may be called the diffuse sound field[2].

To describe the speech intelligibility in a sports hall it is easier to separate the equation into two different equations for the direct sound and the diffuse sound field:

$$L_{dir} = L_W + 10\log\left(\frac{1}{4\pi r^2}\right). \qquad (4a)$$

and:

$$L_{diff} = L_W + 10\log\left(\frac{4(1-\bar{\alpha})}{A_{tot}}\right). \qquad (4b)$$

In many textbooks, this last equation is simplified as:

$$L_{diff} = L_W + 10\log\left(\frac{4}{A_{tot}}\right). \qquad (4c)$$

Equations (3), (4b) and (4c) have a Sabine and an Eyring version, depending on the choice for equations (2a) or (2c) for the total absorbing surface.

At the reverberation radius R_{rev} both levels are equal. It can be calculated as:

$$R_{rev} = \sqrt{\frac{A_{tot}}{16\pi(1-\bar{\alpha})}} \qquad (5)$$

This value is usually surprisingly short. Even for big halls it is often found in the order of only a few meters.

2.2 *The impulse response and the Schroeder curve*

To get an idea about the reverberation within a room two methods have been used over the years:

method 1:

[1] If the absorption coefficient tends to 1, the absorbing surface will be bigger than the actual surface. It seems a bit odd, but only then the value of the reverberation time will tend to zero.

[2] Actually a diffuse sound field is defined by the directions of the traveling waves in a room (Pierce). The constant value of the sound pressure level is a consequence.

An alarm pistol is fired and all the reflections are recorded with their amplitudes as a function of time.

method 2:
A loudspeaker, generating a constant noise level, is placed within a room. When the loudspeaker is switched off, a decaying sound field is perceived, which is registrated on tape or on a level recorder.

In modern measuring techniques the generated sounds have changed considerably (nowadays a “sweep” or “digital noise” is used), but in fact the product from the computer is still the same. Method 1 is now represented by the “sound impulse response”; the second method is given by the response on a “negative step”, calculated from the sound impulse response.

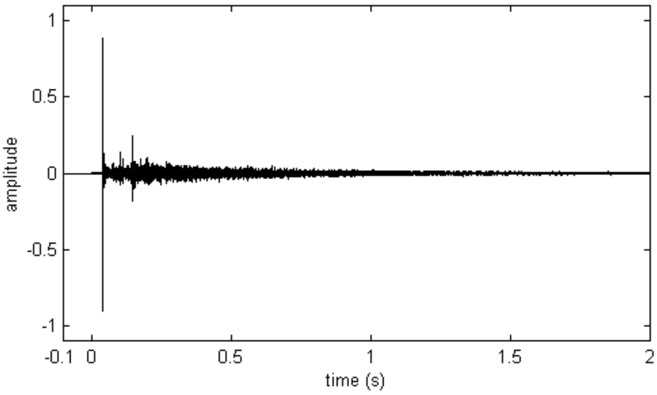

Figure 1: The impulse response as measured in a church where the reverberation time is in the order of 7 seconds. Vertical axis is arbitrary. The first impulse represents the direct sound. It can be much bigger than the other reflections. However, the summed value of all reverberation impulses may be stronger than the energy in the direct sound.

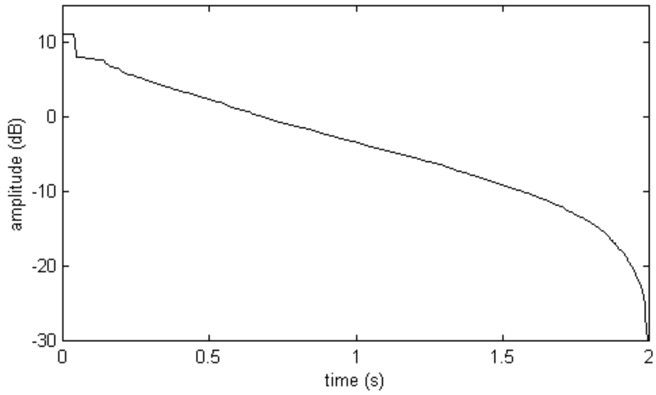

Figure 2: The Schroeder curve as calculated from figure 1. Vertical axis is in decibels. Here the influence of the direct sound can be seen as the big step after a few milliseconds.

