An acoustic model for evaluation of rooms with absorbent ceilings

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Introduction

A room with absorbent ceiling treatment will behave acoustically quite differently from a reverberant room. The non-uniform distribution of absorption will alter the behaviour of the sound field compared to the assumption in the classical diffuse field theory, valid for reverberant rooms. As a consequence, several room acoustic parameters are needed for a relevant evaluation that corresponds to the subjective perception of the sound environment. Rooms with ceiling treatment comprise a large group and many work places like schools, offices, etc. are equipped with this type of acoustic treatment. From engineering point of view there is a need of methods for estimation of relevant acoustic parameters in order to secure an efficient acoustic design. This paper presents a model for estimating room acoustic parameters, suitable for rooms with ceiling treatment. Calculated parameters are reverberation time T20, speech clarity C50 and sound strength G. In rooms with absorbent ceilings, furniture and other equipment will have a large effect on the room acoustic parameters, especially reverberation time and speech clarity. A method for quantification of the sound scattering effect of interior objects like furniture is outlined and incorporated in the model. Theoretical considerations behind the model, including necessary input parameters, are discussed. Results from measurements in a classroom like configuration will be presented.

A model for Sound Strength and Speech Clarity

The sound Strength G (dB) is defined as the logarithmic ratio of the total sound energy in the impulse response compared to the sound energy at 10 m in a free field measured with the same sound source and the same sound power output [1]. Sound Strength quantifies how much the reflected sound in a room contributes to the direct sound from a sound source. It is a very useful parameter that measure how the sound pressure level in a room will be affected by the absorbing surfaces and can be used as a design parameter in the same way as the reverberation time. In rooms with non-diffuse sound fields, as a classroom with ceiling treatment, the late reverberation time T20 is not a good predictor of the noise level since it ignores the early part of the impulse responses [2][3].

Formulas for G have been presented by Barron and Lee [4] and Sato and Bradley [5]. In the paper by Sato and Bradley a modified version of the formula by Barron and Lee is developed. In this paper a modification of the formula by Barron and Lee has been used. The modification takes into account the non-diffusivity effects during the sound decay. The equation for G is

$$G = 10\log(d + e_{50} + l_{50}) \quad \text{[dB]} \qquad (1)$$

where d, e_{50} and l_{50} is direct, early and late arriving sound energy, respectively. Reflected sound up to 50 ms after the direct sound is the early sound energy. Late arriving sound energy means sound arriving later than 50 ms. The normalized components d, e_{50} and l_{50} is as follows

$$d = 100Q/r^2 \qquad (2)$$

Q is the directivity index and is set to 1 since we used an omni-directional loudspeaker in the measurements. The distance source to receiver is given by r.

The early arriving sound energy is given by

$$e_{50}=31200T_{ng}/(V(1+k))[e^{-0.04rT}{}_{ng}(1-e^{(-0,691/T}{}_{ng}))+ ke^{-004rT}{}_{g}(1-e^{-0,691/T}{}_{g}) \qquad (3)$$

The late arriving sound energy is given by

$$l_{50}=31200T_{ng}/(V(1+k))(e^{-(0.04r+0.691)/T}{}_{ng}+ ke^{-(0.04r+0.691)/T}{}_{g} \qquad (4)$$

The speech clarity C_{50} (dB) is given by the logarithmic ratio between the early arriving sound energy to the late arriving sound energy. An estimation of C_{50} is given by

$$C_{50}=10\log((d+e_{50})/l_{50}) \quad \text{[dB]} \qquad (5)$$

The parameters in Eq. 3 and Eq. 4 are as follows.

V is the room volume.

The reverberation time for the grazing part of the sound field is given by

$$T_g=0.127(V/(A_{g,ceiling}+A_{sc}+A_{surf})) \quad \text{[s]} \qquad (6)$$

Eq. 6 is a two dimensional equivalent to Sabine's formula.

$A_{g,ceiling}$ is the equivalent absorption area for the ceiling absorber. This is given by $A_{g,ceiling}=\alpha_g S$ where S is the ceiling area and α_g is the absorption coefficient for grazing sound incidence. This will be defined in the next paragraph.

A_{sc} is the equivalent scattering area. This parameter quantifies the scattering and absorbing effects of furniture and other equipment in the room. Basically, A_{sc} quantifies the energy transfer from the grazing sound field to the non-grazing sound field. How to estimate this parameter is treated further on in a coming paragraph.

A_{surf} is the equivalent absorption area of the remaining surfaces i.e. walls and floor.

