INPUT DATA FOR ACOUSTICAL DESIGN CALCULATIONS FOR ORDINARY PUBLIC ROOMS

1 Erling Nilsson

(1) Saint-Gobain Ecophon AB, Box 500, SE-265 03 Hyllinge, Sweden
email: erling.nilsson@ecophon.se

The basis for acoustical design of ordinary public rooms like schools, offices and healthcare premises is a suspended absorbent ceiling. The non-uniform distribution of the absorbent material as well as the influence of sound scattering objects like furniture and other interior equipment, makes the calculations of room acoustic parameters challenging. Especially since the classical diffuse field assumption is not valid. As input data in calculations and simulations, it is common to use the practical absorption coefficient, provided by manufactures of absorbent ceilings. The practical absorption coefficient is based on measurements according to ISO 354 and calculated according to ISO 11654. The procedure behind the determination of the practical absorption coefficient limits its applicability in simulation and calculation models. The size of the sample area, few available mounting heights and the diffuse conditions under which it is measured are some examples that put restrictions on its usefulness. In rooms with suspended ceiling the angle dependent absorption of the ceiling is an important property that will influence the room acoustic parameters. This paper discusses a model that uses the air flow resistivity of porous products as an input parameter. The beneficial effects of this approach will be exemplified by comparison between calculations and measurements. Room acoustic parameters investigated are reverberation time T_{20}, speech clarity C_{50} and sound strength G. Further on, a method for quantifying the scattering effect of furniture will be discussed. A measure called equivalent scattered absorption area A_{sc} is introduced. Measurements of A_{sc} for different furniture configurations will be presented as well as how it is used in the calculation model.
Keywords: calculation models, absorption, scattering, airflow resistivity

1. Introduction

The most common acoustical treatment in ordinary public rooms is an absorbent suspended ceiling. The reverberation time T_{20} or T_{30}, as defined in ISO 3382-2 [1], are often used in regulations and building codes as a measure to define target values ensuring appropriate acoustical conditions for different room types. The presence of an absorbent ceiling in a room creates a sound field that normally have a non-linear decay and deviates far from the assumptions in the classical diffuse field theory. This has emphasized the need of additional parameters for a differential evaluation of the acoustical conditions in rooms with ceiling treatment [2]. For a more selective evaluation of room acoustics, complementary measures to the reverberation time have been suggested [3]. By using speech clarity C_{50} and sound strength G, measures encapsulating the early reflections as well as the total energy in the impulse response are introduced. The way T_{20} or T_{30} is determined [1] the early part of the impulse response is neglected. Since the importance of early reflections has been reported extensively [4], it is not surprising that subjective judgements and reverberation time exhibits quite low correlation [5] compared to measures that includes the early part of the impulse response.

In models for rooms with ceiling treatment, the scattering and absorbing contribution from furniture and other interior fittings have a crucial influence on room acoustic parameters. In this paper an energy based model is formulated for these types of rooms and for the calculation of reverberation time, speech clarity C_{50} and sound strength G. A method for quantification of the scattering and absorbing effect of furniture is inherent in the model and will be exemplified with measurements.

2. The model

2.1 The model

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. 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 T_{20} is not a good predictor of the noise level since it ignores the early part of the impulse responses [5].

Formulas for G have been presented by Barron and Lee [6] and Sato and Bradley [7]. 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

$$G = 10\log(d + e_{50} + l_{50}) \qquad (\mathrm{dB}) \tag{1}$$

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

$$d = 100Q/r^2 \tag{2}$$

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

$$e_{50} = 31200T_{ng}/(V(1+k))[e^{-\frac{0.04r}{T_{ng}}}\left(1 - e^{-\frac{0.691}{T_{ng}}}\right) + ke^{-\frac{0.04r}{T_g}}\left(1 - e^{-\frac{0691}{T_g}}\right)] \tag{3}$$

The late arriving sound energy is given by

$$l_{50} = 31200T_{ng}/(V(1+k))[e^{-\frac{(0.04r+0.691)}{T_{ng}}} + ke^{-\frac{(0.04r+0.691)}{T_g}}] \tag{4}$$

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

$$C_{50} = 10\log((d + e_{50})/l_{50}) \qquad (\mathrm{dB}) \tag{5}$$

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

$$T_g = \frac{0.127V}{A_{g,ceiling} + A_{sc} + A_{surf}} \qquad (\mathrm{s}) \tag{6}$$

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 absorption area. This parameter quantifies the scattering and absorbing effects of furniture and other equipment in the room. For non-absorbent sound scattering objects, 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

$$T_{ng} = \frac{0.161V}{A_{ceiling} + A_{furniture} + A_{surf}} \qquad (s) \qquad (7)$$

$A_{ceiling}$ 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

$$k = \frac{T_g N_g}{T_{ng} N_{ng}} \qquad (8)$$

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.

