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4pAAa8. The effect of edge caused diffusion on the reverberation time - A semi analytical approach
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The basic numerical model here is the Anisotropic Reverberation Model (ARM). This geometrical/energetic model assumes a homogeneous but anisotropic soundfield in room acoustics. Its system of linear differential equations describes the redistribution of sound energy to different directional ranges by wall reflections, which may be specular or diffuse, where the diffuse reflections are caused also by the edges (edge effect). The reverberation times result from eigenvalues and eigenvectors of the differential equation system. Recently an analytical formula has been found, that calculates the diffracted, angle dependent sound field, averaged over the octave band even for arbitrarily shaped polygons. The reverberation times calculated with the ARM extended by that edge diffraction are presented. So, first time, not only for the typical shoe-box room with an absorbing floor and reflecting walls realistic reverberation times can be calculated, taking the edge effect into account.
INTRODUCTION

In room acoustics, the reverberation time is still the most important perceptional parameter and the well known simple Sabine formula is used in most cases to predict it. However, this is valid only for diffuse sound fields, i.e. homogeneity and isotropy, often not given. On the other side, there are numerical models based on geometrical room acoustics such as raytracing, able to take any absorption and scattering coefficients of surfaces ('walls') into account and to compute any non-diffuse sound fields, also other room acoustical criteria. For practical purposes of architectural design, a method in between these models is desirable. This had been the motivation to develop an Anisotropic Reverberation Model (ARM) [1][2]. Holding the assumption of homogeneity but dropping the isotropy, its basic idea is an energy-interchange between a set of directional ranges. Thereby the surface absorption and scattering coefficients are involved. As it turned out, reverberation times depend very sensitively from scattering coefficients [3] – which, however, are often unknown. So, to allow a success of ARM, it is a must, to pre-compute these. These 'diffusivity coefficients', as used in ray tracing, depend on two influences: First the scattering due to the 'roughness' (or sub-structuring) of the surface of a wall. This effect is usually modelled by a 'scattering coefficient' (defined as the ratio of the scattered energy related to the totally reflected), where the scattered part is described by Lambert's cosine-law. The second influence is due to the finiteness of the walls: the edge diffraction effect, as a modification of the reflection law (due to edge diffraction, the sound is reflected not only into a single mirror direction but the reflected sound beam is widened to a lobe.) This is the focus here.

Models to compute edge diffraction for its own are well known, but only for the special cases of a semi-infinite screen (commonly used Fresnel's theory) or the slit (Fraunhofer diffraction). But there is no exact formula for arbitrary polygons.

This paper will show how the effect of edge diffraction, even at arbitrary polygons, can be computed analytically and implemented, as an energetic coefficient, in ray tracing or ARM. It is organized as follows: First a short description of the Anisotropic Reverberation Model; next the main steps of the derivation of a transmission coefficient due to edge diffraction at flat polygons; then the description of the evaluation method; at last the discussion of the results, i.e. the effect on the reverberation times in three typical rooms.

THE ALGORITHM OF THE ANISOTROPIC REVERBERATION MODEL (ARM)

To handle the anisotropy and the interchange of different energy flows, the full angular range is sub-divided into a set of \( D \) directional ranges; their representative middle directional unit vectors are \( \vec{r}_i \) \((i = 0 \ldots D - 1)\). For these energy flows, a balance is set up, - similarly as with the derivation of the Sabine formula - resulting finally in a system of linear differential equations. The absorption at walls diminishes each flow (absorption coefficient \( \alpha_w \), \( w = 0 \ldots W - 1 \), the room is enclosed by \( W \) walls).