The reverberation time for the non-grazing part of the sound field is given by

$$T_{ng}=0.161(V/(A_{ceiling}+A_{furniture}+A_{surf})) \quad \text{[s]} \qquad (7)$$

$A_{ceiling}$ is the equivalent absorption area for the ceiling absorber. This is given by $A_{ceiling}=\alpha_r S$ where S is the ceiling area and α_r is the random (statistical) absorption coefficient.

$A_{furniture}$ is the equivalent absorption area for the furniture and other equipment in the room.

A_{surf} is the equivalent absorption area of the remaining surfaces i.e. walls and floor.

The factor k is determined by the ratio of the steady-state energy for grazing and non-grazing sound field. It is estimated as

$$k=(T_g/T_{ng})(N_g/N_{ng}) \tag{8}$$

T_g and T_{ng} are defined above. N_g and N_{ng} are the number of modes in the grazing and non-grazing group, respectively.

Definition of the grazing and non-grazing sound field

A wave theoretical solution of the decay process in a rectangular room with absorbent ceiling treatment can be expressed as a summation of resonant modes. This is illustrated in Figure 1.

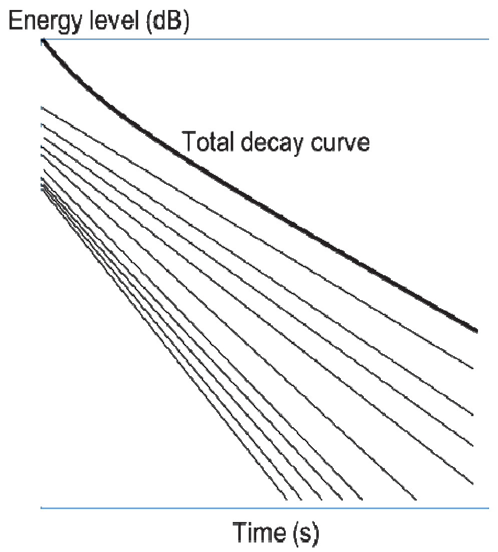


Figure 1. The total sound decay as build-up of the decay of individual modes.

A disadvantage with this approach is the difficulties that appear when handle the effect of sound scattering objects. A consequence of scattering will be a coupling between all resonant modes which makes the calculations complicated.

By subdividing the sound field into a grazing and non-grazing part the sound scattering is interpreted as an energy transfer from the grazing to the non- grazing sound field. This is illustrated in Figure 2.

Also worth noting is that measured reverberation times in rooms with ceiling treatment better agrees with the grazing reverberation times Tg than the Sabine reverberation time.

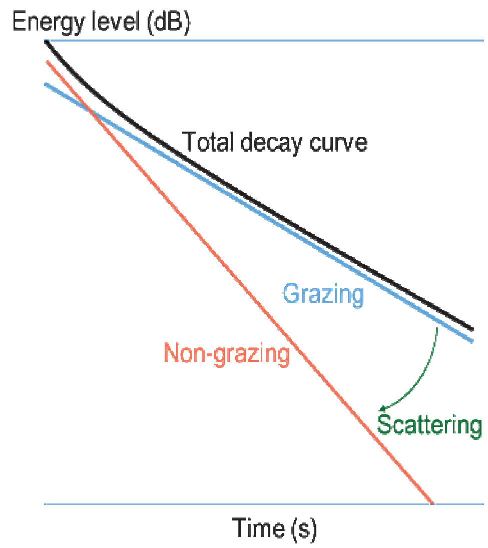


Figure 2. Subdivision of the the sound field into a grazing and non-grazing part.

The grazing part of the sound field is defined by an angle given by

$$\Theta_g = arcos(c/(4fL)) \tag{9}$$

where c is the speed of sound, f the frequency and L the height from floor to ceiling. Equation 9 is a high frequency assumption but it seems to work reasonably well at middle frequencies. The results for the mid frequencies are also used for the low frequency range as a rough approximation. Modes with an angle equal or larger than θ_g defines the grazing sound field.

The number of modes in a frequency band Δf and in an angle segment defined by θ is given by

$$\Delta N(\theta)=[(4\pi f^2 V/c^3)cos(\pi/2-\theta)+(2f/c^2)(\pi L_y L_z+\theta(L_x L_z+L_x L_y))+$$
$$(1/c)(L_y+L_z)]\Delta f \tag{10}$$

where L_x, L_y, and L_z are height, length and width of the room.

The number of grazing modes is determined by inserting θ_g into equation 10.