2.2 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 1a.

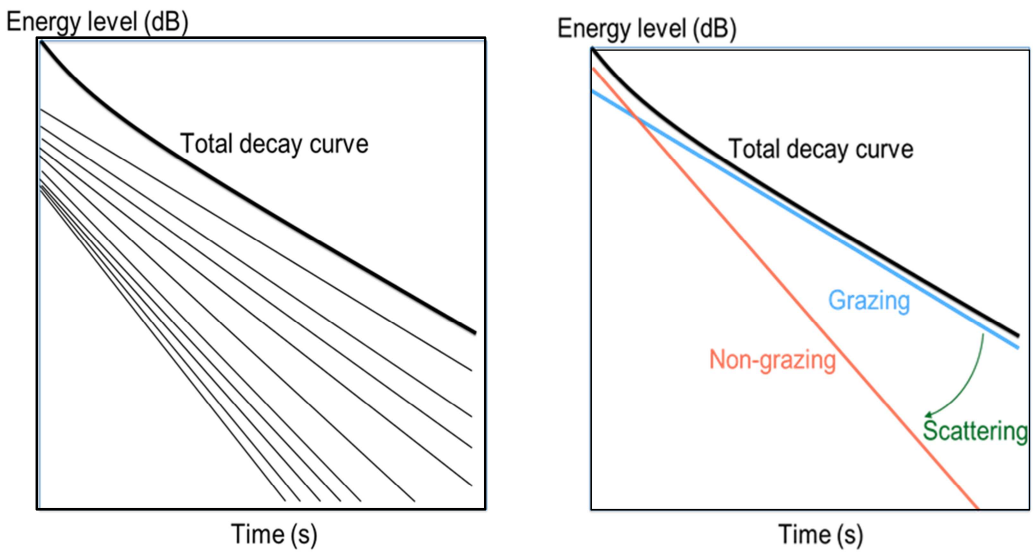

Figure 1: a) The total sound decay as build-up of the decay of individual modes b) the total sound decay as build-up of a grazing and non-grazing group of modes

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 1b.
Also worth noting is that measured reverberation times in rooms with ceiling treatment better agrees with the grazing reverberation times T_g than the Sabine reverberation time.
The grazing part of the sound field is defined by an angle given by

$$\theta_g = \arccos(\frac{c}{4fL}) \tag{9}$$

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 related to angles equal to 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

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

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 2. 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.

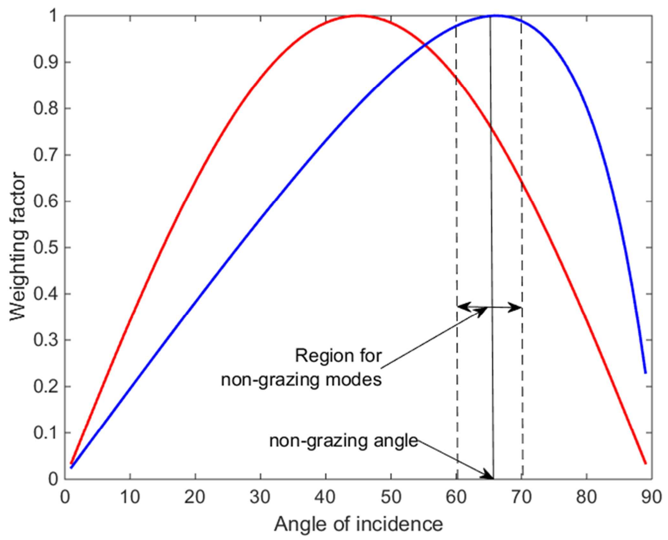

Figure 2: Sound energy distribution in a diffuse (symmetrical curve) and non-diffuse sound field as a function of angle of incidence towards the ceiling absorber.

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.

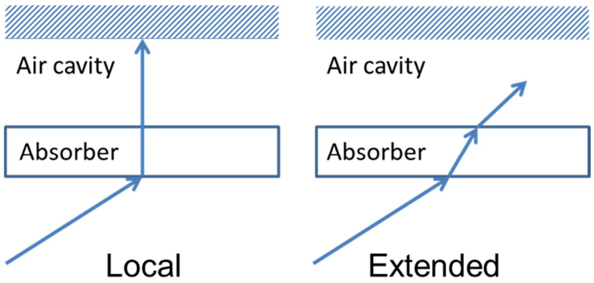

Figure 3: Local and extended reaction for sound propagation in a porous ceiling absorber backed by an air cavity.