The sound energies transferred from one direction to another by diffuse or specular reflection are also influenced by the scattering coefficients \( \sigma_w \). Summarized, the energy flow interchange (per second) from the \( j \)-th to the \( i \)-th directional range via possibly all walls \( w \) is described by a matrix of transition coefficients

\[
\alpha_{ij} = \sum_{w=0}^{W-1} e_j \cdot q_{wj} \cdot (1 - \alpha_w) \cdot [\sigma_w \cdot d_{iw} + (1 - \sigma_w) \cdot m_{iwj}] \quad (1)
\]

Herein:

- \( m_{iwj} \) handles possible geometric reflections; it is 1, if the incident vector \( \vec{r}_j \), mirrored at wall \( w \), falls into the \( i \)-th directional range, else 0
describes Lambert’s cosine law for diffuse reflections from the \( w \)-th wall into the direction \( \vec{r}_i \); normalized for all walls by reason of energy conservation;

2. \( q_{wj} \) is the fraction of the area of wall \( w \) projected into the direction \( r_j \), related to the total cross section of the room perpendicular to \( n_w \);

3. \( e_j = \frac{c S_j}{V} \) is the inverse of the free path length, specific for the direction \( \vec{r}_j \); where \( S_j \) is the cross section of the room for direction \( \vec{r}_j \), and \( V \) is the room volume).

Now, the system of linear differential equations, reads:

\[
\frac{dx}{dt} = Ax
\]

where the matrix \( A \) consists of the coefficients \( a_{ij} \) and the vector \( x \) represents the set of relative sound energies \( x_i \) travelling into the \( D \) directions.

The differential equation system (2) is solved either semianalytically by computation of the eigenvectors and eigenvalues; or the equation system is solved numerically by e.g. a forward Euler iteration.

However an exact geometric reflection is only achievable with an infinite wall. As the wall is limited in size, the sound is reflected not only in a single mirror direction but the reflected sound beam is widened to a lobe due to the effect of edge diffraction.

### The Introduction of Edge Diffraction

Now, to introduce edge diffraction as a supplement to reflection into ARM, it is the aim to replace the simple coefficient \( m_{iwj} \) by a more appropriate coefficient that takes the edge diffraction of a wall into account.

Actually it had been intended to include edge diffraction as a special case of the diffusivity coefficient. However, it seemed more suitable, to replace \( m_{iwj} \) by a suitable transmission degree, allowing to handle the geometric reflection as a special case of edge caused diffraction.

This is achieved with a formula introduced by Gordon [4] for electromagnetic waves that was already used in acoustics by Lee and Seong [5]. Gordon assumes a plane wave incident to a scatterer and describes the scattered wave as a spherical wave with different amplitudes for different directions. The scatterer is an arbitrarily shaped flat polygon \( \{ \vec{a}_n \} \) with the vertices \( \vec{a}_n \) as shown in figure 1, the edges \( \Delta a_n = \vec{a}_{n+1} - \vec{a}_n \) and the edge mid points \( \vec{a}_n = \frac{1}{2}(\vec{a}_{n+1} + \vec{a}_n) \). Its area is \( A \).

Gordon’s formula assumes the Kirchhoff approximation and uses some other approximations for a finite distance of the receiving point but the modification of this formula presented here for plane waves only uses the Kirchhoff approximation.

According to figure 1 the unit vector \( \vec{r}_1 \) points into the direction the incident plane wave is coming from and \( \vec{r}_2 \) is the direction of the reflected plane wave. That means that \( \vec{r}_1 \) is opposite to the propagation direction of the incident wave.

Here a slight modification of Gordon’s formula describes the complex transfer coefficient \( Q \) for plane waves for incident and scattered sound with frequency \( f = \frac{ck}{2\pi} \) (with sound velocity \( c \) and wave number \( k \)) from incident direction \( \vec{r}_1 \) and scattered into direction \( \vec{r}_2 \) by the polygon \( \{ \vec{a}_n \} \). According to this the transfer coefficient \( Q \) is defined as the reflected wave amplitude related to the incident one as a function of the shape, size and orientation of the polygon and with the wave number \( k \) also a function of the frequency of the scattered wave. Due to the smooth distribution of plane waves to different directions the reflected wave amplitude needs to be interpreted as an amplitude density leaving the coefficient \( Q \) with the unit \([m]\).
The scatterer is an arbitrarily shaped flat polygon with area $A$ defined by its $N$ vertices $\vec{a}_n$. The vector $\vec{n}$ is its unit normal vector. The direction to the source of the plane wave $\vec{r}_1$ and the direction of the outgoing wave $\vec{r}_2$ are also unit vectors.