To calculate the number of modes in the non-grazing group the distribution of energy over angle of incidence towards the ceiling absorber is taken into account. The distribution of sound energy as a function of angle of incidence in a diffuse sound field and in a room with ceiling treatment is shown in Figure 3. The skewed distribution is typical for a room with absorbent ceiling. The angle corresponding to the maximum value is used to determine the absorption coefficient for non-grazing incidence. The angle segment given by ±5% around the maximum value is used for calculating the number of modes in the non-grazing group.

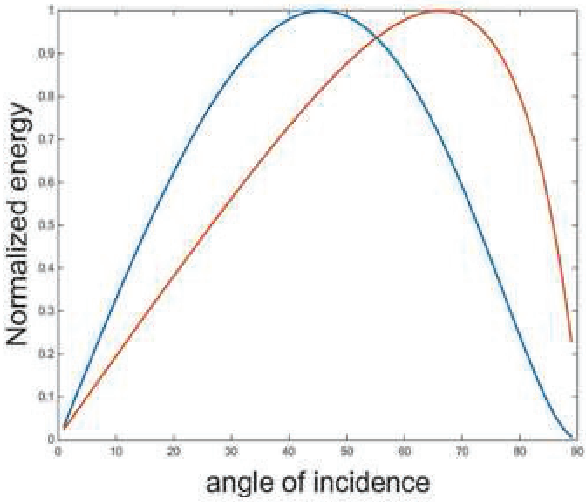


Figure 3. Sound energy distribution in a diffuse (symmetrical curve) and non-diffuse sound field as a function of angle of incidence towards the ceiling absorber.

To be able to calculate the angle dependent absorption of the ceiling absorber the input impedance has to be known. For a porous absorber the input impedance is calculated based on the air flow resistivity of the material and the mounting height. An advantage using this approach is that extended reaction can be taking into account as shown in Figure 4. At low frequencies and high mountings height this will be of importance.

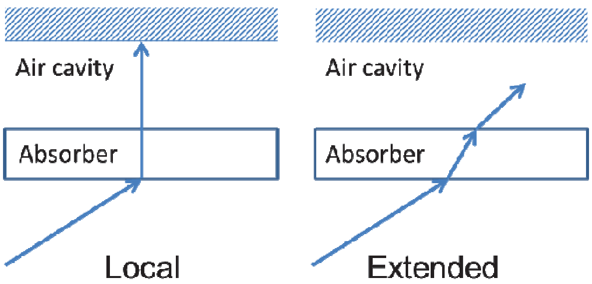


Figure 4. Local and extended reaction for sound propagation in a porous ceiling absorber backed by an air cavity.

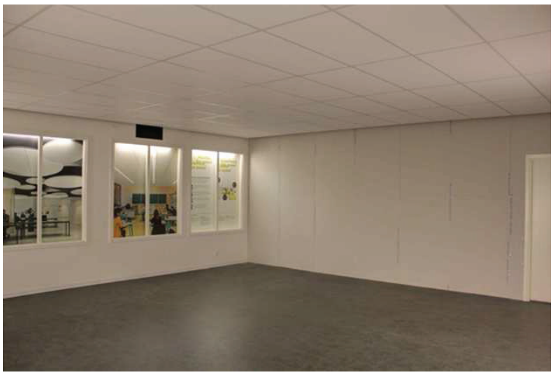
The equivalent scattering area

The sound scattering effects of furniture and other equipment in the rooms will have a large influence on the room acoustic parameters. Especially reverberation time T20 and Speech Clarity will be affected. Sound Strength G will normally be less affected. To quantify the scattering effect the following procedure has been used. The reverberation time T20 has been measured with and without furniture in the room with a highly absorptive ceiling, see Figure 5. The equivalent scattering area is calculated using equation 6 and given by

$$A_{sc}=0.127V(1/T_{20,with}-1/T_{20,without}) \qquad (11)$$

where $T_{20,with}$ and $T_{20,without}$ are the reverberation times in the room with ceiling absorber, with and without furniture, respectively.

a)



b)

Figure 5. a) Room with furniture and ceiling absorber b) Room without furniture but with ceiling absorber.

The measured A_{sc} for the furniture in Figure 5a is shown in figure 6. It appears that the main scattering effect of the furniture in Figure 5a is in the mid frequency region.