Figure 1 gives an example of the sound pressure *p(t)*, measured as a function of time *t* in a strongly reverberating church.

Mathematics teaches us that the response to a negative step (the second method) can be found as a backward integration of the square of the impulse response:

$$L_p(t) = L_{norm} + 10\log\int_t^\infty \frac{p^2(\tau)\,d\tau}{p_{ref}^2}, \qquad (6)$$

where L_{norm} is an arbitrary value representing the source strength; it will be eliminated later. The curve found as a function of time is called the Schroeder curve (Schroeder, 1965) and an example is given in figure 2.

2.3 *Early and late reflections*

Sound energy from late reflections may disturb the speech intelligibility, while early reflections contribute to an increase of the sound energy of the talker. It is generally accepted that the switch between the early "useful" sound and the late "detrimental" sound energy is at 50 ms from the arrival of the direct sound. By adding absorbing materials to a room the late energy is more affected than the early energy (the direct sound is not affected at all), so the speech intelligibility is increased. However, the early energy may be too low, so it is always a challenge for the hall designer to find the optimum amount of absorbing material

The early and late energies can now be written by introducing t = 0.05 s (50 ms) in the integral of equation (6) respectively as:

$$L_{early} = L_{norm} + 10\log \int_{0}^{0.05} \frac{p^2(\tau)\,d\tau}{p_{ref}^2}\,, \qquad (7a)$$

$$L_{late} = L_{norm} + 10\log \int_{0.05}^{\infty} \frac{p^2(\tau)\,d\tau}{p_{ref}^2}\,, \qquad (7b)$$

The acoustical quantity determining the difference between early and late energy is called C_{50} and can, departing from Eqs. (7), be written as:

$$C_{50} = L_{early} - L_{late}\,. \qquad (8)$$

So far we have assumed only one source in the hall and then the detrimental sound is only caused by the talker him/herself. When more sources are present (other talkers or ventilation systems etc.) a noise level (called L_{noise}) must be added to the late energy. Then the difference in useful and detrimental sound is no longer called C_{50} but U_{50} (see, for instance, Bradley, 1986).

2.4 *Ideal reverberation*

If the hall is considered as a cube with absorption equally spread along all six surfaces the sound decay may be written as an exponential decaying function, and hence, because of the logarithmic scale, as a straight line in figure 2. Now the integral in the Schroeder curve can be written as:

$$S(t) = S(0)\exp(-\beta t) \qquad (9a)$$

$S(0)$ can be written as:

$$S(0) = \frac{10^{L_W/10}\,c}{\beta V} \qquad (9b)^{3}$$

and the value of β can be calculated as:

$$\beta = \frac{-cS\ln(1-\alpha)}{4V} \qquad (9c)$$

If we furthermore use Eyring's definition of the reverberation time, β from equation (9c) can be written as:

[3] S(0) has the dimension of m^{-2}. This seems a bit odd, but it is in conjunction with equations (4). These are found in every textbook, but actually violate the mathematical rule that values after a log-sign should be dimensionless.

$$\beta = \frac{13.8}{T} \qquad \text{(9d)}$$

Combining Eqs. (9b) and (9c) gives:

$$S(0) = \frac{-4 \times 10^{L_W/10}}{S \ln(1-\alpha)} \qquad \text{(10)}$$

In measurements the integration in formula (6) is always done from $t = \infty$ backwards to t = 0 to find the sound pressure level. Doing so, the direct sound is automatically incorporated. In our case, however, we want to split the direct sound and the reverberant field and if the lower integration value is taken as $t = 0$, equation (4c) is found instead of the more accurate equation (4b). It is more accurate to stop the integration at the distance of the first mirror sources, which is estimated when ct_{min} equals the mean free path.

