State-of-the-art in Determining the Absorption, Scattering and Diffusion Coefficients

by

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Coefficient Suite

Absorption

Diffusion

Scattering
Complete Performance Specs

Absorption Coefficient ISO 354: How much of the incident sound is absorbed (Must be measured full scale). Chairman Martijn Vercammen

Scattering Coefficient ISO 17497-1: How much of the incident sound is scattered (Can be measured in scale and calculated). Chairman Trevor Cox

Diffusion Coefficient ISO 17497-2: How uniformly is the incident sound scattered (Can be measured in scale and calculated). Chairman Trevor Cox
Calculation of the equivalent absorption area

\[ A = 55.3 \cdot V \left( \frac{1}{c_2 T_2} - \frac{1}{c_1 T_1} \right) \cdot 4V \left( m_2 - m_1 \right) \]

Calculation of the absorption coefficient:

\[ \alpha_s = \frac{A}{S} \]

\( m_1 \) = air attenuation empty

\( m_2 \) = air attenuation with sample

\( c_{1,2} \) = speed of sound

\( V \) = room volume

\( \alpha_s \) = random-incidence absorption coefficient

\( S \) = sample surface area

\( A \) = equivalent absorption area
Revision of ISO 354 Chaired by Martijn Vercammen (Peutz consultants, NL)

Round Robin 2009 (Wide disparity among labs and coefficients exceeding unity)

**Topics Under Discussion:**

**- Excess Absorption**

  - Correcting Edge Diffraction, primarily at low frequencies
  - Evaluate using Eyring instead of Sabine to reduce high frequency excess absorption
  - Correct for reduced mean free path \( (4V/S) \) caused by suspended diffusers and not accounted for in current calculations
    - Proposed boundary diffusors

**- Reproducibility**

  - Calibration of rev rooms using a reference absorber (reflector)

M.L.S. Vercammen, ISRA Proceedings 2010, Melbourne, Australia
13 laboratory round robin

Sample 1

Rockwool Type 211, 100 mm, density 44 kg/m3, wooden perimeter frame

ISO 354 2009

M.L.S. Vercammen, ISRA Proceedings 2010, Melbourne, Australia
Edge Effect

- This is related to the wavelength relative to the dimensions of the sample.
- The absorption of a finite sample is composed of the absorption of an infinite sample $\alpha_s$ and a factor $\beta$ multiplied by the edge length $E$.
- The graph shows the beta from experimental and theoretical studies.

A. de Bruijn, The edge effect of sound absorbing materials “revisited”, NAG 2007
• Clouds reduce the mean free path which is the basis of the Sabine equation

• One may correct the shorter mean free path occurring with clouds using a ray tracing program and correct the volume \( V = \frac{MFP \times S}{4} \)

• A calculation indicated 12% lower absorption using this reduced volume

\[
\frac{s}{55.3} \frac{V}{S} \frac{1}{c_2 T_2} \frac{1}{c_1 T_1} \frac{4V}{S} m_2 \quad m_1
\]

• Use of Eyring instead of Sabine, might prevent the high frequency excess above 1 (Error estimated at 0.03).

\[
\varepsilon \frac{S_0}{S} \exp \frac{V}{S_0} \frac{55.3}{c_1 T_1} 4m_1 \quad \exp \frac{V}{S_0} \frac{55.3}{c_2 T_2} 4m_2
\]

M.L.S. Vercammen, ISRA Proceedings 2010, Melbourne, Australia
With boundary diffusers, the known volume behind the diffusers can be subtracted to determine the correct room volume, $V$.

- Shadowing caused by hanging clouds is eliminated.
- The correct room surface area, $S_0$, can be used.
- Boundary diffusers result in higher diffusivity and standard deviation between mic-speaker pairs.

\[
\epsilon = \frac{S_0}{S} \exp \left( \frac{V}{S_0} \frac{55.3}{c_1 T_1} \right) 4m_1 \exp \left( \frac{V}{S_0} \frac{55.3}{c_2 T_2} \right) 4m_2
\]

M.R. Lautenbach, M.L.S. Vercammen, Proc. 20\textsuperscript{th} ICA, Sydney, Australia (August 2010)
Ceiling Clouds vs. Boundary Diffusers
Use of a standard absorber is proposed to calibrate measurement results of other samples and insure reproducibility among labs. D’Antonio has proposed use of a non-absorbing reference reflector of the same area & perimeter to calibrate a reference zero absorption and the use of Eyring instead of Sabine.
### Scattering Coefficient Relations: ISO 17497-1

Absorption coefficient on stationary table

\[
\alpha_s = 55.3 \frac{V}{S} \left( \frac{1}{c_1 T_1} - \frac{1}{c_2 T_2} \right) - \frac{4V}{S} (m_2 - m_1)
\]