2.3 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 T_{20} and Speech Clarity C_{50} 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 T_{20} has been measured with and without furniture in the rooms with a highly absorptive ceiling, see Figure 4a. The equivalent scattering absorption area A_{sc} is calculated using equation 6 and given by

$$A_{sc} = 0.127V\left(\frac{1}{T_{20,with}} - \frac{1}{T_{20,without}}\right) \quad (11)$$

where $T_{20,with}$ and $T_{20,without}$ are the reverberation times in the room with ceiling absorber, with and without furniture, respectively. Figure 4 and 5 shows the empty room and the room with densely, normal and sparsely office furnishing.

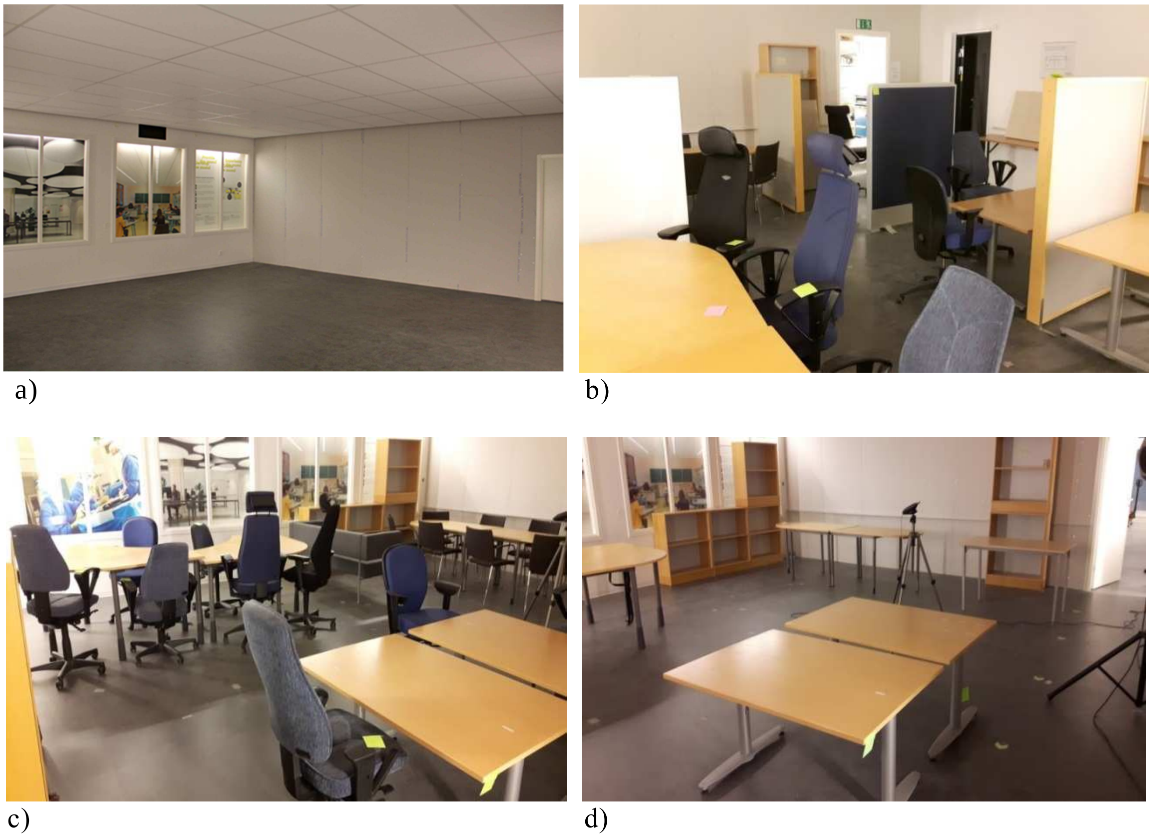

Figure 4: a) empty room with ceiling absorber b) densely furnished office c) normal furnished office d) sparsely furnished office

The measured A_{sc} per m^2 floor area for the furniture in Figure 4b-d are shown in figure 5. It appears that the main scattering effect of the furniture is in the mid frequency region.