If done so an extra term (1-α) emerges and equation (4b) is found instead of equation (4c):

$$S(t_{\min}) = \frac{-4 \times 10^{L_W/10}}{S \ln(1-\alpha)} (1-\alpha) \qquad \text{(11)}$$

It is now also possible to calculate the late energy by introducing the value of 50 ms:

$$L_{late} = L_{diff} + 10 \log[\exp(-0.69 / T)]. \qquad \text{(12a)}$$

where the number 0.69 emerges from the multiplication of 13.8 en 0.05.

The reverberant component (so without the direct sound) of the early energy is its complement:

$$L_{early} = L_{diff} + 10 \log[(1 - \exp(-0.69 / T))]. \qquad \text{(12b)}$$

It is interesting to see that the early and late energies are equal when $T \approx 1$ s.

In equation (12b) the influence of the direct sound is left out. It can easily be added to this early energy, which is in fact nothing else than switching from equation (4b) to equation (3) (Nijs et al., 2001)

Adding the direct sound may increase the value of C_{50} considerably, which is in conjunction with everyday experience: by far the best way to improve speech intelligibility in a noisy or reverberant environment is to get closer to the speaker.

2.5 *A value for acceptable speech transmission*

A few decades ago Houtgast en Steeneken developed the "Speech Transmission Index" (usually called *STI*), to measure the speech intelligibility in different speech transferring systems such as telephones, public address systems, but also in rooms (Houtgast en Steeneken, 1985). The method results into a *STI* value ranging from 0 to 1, but practical values lie between 0.3 to 0.8. *STI* = 0.3 is taken as the lowest value to understand speech. A value *STI* = 0.7 is often considered as excellent, but hearing impaired people or non-native listeners require values that are 0.10 to 0.15 higher.

It is beyond the scope of this paper to explain the method to measure or calculate *STI* values. The method is probably more accurate than the method behind C_{50} and U_{50}, but the latter two have the advantage of their simplicity to explain them to people who are new to the field of building physics. Besides, there is a very high correlation between the three values (Bradley, 1998). In a sports hall a value of U_{50} = 0 dB will be more or less equal to *STI* = 0.5. To reach the value *STI* = 0.8, the value of U_{50} has to be in the order of +9 dB. In fact, the actual range in U_{50} for a sports facility with a good speech intelligibility lies only between 0 and +6 dB.

3 MEASURING AND CALCULATING THE REVERBERATION TIME

3.1 *Homogeneous and inhomogeneous decay curves*

Sabine's definition of the reverberation time demands a 60 dB decrease of the sound pressure level. This dynamic range is almost impossible in common measurements. For that reason the present recommendations for measurements require a curve fitting along the measured Schroeder curve in the time interval given between a sound pressure level decrease of -5 dB and -35 dB below the initial sound pressure level. Still these values may cause problems, so a value of -20 or -25 dB at the lower end is used as well.

There is a second problem with the reverberation time: a linear curve is theoretically only found in a "homogenous space". One example is the cube from the previous section with equal distribution of sound absorbing materials. In figure 3 an example is given (as curve a) for a 10, 10, 10 m cube, where all surfaces have a 0.3 absorption coefficient.

The curve is calculated in a model based on mirror sources. At first sight it looks like a straight line but it appears slightly concave. The Sabine reverberation time equals 0.90 s; Eyring's value equals 0.76 s. The mirror source model yields 0.79 s for the region between -5 and -20 dB and 0.82 s for the region between -5 and -35 dB.

In many practical cases the absorption is concentrated on the ceiling. That is shown in curve b of figure 3. The total amount of absorbing surface (180 m^2) is kept constant, but it is mainly positioned on the ceiling. This leads to a concave curve and if the reverberation time is calculated between -5 and -35 dB it is found as long as 1.50 s. From this value a mean absorption coefficient can be calculated using equations (1) to (2) backwards. Then the absorption coefficient can be found as 0.17.