Absorption coefficient on rotating table

\[
\alpha_{spec} = 55.3 \frac{V}{S} \left( \frac{1}{c_4 T_4} - \frac{1}{c_3 T_3} \right) - \frac{4V}{S} (m_4 - m_3)
\]

Scattering coefficient

\[
S = \frac{\alpha_{spec} - \alpha_s}{1 - \alpha_s} = 1 - \frac{E_{spec}}{E_{total}}
\]

- **V** is the volume of the reverberation room
- **S** is the area of the test sample
- **C\(_1,2,3,4\)** are the speed of sound in air during the measurement of T\(_1,2,3,4\)
- **m\(_1,2,3,4\)** are the energy attenuation coefficient of air in m\(^{-1}\) during the measurement of T\(_1,2,3,4\), respectively

<table>
<thead>
<tr>
<th>Reverberation time</th>
<th>Test sample</th>
<th>Turntable</th>
</tr>
</thead>
<tbody>
<tr>
<td>T(_1)</td>
<td>not present</td>
<td>not rotating</td>
</tr>
<tr>
<td>T(_2)</td>
<td>present</td>
<td>not rotating</td>
</tr>
<tr>
<td>T(_3)</td>
<td>not present</td>
<td>rotating</td>
</tr>
<tr>
<td>T(_4)</td>
<td>Present</td>
<td>rotating</td>
</tr>
</tbody>
</table>
Specular Separation

Frequency below the onset of scattering

No change with orientation

100 Hz

500 Hz

2 kHz

Propagation distance [m]

Impulse response [mPa]

Time [ms]

Orientation 1

Orientation 2
• Dual source/Multiple-mic simultaneous measurement method
  – Conventional measurements with two sources and 6 microphones results in long measurement times
  – If you are using a 3 sec MLS this results in a measurement time of 43 min (3s x 72 x 2 x 6)/60) for each rotating table measurement with and without sample, plus the traditional stationary table measurements
  – In larger chambers where a longer MLS is required these times are much longer
  – By using a dual source and simultaneously measuring the 6 mics this time is reduced to 3.6 min (3x72)/60) each

Brian Rife will describe the dual source theory in a presentation later in the session, as well as the relationship between the scattering and diffusion coefficient.
Commissioning: Sinusoid

- RPG (3/5 scale)
- ITA reduced scales average
  (1/10, 1/5, 2/5)
- KUL full scale
- Table scattering
- ISO table tolerance

Scattering coefficient

Frequency [Hz]

125 250 500 1k 2k 4k
Commissioning: Periodic Battens

Scattering coefficient vs. Frequency [Hz]

- RPG (round, 1/1.13 scale)
- RPG (square, 1/1.13 scale)
- Sakuma 2009 (round, scale 1/4)
- Table scattering
- ISO table tolerance

Frequency [Hz]: 125, 250, 500, 1k, 2k, 4k
Scattering coefficient: 0.2, 0.4, 0.6, 0.8, 1.0
Flush 2D Diffusors

Scattering coefficient vs Frequency [Hz]

- Periodic (2/3 scale)
- Aperiodic (2/3 scale)
- Table scattering
- ISO table tolerance
Limitations:

Fooled By Redirection

Measure arrays rather than single objects
Limitations: Sample Mounting

Measure either a circular sample with a rigid circumference or a square sample flush with the plane of the rotating table, which is more convenient for full scale commercial samples.
Limitations:

Sample height

$h \leq \frac{d}{16}$  Example: If $d=24”$, $h=1.5”$

Make sure the height does not exceed the table diameter $\frac{d}{16}$
Limitations:
1D vs 2D

ISO produces higher values for anisotropic (1D) surfaces and may not differentiate between 1D and 2D surfaces.
s_c can be determined from the cross correlation of the sample (red) and reflector (blue) polar responses

\[ s_c = 1 - \left( \frac{\sum_{i=1}^{n} p_1(\theta_i) p_0^*(\theta_i)}{\sum_{i=1}^{n} |p_1(\theta_i)|^2 \sum_{i=1}^{n} |p_0(\theta_i)|^2} \right)^2 \]

\( p_1 \) is the pressure scattered from the test surface

\( p_0 \) is the pressure scattered from the flat surface

denotes complex conjugate

\( \theta_i \) the receiver angle of the \( i^{th} \) measurement position, and

n is the number of measurements in the polar response
The specular zone or energetic scattering coefficient, $s_{sz}$, can be obtained from polar responses:

$E_{\text{spec}}$ is the energy in the specular zone of a polar response.

$E_{\text{total}}$ is the total energy under the polar response.

$s_{sz}$ will consider edge diffraction and surface roughness as diffusion.

To eliminate the edge diffraction, one can subtract $s_{sz}(r)$ of a reflector of similar size from $s_{sz}(d)$ of a diffusing surface.