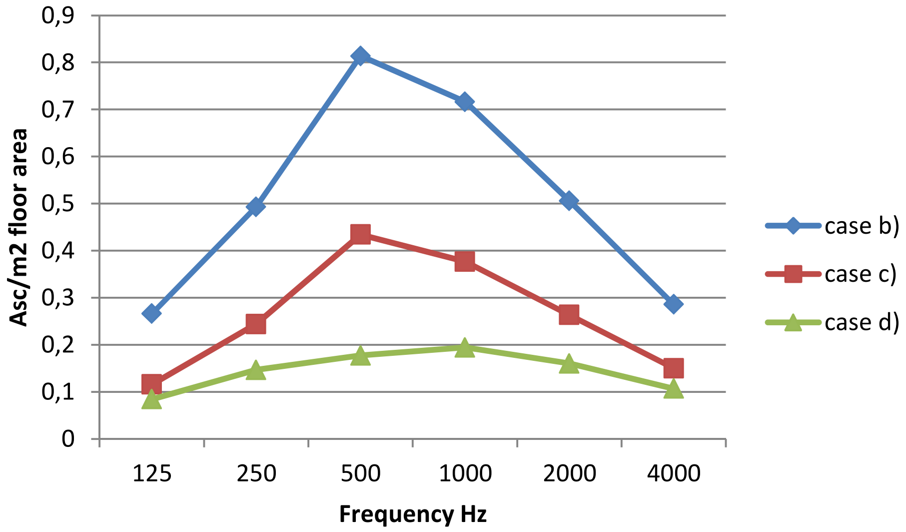

Figure 5: The equivalent scattering absorption area, A_{sc} per m2 floor area, for the furniture configurations in Figure 4b-d.

3. Results

The model presented in this paper has been used for calculation of T_{20} and C_{50} for the classroom shown in Figure 6. The estimation of scattering is crucial and the values given in Figure 7 have been used. The results are given in Figure 8. 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 [8] is presented.

Figure 6: A sparsely furnished class room

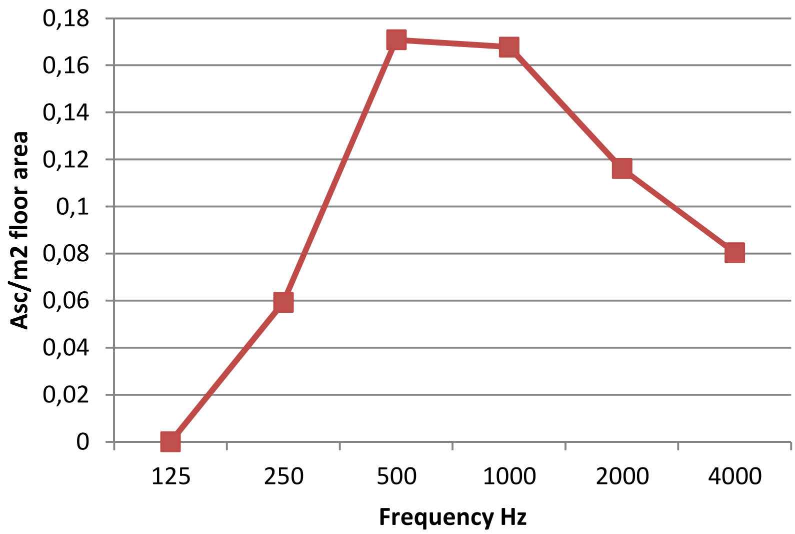

Figure 7: The A_{sc} per m2 floor area for a sparsely furnished class room.

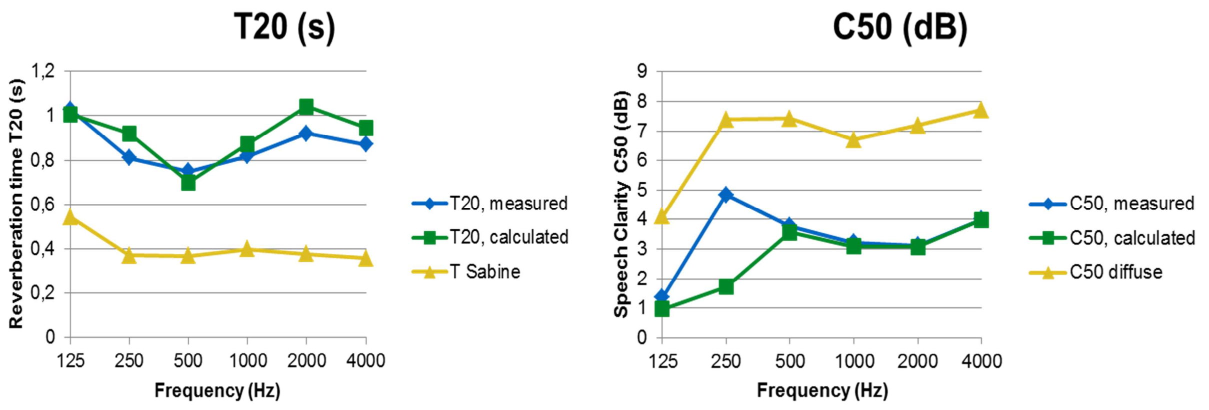

Figure 8: Measurements and calculations of T_{20} and C_{50} for the classroom shown in Figure 6. For comparison, results given by the diffuse field assumption are added.

4. 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 absorption area is defined. Comparison with measurements in a classroom shows good agreement. It will be further investigated if the equivalent scattering absorption area of furniture and other objects, measured in specified room types corresponding to classroom, offices, day-care centres, ward rooms etc., can be used for calculations in similar but not exactly the same sized rooms.

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