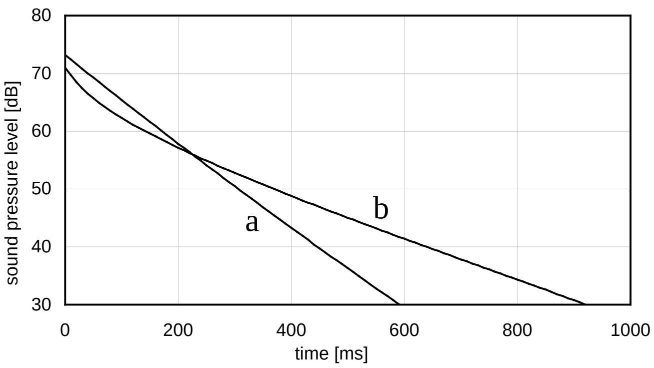

Figure 3: Two Schroeder curves calculated in a 10 × 10 × 10 m cubic room. Curve a: all absorption homogeneously distributed; curve b has main absorption on ceiling. Sound power level from the source (L_W) is, rather arbitrary, chosen as 90 dB.

It is interesting to see that the value of an early decay time (calculated between -1 and -11 dB is 0.84 s, so between the Sabine and Eyring values..

When actually measuring reverberation curves, the same sorts of problems are encountered, but they are less severe. In most existing rooms and halls, there is always some diffusion and this effect decreases the concave behavior found with the pure mirror source model. A curve somewhere between curves a and b is most likely.

3.2 *Speech intelligibility and noise levels in rooms with (in)homogeneous absorption*

The reverberation curves in figure 3 have been generated in a model that is also able to calculate the values for the speech intelligibility. Now there is a surprising result. Despite the longer reverberation time found from curve b, the speech intelligibility is not decreasing. It is even slightly *better*. The values of C_{50} for curves a and b are 1.6 en 3.5 dB respectively. For *STI* these values are 0.64 en 0.66.

There is a second reason to prefer curve b. The value at t = 0 represents (approximately) the sound energy for the reverberant field (L_{diff}). Since it is somewhat lower in case b, the influence of noise sources will be lower as well.

With the aid of equation (4b), another value for the mean absorption coefficient can be calculated backwards. It yields the value 0.32, which is close to the input value 0.30.

In practical cases a designer has to consider the absorption of all materials and the positioning of these materials through the hall. When the hall is finished, someone has to evaluate the designer's work: did he or she choose the right materials and did he or she calculate the right amount of square meters?

However, in our example of figure 3 the mean absorption coefficient calculated in advance is 0.30. Measurements using the official reverberation time would give a value of 0.17. So the question arises which measured quantity should be preferred?

4 A CASE STUDY: A NORMAL SPORTS HALL VERSUS A BIG HALL

4.1 *Calculations for two halls with homogeneous absorption*

The knowledge from the previous section will now be applied to a case from practice. First a "normal" sports hall is considered which has the more or less usual dimensions 45 × 30 × 8 m, so the volume is 10800 m^3. The total surface within the hall is 3900 m^2. If all surfaces have the same absorption coefficient of 0.25, the total absorbing surface is 975 m^2 and Sabine's reverberation time (T_{Sab}) is 1.79 s, so just within the Dutch limit of 1.8 s. The total sound power of the diffuse sound field (L_{diff}) from equation (4b) is found as:

$$L_{diff} = L_W - 25.1 \qquad (13)$$

Through the remaining of this paper we will use L_W = 70 dB (which is more or less for a normal speaker), so L_{diff} = 44.9.

Using equations (7a) and (7b), it is found that 32% of the sound energy contributes to the useful early energy; the other 68% is detrimental sound energy. This low contribution of early energy can also be considered from a different point of view. If there is one coach in the hall, speaking to his/her pupils, the reflection from the floor will add sound energy to the spoken word. When the coach is in the middle of the hall *all* other reflections are detrimental, because they arrive later than 50 ms from the direct sound. If he or she stands close to one or two walls, some extra help is found, but it is better to depart from the worst source position, which is in the middle of the hall.

Introducing the direct sound, the reverberation radius (R_{rev}) is 5.1 m, and when the coach is the only sound source in the hall, the speech intelligibility at 5.1 m will be "fair". C_{50} will be about 0 dB if all reflections in the hall are considered as disturbing. *STI* will be in the order of 0.5. The effect of the reflection against the floor improves both values.