For simplicity we use $\vec{r} = \vec{r}_1 + \vec{r}_2$. With this the case of geometric reflections is described by $|\vec{r} \times \vec{n}| = 0$. In this well known special case we have:

$$Q = \frac{i}{4\pi} kA \vec{r} \cdot \vec{n}$$  \hspace{1cm} (3)

with $i$ being the imaginary unit $\sqrt{-1}$. In all other cases:

$$Q = -\frac{1}{4\pi} \frac{\vec{r} \cdot \vec{n}}{(\vec{r} \times \vec{n})^2} \sum_{n=0}^{N-1} \frac{(\vec{r}_1 \times \vec{n})\sin(\frac{k}{2}\vec{r} \cdot \vec{a}_n)}{k\vec{r} \cdot \vec{a}_n} e^{ik\vec{r} \cdot \vec{a}_n}$$  \hspace{1cm} (4)

This is the transfer coefficient for the amplitude of the waves at a single frequency, a sum over the contributions from all edges. Note that the choice of the origin of the coordinate system has only an influence on the phase of the scattered waves. Therefore the choice of the coordinate system is for our purposes free. Its dimension is $[m]$ because this coefficient has to be interpreted as a ratio of an amplitude density - for different scattered directions - to the amplitude of a single incident wave.

To illustrate the results of this formula, it is evaluated for two cases of incident directions on $2m \times 2m$ quadratic scatterer as shown in fig. 2. Fig. 3 shows for an incident direction at $-45^\circ$ the quantity $|Q|^2$ the quantity $|Q|^2 = \frac{A(\vec{r}_1 \cdot \vec{n})}{A(\vec{r}_1 \cdot \vec{n})}$. A central lobe with a maximum at about $45^\circ$ gets wider with decreasing frequency, in the case of a grazing incident angle of $80^\circ$ the maximum of the reflected intensity is not at the geometric reflection angle at $-80^\circ$. Further there are side lobes with deep notches between them.

**The Energy Transmission Averaged over an Octave Band**

To get an energetic transmission coefficient $T$, defined as the ratio of the diffracted to the incident sound power per solid angle, suitable for the usual energetic approaches, especially for ARM an averaging over all frequencies of an octave band is performed. As $Q$ is an amplitude proportion, a superposition of the waves with different frequencies leads to an averaging over the energetic quantity $|Q|^2$.

Furthermore the value of $Q$ depends on the size of the Polygon as can easily be seen in its dimension $[m]$. In ARM this effect is already taken into regard by the coefficient $q_{w_j}$ in equation
FIGURE 3: Directional scattering diagrams of a 2m × 2m square for two different cases of incident angles according to fig. 2. On the left side the case of a grazing incident for four different frequencies. The angle for geometric reflection is at −80°. On the right side for the same frequencies the geometric reflection is at 45°. For comparison the shape of Lambert’s cosine law is also shown.

(1). To use the coefficient \( Q \) in ARM it is necessary to divide \(|Q|^2\) by \( A\mathbf{r}_1 \cdot \mathbf{n} \) to get a dimensionless quantity.

This leads to the above mentioned transmission degree of the polygon:

\[
T = \frac{1}{A\mathbf{r}_1 \cdot \mathbf{n}} \frac{1}{k_o - k_u} \int_{k_u}^{k_o} |Q|^2 \, dk
\]

where \( k_u \) and \( k_o \) mark the upper and lower wave numbers of the frequency band.