Then normalize by $[1-s_{sz}(r)]$, to provide a normalized specular zone scattering coefficient, $s_{n,sz}$.

$$s_{sz} = 1 - \frac{E_{\text{specular zone}}}{E_{\text{total}}}$$

$$s_{n,sz} = \frac{s_{sz}(d) - s_{sz}(r)}{[1 - s_{sz}(r)]}$$
Scattering vs Diffusion

The batten polar response at the structural wavelength frequency of 2000 Hz illustrates why the scattering coefficient is high in that energy is scattered away from the specular zone. It also shows why the diffusion coefficient is poor and non-uniform.
Scattering silliness

Here is an example of data presented in a specification

At 3150 Hz, the absorption coefficient is 0.87, which means there is 13% of the incident energy left to be scattered

The scattering coefficient, which is incorrect according to ISO 17497-1 because absorption is greater than 0.5, is 0.53

Therefore, 6.9% of the energy is scattered in non-specular directions

And the product is called an absorber and diffuser!
Diffusion Coefficient: ISO 17497-2

\[ d_{\psi} = \frac{\left( \sum_{i=1}^{n} 10^{L_{i}/10} \right)^2 - \sum_{i=1}^{n} \left( 10^{L_{i}/10} \right)^2}{(n-1) \sum_{i=1}^{n} \left( 10^{L_{i}/10} \right)^2} \]
Extraction of scattered sound

\[ h_4(t) = IFT \left\{ \frac{FT[h_1(t) - h_2(t)]}{FT[h_3(t)]} \right\} \]

Sample background subtraction with oversampling suggested by Robinson
• Presentation template

• The Diffusion Coefficient measured in free space includes contribution from:
  – Surface topology
  – Edge Diffraction

• To remove the edge diffraction, we calculate

\[ d_n = \frac{(d_d - d_r)}{(1 - d_r)} \]
**Improvements:**

**Goniometer Optimization**

**Given:**
- L, W, H of measurement room
- (5) 120x120 mm samples
- 360° specular zone (7 mics normal incidence)
- 4 ms minimum reflection free zone in impulse response

**Find:**
- Specular Zone for all angles of incidence
- Reflection Free Zone (RFZ) for all angles of incidence
- Optimal Speaker radius
- Optimal Mic radius

**Result:**
- Allowable sample width increased by 40% with no widening of specular zone
- Reflection arrivals are balanced to arrive at least 2 ms after direct sound and approximately 2 ms before room reflections
Improvements:

1983-1993: Single Mic, Full Scale
1994: Multiple Mics, 1:5 Scale

Single microphone was moved 37 times at 5 degree angular increments to collect 37 impulse responses.

TEF was set to automatic delay and operator had to run into the reflection free zone, move the mic and run out of the RFZ!! The precursor to P90X!

MLS stimulus emitted 37 times with automatic sequential microphone switcher
• 32 channels of preamps
• 32 channel simultaneous hard disk recording of scattered sounds, using an MLS stimulus
• 32 simultaneous MLS measurements reduces measurement time to 3 s for each sample, background and reference reflector
• Impulse responses are obtained by deconvolution with MLS stimulus
• Automatic data reduction to subtract background, deconvolve mic/speaker response, gate scattered sound and generate polars and diffusion coefficient
Deconvolved Impulse Responses

- Direct Sound to 32 mics
- Scattered Sound
- Reflection Free Zone
- Room Sound
Hemi-Cylinder Reproducibility

Frequency, Hz

Diffusion Coefficient

-0.2 0.2 0.4 0.6 0.8 1.0

100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3200 4000

HCL3A _8_21_2008  HCL3a_4_9_2010  Standard Deviation
Sensitivity

Diffusion Coefficient vs. Frequency, Hz

- OMS3A 001
- OMF3A 123A
- OM43A 123B
A specular zone occurs because we can never practically be in the far field.

There is a compromise between minimizing the specular zone and measuring a sufficiently large array to account for grating lobes.

After 4 periods, periodicity effects are minimized.

Goniometers should be designed to measure 4 periods and maintain 80% of the mics outside the specular zone (360° specular zone).
Limitations:

Boundary Plane Measurement

Figure 4.7 Top row: boundary plane measurement and below that the equivalent image source configuration. Left column: extruded sample; right column: non-extruded surface. The insert shows distances used for calculating maximum frequency.

Boundary measurement includes mirror image sample. Not a problem in anechoic chamber.
• The diffusion industry has grown since the early 1980s and there are many products on the market claimed to be diffusers

• There is evidence, however, that some published diffusion coefficients are fabricated and/or polars are improperly interpreted

• If polars are actually measured, it is for 1 unit, instead of an array as required in the standard to account for grating lobes

• Therefore, you should request the complete normalized diffusion coefficients, with polars for 4 samples and reference reflector and a photo of the measurement setup!
...This is only the beginning!