If the distance between source and receiver is decreased to 1 or 2 m, the contribution of the direct sound increases and the speech intelligibility turns into "excellent".

The given case is not very realistic. In most cases the coach is not the only sound source and other detrimental sound sources will decrease the speech intelligibility of the coach.

Suppose, for instance, twelve coaches talking simultaneously and talking at the same constant level. It is then possible to adapt equation (4b) to calculate the noise level for 12 talking coaches:

$$L_{noise} = L_W - 10\log\left(\frac{12 \times 4 \times (1 - 0.25)}{975}\right) \quad (14)$$

which gives L_{noise} = 55.7 dB if L_W = 70 dB.

The distance where a "fair" speech intelligibility is found ($U_{50} = 0$), is now at 1.47 m from the source. This can also be calculated by dividing the reverberation radius by $\sqrt{12}$.

Recently a new hall has been built in the Netherlands, which contains a special track for athletics. Therefore it has much bigger dimensions: 80 × 35 × 10 m. For this hall the same calculations have been carried out. The results for both halls are given in table 1 (column Type denoted by “hom.”).

Looking at the results one might be surprised: the bigger hall has a longer reverberation time (2.28 s), but the other values (L_{diff} and R_{rev}) are *better* in the big hall. The most important value to describe the speech intelligibility in these halls is *not* the reverberation time. The ratio between speech and disturbing sources and reverberation is improved by increasing the value of A, so the total amount of absorbing surface, is a better indicator for the acoustical quality of a sports hall.

However, this comparison is not fully adequate. The floor surface in the big hall is twice that of the smaller one, so the number of coaches plus pupils can be increased from 12 to 24. Taking that into account, both halls appear to have equal acoustical qualities. The only difference remains the reverberation time, which is not affected by the number of noise sources.

Table 1: Comparison of two types of halls, “normal” (45×30×8) and “big” (80×35×10). One case is for homogeneous 25% absorption for all surfaces (“hom.”); the other case (“inhom.”) has 10% absorption along four walls, 5% on the floor and 58% on the ceiling. See text for extra explanations.

Values from Sabine’s equations									Mirror source model			
Hall	Type	α_{Sab} [-]	A [m^2]	T_{Sab} [s]	L_{diff} [dB]	R_{rev} [m]	N [-]	L_{noise} [dB]	T_{15} [s]	α_{15} [-]	L_{diff} [dB]	α_{diff} [-]
Normal	hom.	0.25	975	1.79	44.9	5.1	12	55.7	2.69	0.16	45.3	0.26
Big	hom.	0.25	1975	2.28	41.8	7.2	24	55.6	3.86	0.14	42.3	0.26
Normal	inh.	0.25	975	1.79	44.9	5.1	12	55.7	6.34	0.07	45.8	0.24
Big	inh.	0.25	1975	2.28	41.8	7.2	24	55.6	8.28	0.07	42.8	0.23

4.2 *Results from the mirror source model*

Although the previous halls have the same absorption coefficient for all surfaces, this is *not* a homogeneous case in acoustical terms. Then its form should be cubic as well and these halls are far from it. This means that, also for the hall with evenly spread absorbing material, concave curves are found (like curve b from figure 3) when a mirror source model is used to calculate such a curve.

In table 1 these results are also given for both halls. It gives the reverberation time calculated over the interval from –5 to –15 dB (T_{15}) plus the value of the absorption coefficient (α_{15}) calculated from it. The differences with the values from Sabine’s model are huge. The input value of α_{Sab} is 0.25, while α_{15} is 0.16 or 0.14. This comparison does improve only marginally if EDT is calculated from –1 to –11 dB.

Again it is found that the reverberation time is not a good predictor of the acoustical qualities of both halls. A much better agreement between Sabine values and the mirror source model is found when the sound energy (L_{diff}) in the diffuse field is calculated. The absorption coefficient (α_{diff}), calculated backwards from it, is in good agreement with the initial value (α_{Sab}).

There is one reason why this value is not used in practice: it is impossible to measure it.