As \( Q \) is complex the integral splits in a real and an imaginary part so that \(|Q|^2 = Q_r^2 + Q_i^2\). In case of the geometrical mirror direction the result is:

\[
T = \frac{(\mathbf{r} \cdot \mathbf{n})^2 A(k_o^3 - k_u^3)}{3(k_o - k_u)}
\]

In the other case the integrand consists of a squared sum that yield double sums:

\[
T = \frac{1}{A\mathbf{r}_1 \cdot \mathbf{n}} \frac{1}{16\pi^2} \frac{1}{k_o - k_u} \sum_{i=0}^{N} \sum_{j=0}^{N} a_i a_j \int (I(b_i, b_j, c_i, c_j, k_o) - I(b_i, b_j, c_i, c_j, k_u))
\]

with the coefficients \( a_i = \frac{\mathbf{r} \cdot \mathbf{\Delta a}_i}{(\mathbf{r} \times \mathbf{n}) \cdot (\mathbf{r} \times \mathbf{n})} \), \( b_i = \frac{\mathbf{r} \cdot \mathbf{\Delta a}_i}{2} \) and \( c_i = \mathbf{r} \cdot \mathbf{\bar{a}}_i \) and the integral:

\[
I(b_i, b_j, c_i, c_j, k) = \frac{1}{4b_i b_j} \left( -\frac{\cos((b_i - b_j + c_i - c_j)k)}{k} \right)
\]

\[
+ \frac{\cos((b_i + b_j + c_i - c_j)k)}{k} + \frac{\cos((b_i - b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j - c_i + c_j)k)}{k} + \frac{\cos((b_i - b_j - c_i + c_j)k)}{k} - \frac{\cos((b_i - b_j + c_i - c_j)k)}{k} - \frac{\cos((b_i - b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j - c_i + c_j)k)}{k} + \frac{\cos((b_i + b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j - c_i + c_j)k)}{k} + \frac{\cos((b_i + b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j + c_i - c_j)k)}{k} + \frac{\cos((b_i + b_j + c_i - c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j + c_i - c_j)k)}{k} + \frac{\cos((b_i + b_j + c_i - c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i - b_j + c_i - c_j)k)}{k} - \frac{\cos((b_i - b_j + c_i - c_j)k)}{k} - \frac{\cos((b_i + b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j - c_i + c_j)k)}{k} + \frac{\cos((b_i + b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j + c_i - c_j)k)}{k} + \frac{\cos((b_i + b_j + c_i - c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j - c_i + c_j)k)}{k} + \frac{\cos((b_i + b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j - c_i + c_j)k)}{k} + \frac{\cos((b_i + b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i - b_j + c_i - c_j)k)}{k} - \frac{\cos((b_i - b_j + c_i - c_j)k)}{k} - \frac{\cos((b_i + b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j - c_i + c_j)k)}{k} + \frac{\cos((b_i + b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j + c_i - c_j)k)}{k} + \frac{\cos((b_i + b_j + c_i - c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i - b_j + c_i - c_j)k)}{k} - \frac{\cos((b_i - b_j + c_i - c_j)k)}{k} - \frac{\cos((b_i + b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j - c_i + c_j)k)}{k} + \frac{\cos((b_i + b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j + c_i - c_j)k)}{k} + \frac{\cos((b_i + b_j + c_i - c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i - b_j + c_i - c_j)k)}{k} - \frac{\cos((b_i - b_j + c_i - c_j)k)}{k} - \frac{\cos((b_i + b_j - c_i + c_j)k)}{k}
\]

\[
+ \frac{\cos((b_i + b_j - c_i + c_j)k)}{k} + \frac{\cos((b_i + b_j - c_i + c_j)k)}{k}
\]
with the usual integrated slit function \( \text{Si}(x) = \int_0^x \frac{\sin(t)}{t} \, dt \) for cases where both \( b_i \neq 0 \) and \( b_j \neq 0 \). In cases where one of the \( b_{i,j} \) is zero:

\[
I(b_i,0,c_i,c_j,k) = I(0,b_i,c_i,c_j,k) = \frac{1}{2b_i} \left( \text{Si}((b_i + c_i - c_j)k) + \text{Si}((b_i - c_i + c_j)k) \right)
\]

When both \( b_{i,j} = 0 \):

\[
I(0,0,c_i,c_j,k) = \frac{\sin((c_i - c_j)k)}{c_i - c_j}
\]

In this case another special case is distinguished when \( c_i = c_j = c \):

\[
I_{12}(0,0,c,c,k) = k
\]

Fig. 4 shows the result of \( T \) for an averaged octave band compared to the \( \frac{Q}{4\pi T} \) for several single frequencies within the same octave band. The deep notches are levelled by averaging but there are still minima between the side lobes for this case of 1kHz octave band mid frequency.