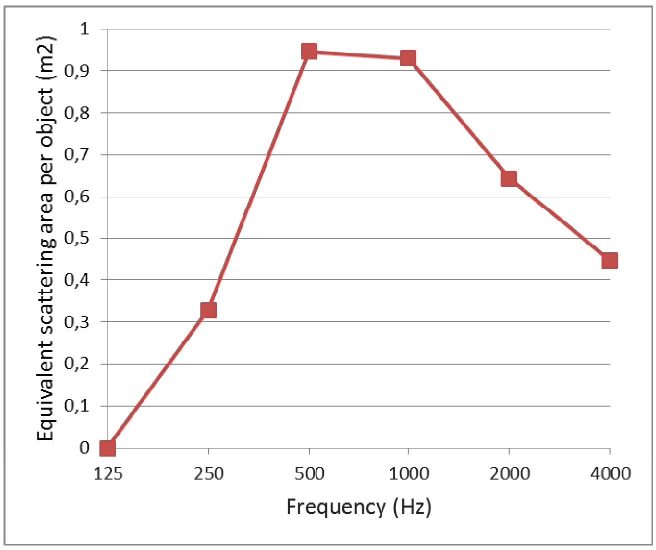


Figure 6. The equivalent scattering area A_{sc} for the furniture configuration in Figure 5a.

Results

The model used in this paper has been used for calculation of T20, C50 and G for the classroom shown in Figure 5. The results are given in Figure 7. The estimation of scattering is crucial and the values given in Figure 6 have been used. The generally good agreement is not surprising since the A_{sc} values have been estimated in the same room. For comparison the Sabine calculations according to EN 12354-6 [6] is presented.

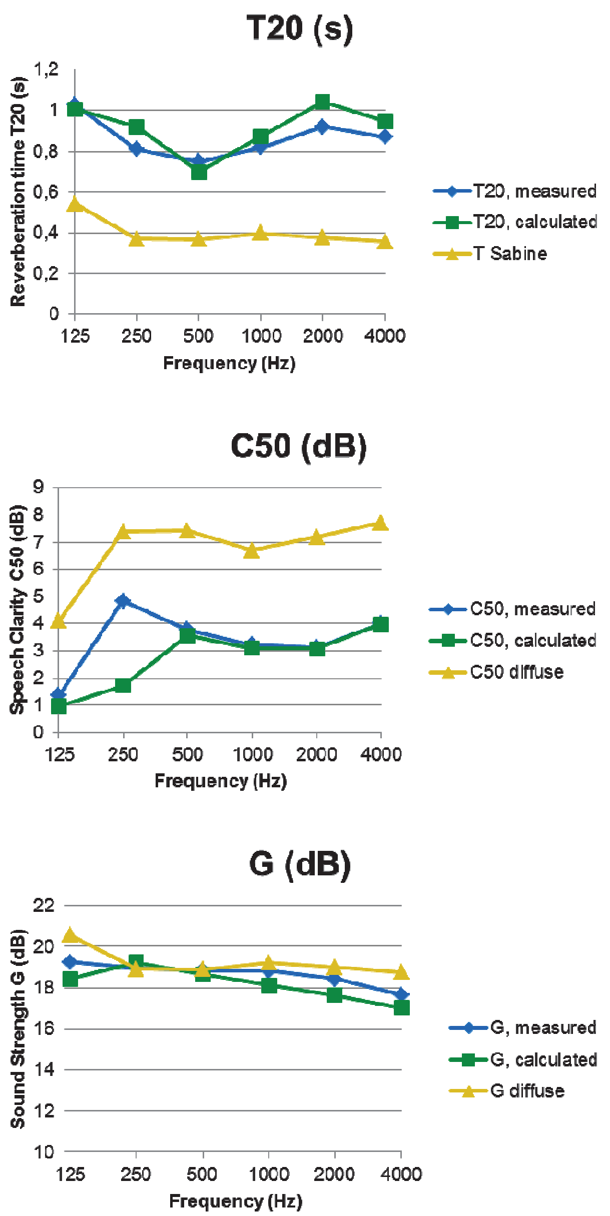


Figure 7. Measurements and calculations for the classroom shown in Figure 5a. For comparison results given by the diffuse field assumption are added.

Concluding remarks

An energy based model for calculating T_{20}, C_{50} and G in rooms with absorbent ceiling treatment is presented. A crucial factor in these calculations is the quantification of sound scattering due to furniture and other equipment in the room. A measure denoted equivalent scattering area is defined. Comparison with measurements in a classroom shows good agreement. The good correspondence is mainly due to the fact the estimation of the scattering area of the furniture is carried out in the same room. It will be further investigated if the equivalent scattering area of objects measured in specified room types e.g. corresponding to classroom, offices, day-care centres, ward rooms etc., can be used for calculations in similar but not exactly the same room.

References

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[6] EN 12354-6: Building acoustic – Estimation of acoustic performance of buildings from the performance of elements – Part 6: Sound absorption in enclosed spaces.2004