4.3 *Inhomogeneous distribution of absorption*

It is not very realistic to give all surfaces the same absorption coefficient like done in the previous section. What happens when the majority of absorbing surface is on the ceiling, may be calculated with the mirror source model as well.

As a start the total amount of absorbing surface is kept constant, and hence the mean value of the absorption coefficient. All walls have a 10% absorption coefficient; 5% floor absorption and 58% on the ceiling.

Of course, all values from the Sabine model are just the same as in the homogenously distributed case, since Sabine's formulas don't carry any information about hall shape and absorption positioning.

The resulting reverberation times, calculated with the mirror source model appear even more concave compared with the calculations in the homogeneous case. The values of T_{15} increase by another factor 2.2. However, the increase for L_{diff} is below 1 dB. Again this means that the speech intelligibility is only slightly lower. The values of *STI* and C_{50} are not shown in table 1. They show just the same effects.

4.4 *The influence of diffusion*

In many practical cases there will be some diffuse reflections from the surfaces. If we introduce that aspect, a curve will be found which lies somewhere between curves a and b from figure 3. This has been verified by calculations in two ray tracing models (Epikul and CATT Acoustic). They show the same curves as found from the mirror source model if specular reflection is applied. However, when a common value of 10% diffusion is used, the results are between curves a and b. Therefore the increase in the reverberation time will be a bit smaller. In fact the mirror source model gives a worst-case scenario.

5 BUT IS THERE ANY ALTERNATIVE FOR THE REVERBERATION TIME?

5.1 *Expressing legal demands in acoustical quantities*

In this paper the reverberation time has been criticized as a predictor for the acoustical quality in a sports hall. It is beyond the scope of the present paper to formulate an alternative, but on the other hand we still want to give some views. They should, however, be seen as opinions to be discussed.

Furthermore it is assumed that there is nothing wrong with the existing Dutch demand of 1.8 seconds for the "normal" hall, so when the room volume is in the order of 10,000 m^3. In that case the mean absorption coefficient α_{mean}, calculated with Sabine's equation, is about 0.25.

Two problems have been mentioned with the reverberation time as a legal demand:
1. The reverberation time depends too much on the volume of the room,
2. It is very difficult to determine what should be taken as *the* reverberation time, because decay curves may be very concave.

Since, in our views, the acoustical quality in a sports hall should be considered as a noise problem, we think that α_{mean} = 0.25 can be taken as a basis for a very satisfying acoustical quality for any volume. By taking this mean absorption coefficient, the first mentioned drawback of the reverberation time is avoided.

If, for some reason, future legal demands will still be given in terms of the reverberation time, an alternative legal demand can be formulated as:

$$T = 0.4\left(\frac{V}{100}\right)^{1/3} \qquad (15)$$

with *V* in cubic meters and *T* in seconds.

This formula is based on $\alpha_{mean} = 0.25$, and can be calculated for common hall shapes[4].

5.2 *Meeting demands for* the *reverberation time*

Finding reliable absorption coefficients for the different materials, is probably the most time-consuming part of the design process when the hall is yet to be build. If all absorption coefficients could be trusted a "simple" calculation of the mean absorption coefficient would be sufficient. Measurements (when the hall has just been finished) are required to see if the designer did his/her work well and if the absorption coefficients as provided by manufacturers were right.
We think that in a sports hall the main task is to predict the noise levels, so an estimation of α_{diff} (as defined in table 1 and the text behind it) must be found from measuring results. If the absorption coefficient is calculated from one of the many measured reverberation times (*EDT*, $T_{5\to15}$, $T_{5\to25}$, $T_{5\to35}$ or *T* over the first 150 or 200 ms) this value can be measured quite accurately for linear decay curves. However, in concave curves this quantity will be underestimated. To meet legal demands, the total absorbing surface must be overestimated. As a consequence, the hall's acoustical quality will eventually be better than calculated. This can be regarded as an advantage for future users of the sports hall. It is, on the other hand, unfair to the hall's designer.