**Figure 4**: Scatter diagrams for single frequencies (red) within the octave band from 707Hz to 1.41kHz with mid frequency 1kHz compared with the diagram for the averaged octave band that balances the deep notches of the single frequencies.

Using \( T \) for the representative vectors of the directional ranges of the ARM still a normalisation is necessary to grant the conservation of energy for the chosen set of directional ranges. This normalised coefficient \( T \) replaces the \( m_{iwj} \) in eq. (1) when introducing edge diffraction.

So, finally, it is reached that the edge diffraction at polygonal walls is introduced in the ARM algorithm to compute diffraction dependent sound decay and reverberation times.

**Method of Evaluation**

To evaluate the new ARM combined with edge diffraction, its results were compared with results of corresponding ray tracing experiments. For comparison also the decay curves for Sabine’s and Eyring’s formulae for reverberation times are shown additional to the decay curves for geometric reflection both in ARM and with raytracing.

To be consistent with the condition of the ARM which principally does not distinguish different locations the raytracing simulations start with a diffuse sound field i.e. the sound
particles are emitted not only into random directions but also from random positions. Also the whole room is used as a sound particle detector. This spatial distribution explains the smooth course of the decay curves and the lack of distinct reflections therein. The raytracing algorithm uses a random decision algorithm to model both Lambert scattering due to the roughness of the surface and geometric specular reflection without edge diffraction.

The reverberation times $T_{30}$ in table 1 were evaluated from the decay curves using the slope of the regression line between $-5dB$ and $-35dB$ [6].

<table>
<thead>
<tr>
<th>example</th>
<th>125Hz</th>
<th>250Hz</th>
<th>500Hz</th>
<th>1kHz</th>
<th>2kHz</th>
<th>4kHz</th>
<th>geo</th>
<th>ray</th>
<th>sab</th>
<th>eyr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>0.519</td>
<td>0.646</td>
<td>0.891</td>
<td>1.184</td>
<td>1.330</td>
<td>1.370</td>
<td>1.259</td>
<td>1.238</td>
<td>0.238</td>
<td>0.126</td>
</tr>
<tr>
<td>Ib</td>
<td>0.478</td>
<td>0.569</td>
<td>0.711</td>
<td>0.839</td>
<td>0.890</td>
<td>0.901</td>
<td>0.880</td>
<td>0.733</td>
<td>0.234</td>
<td>0.120</td>
</tr>
<tr>
<td>II</td>
<td>1.262</td>
<td>1.338</td>
<td>1.445</td>
<td>1.652</td>
<td>1.964</td>
<td>2.195</td>
<td>2.207</td>
<td>2.157</td>
<td>1.209</td>
<td>1.139</td>
</tr>
<tr>
<td>III</td>
<td>0.389</td>
<td>0.429</td>
<td>0.466</td>
<td>0.493</td>
<td>0.501</td>
<td>0.511</td>
<td>0.526</td>
<td>0.551</td>
<td>0.281</td>
<td>0.212</td>
</tr>
</tbody>
</table>

In all octave bands the same values for absorption coefficients $\alpha$ and scattering coefficients $\sigma$ were used. The effect of edge diffraction is, for comparison, computed and displayed for the six octave bands from $125Hz$ up to $4kHz$.

Starting with the usual case of omnidirectional emission the $x_i$ of equation (2) all have the same value at $t = 0$. In all ARM-calculations 980 directional ranges were used that divide all possible sound directions - visualized as surface of a unit radius sphere - into 980 non-overlapping triangles.

The Three Example Rooms

The first example is a rectangular room of dimensions $15.8m \times 8m \times 4m$ with reflecting front and rear walls ($\alpha = 0.0$ in case Ia and $\alpha = 0.1$ in case Ib) and all other walls absorbing ($\alpha = 0.9$). Here no scattering due to roughness was modelled. This room type was chosen to investigate flutter echoes, one of the original aims with the development of ARM[2].