Let's, as an example, assume that a new hall is built with a simple shoebox shape and let's assume that the main absorption is positioned on the ceiling. When the hall is brand new, the reverberation time is measured and it turns out a bit too long. Now what should the designer do?

It looks a bit strange, but probably the best measure to start with is to increase the *diffusitivity* of the hall and not the total *absorption*. The reverberation time is mainly determined by the reflections along the longest axis of the hall (the reflections in the vertical direction decrease very rapidly because of the absorption on the ceiling) and hence treating both (small) walls perpendicular to this long axis decreases the measured reverberation time. Inclined walls may improve the effectiveness of the absorption on the ceiling. However, as the influence on the reverberation time may be quite large, the influence on the noise level is only marginal.

5.3 *Are there better acoustical quantities to be measured?*

A method using the speech transmission index *STI* (or similar values like for instance C_{50}) for the speech intelligibility will give a better idea about the acoustical quality in a sports hall. However, it can only be used if "*STI in noise*" is measured and hence the background noise level should be defined, plus the measuring distance between the source and the microphone. It is, for instance, possible to measure *STI* at a certain microphone position with one loudspeaker at 1 or 2 m distance, while a noise-generating speaker is positioned at 10 or 20 m. It is beyond the scope of this article to go into further detail.

If, however, the acoustical quality of a sports hall is mainly seen as a noise problem, why not measure it as a noise problem? In our view the background noise level may be calculated with

[4] It is interesting to see that using this formula for Dutch class rooms as well (where the volume is about 150 to 200 m^3) would greatly improve the speech intelligibility. Nowadays the legal demand asks for *RT* = 1.0 seconds, which is too long for a good speech intelligibility.

the aid of equation (4b), for instance at a distance of 10 m from the source. This method suffers from the same problem as the reverberation time itself: it depends too much on the size of the hall, since the total surface is not eliminated.

Using a fixed number of sound sources per square meters floor space, eliminates this problem almost totally. The total hall surface in equations (2) is not completely proportional to the floor space, but differences are very small. So, for instance, one noise source (equally loud as the source itself) per 100 m^2 floor surface can be defined, and a method similar to equation (13) is chosen as a basis for measurements.

A loudspeaker, generating white or pink noise, may be positioned according to the standards for reverberation measurements (not too close to the wall etc.). The sound levels are monitored at several microphone positions through the hall. If measurements are taken on a 10×10 m grid, the maximum level may be set at L_w-25 dB (for any microphone position but excluding, of course, positions close to the source) to reach the equivalent of α_{mean} = 0.25. Then the sound level at 1 m from the source is theoretically L_W-11 dB for an ideal point source; in practice there is an extra gain from the reflection from the floor and from the directivity of the human speaker, leading to an extra 4 to 5 dB, and the speech intelligibility in the hall will be very good. It needs, however, more research on this method before a legal demand can be set. It is based on one source per 100 m^2 and if there are more sound sources, higher values of the mean absorption coefficient may be required. Lower values may be used for lower noise levels. On the other hand, values of α_{mean} below 0.20 are never recommended.

There is an extra advantage when measuring at a microphone grid. The acoustical theory predicts a limiting value of the sound pressure level with increasing distance (equation (3) when r tends to infinity), but measurements plus calculations in ray-tracing models predict ever decreasing curves for larger distances (Barron, 1993). This decrease of the measured sound pressure levels as a function of distance, adds to the acoustical quality.

There is also a *dis*advantage of the simple method: the value of L_W must be known. It can be found from an extra measurement at 1 or 2 m., but then the directivity of the source may play a big role In the first place a omni-directional source may be used, but another possibility is to use a “talker-like” source, with a gain of 2 on the axis. That is the type of source that is required for the measurement of *STI* as well. That is the only advantage of the measurement of the reverberation time: it does not depend on the characteristics of the loudspeaker.

Our considerations lead to the conclusion that one reverberation time is not a good predictor for the acoustical quality of a sports hall if it disregards the hall’s volume and should therefore be avoided in legal demands. There is one very simple alternative: the mean value of the absorption coefficient. However, a simple method to measure this value is not available.

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