The second example is a typical classroom where flutter echoes may disturb speech intelligibility taken from [7] chosen as a practical example. This room is exactly rectangular shaped of size of $13.7m \times 7.8m \times 2.6m$ including several blackboards with a non-uniform absorption and main absorption on the ceiling. A scattering coefficient $\sigma = 0.1$ was assumed due to an often used thumb rule.

A third example is a room without parallel walls (See fig. 6) chosen as an example without the danger of extraordinary reverberation times due to flutter echoes and also to show that ARM can handle arbitrarily shaped polyhedral rooms. With absorbing floor and ceiling and all other walls reflecting this room has also a non-uniform distribution of absorption.

Results

In case I the wider reflection lobes at lower frequencies lead more sound energy from the flutter echo path between the front and rear walls to the other absorbing walls. This results in lower reverberation times at lower frequencies. In the lowest octave band the reverberation time $T_{30}$ deviates almost by the factor 2 (See tab. 1). For case Ia the reverberation times are even higher than in case Ib and differ more for different octave bands as the effect of edge diffraction is here not superposed by other effects.

The classroom II example shows (fig. 5) a rather good congruence of the decay curves and reverberation times of ARM with geometrical reflections and raytracing with geometrical reflections (Fig. 5 and tab. 1). Here also the edge diffraction at lower frequencies give more
FIGURE 5: Example Room II. The sound energy decay for different octave bands compared with values for geometric reflection model in the Classroom and the decays in a diffuse sound field according to Sabine and Eyring.

<table>
<thead>
<tr>
<th>i</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
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<td>0.0</td>
<td>0.0</td>
</tr>
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<tr>
<td>7</td>
<td>0.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

FIGURE 6: The coordinates and the shape of the room III without parallel walls. The floor and the ceiling is absorbing ($\alpha = 0.9$) and all other walls are reflecting ($\alpha = 0.1$). For all surfaces the roughness scattering coefficient is $\sigma = 0.1$.

The results of the third example (fig. 7) confirms the trends of the former examples. Here the effect of edge diffraction reduces the reverberation time by only about 25% as here the walls are not parallel. Again the decay curves of the lower frequencies are closer to Sabine’s decay curve while the decay curve of higher frequencies approaches the simulations with geometric reflection without edge diffraction.

CONCLUSION AND OUTLOOK

The derived formula to describe edge diffraction at a flat polygon is particularly suitable for implementing in the algorithm of the Anisotropic Reverberation Model. With that, edge diffraction dependent reverberation times can be computed much faster than with raytracing; though, ray tracing had been used to validate the ARM results without edge diffraction.

There is a significant effect of edge diffraction on the reverberation time. The higher the frequency (approaching the optical limiting case of geometric reflections) the smaller the overall diffuseness to the sound field so that the assumptions for isotropy are better fulfilled. So for the lowest octave band the ARM decay curve is quite close to that of Sabine.

The results of the third example (fig. 7) confirms the trends of the former examples. Here the effect of edge diffraction reduces the reverberation time by only about 25% as here the walls are not parallel. Again the decay curves of the lower frequencies are closer to Sabine’s decay curve while the decay curve of higher frequencies approaches the simulations with geometric reflection without edge diffraction.
scattering effect, and the longer the reverberation time - especially in the critical cases of mutual parallel walls, where they may reach a multiple of the Sabine value; the lower the frequency the more diffuse are the reflections, and thus the reverberation time approaches the low Sabine or Eyring values. The effects are even strong if a realistic value for usual average scattering due to rough or sub-structured surfaces is assumed; even then, edge diffraction must not be neglected.

As the effects of edge diffraction is similar to that of scattering on a rough surface, this formula may be used to derive a coefficient that can be used like the scattering coefficient $\sigma$ in other room acoustical models.

The raytracing results do not substitute comparison with measurements, of course. Particularly the new ARM still has to show in such comparisons its applicability to practical room acoustics.

**REFERENCES**


