Laboratory and In Situ Sound Absorption Measurement under a Synthetized Diffuse Acoustic Field: a Case Study on Five Materials

Olivier Robin, Celse Kafui Amedin, Alain Berry, Noureddine Atalla, Olivier Doutres and Franck Sgard
• Random-incidence sound absorption coefficients or Sabine absorption coefficients are estimated in reverberant chambers following standards (ASTM C423, ISO 354)

• The reverberation times with and without a sample ($T_{sample}$ and $T_0$, respectively) are measured, then the absorption coefficient is deduced following

$$\alpha = \frac{55.3 \, V}{c_0 \, S} \left[ \frac{1}{T_{sample}} - \frac{1}{T_0} \right]$$

with $V$ the room volume and $S$ the sample area

A first issue...

ASTM C423: $V=125 \, \text{m}^3$ minimum - $S=6.7 \, \text{m}^2$

ISO 354: $V=150 \, \text{m}^3$ minimum - $S=12 \, \text{m}^2$
A second issue...

This measurement is highly dependent on sample size and arrangement, with possible overestimation of measured coefficient (non-physical result >1) - not to be directly used in room acoustics simulation.

**DEPENDENCE OF SOUND ABSORPTION UPON THE AREA AND DISTRIBUTION OF THE ABSORBENT MATERIAL**

By V. L. Chrisler

Journal of research of the national bureau of standards, RP700, **1934**

**ABSTRACT**

This paper contains a report of work on sound absorption where large areas of absorbent material are installed. The measurements show that under these conditions it is impossible to obtain a logarithmic decay, hence the sound absorption is less than would be expected from the absorption coefficient of the material. Measurements were also made on very small areas. In this case the absorption was more than would be expected from the coefficient determined by measuring the absorption of an area of 72 square feet.
Introduction - context

A third issue... This measurement shows a poor interlaboratory reproducibility (depending on room size, diffusers effect).

A fourth issue... This method can not be applied in situ.
A method for estimating the sound absorption coefficient of a material under a synthesized Diffuse Acoustic Field (DAF) was recently proposed. Experimental and simulations results concerning the estimation of the sound absorption coefficient of five different materials using this method in laboratory and \textit{in situ} conditions will be summarized.

**Introduction - context**

Main advantages:
- No need to prepare samples (perimeter sealing)
- Smaller samples can be tested
- Estimation is made at a post-processing step, making it flexible (the excitation can be numerically varied)

Main drawback: a low frequency limitation
Absorption coefficient under a single point source

Using a pair of microphones \((M_1 - M_2)\) and a point source of volume velocity \(q_i\)

- At microphone \(j\) for a \(i\)-position of the source, the acoustic pressure \(p_{ij}\) is

\[
\tilde{p}_{ij}(\theta_i, \omega) = \rho_0 q_i(\omega) e^{-jk_0 r_{ij}} + R(\theta_i, \omega) \rho_0 q_i(\omega) e^{-jk_0 r'_{ij}}
\]

- Measuring \(H(\theta_i, \omega)\), the transfer function between the acoustic pressure at each microphone gives

\[
R(\theta_i, \omega) = \frac{e^{-jk_0 r_{i1}}}{r_{i1}} - H(\theta_i, \omega) \frac{e^{-jk_0 r_{i2}}}{r_{i2}}
\]

\[
H(\theta_i, \omega) \frac{e^{-jk_0 r'_{i1}}}{r'_{i1}} - \frac{e^{-jk_0 r'_{i2}}}{r'_{i2}}
\]

The absorption coefficient \(\alpha(\theta_i, \omega) = 1 - |R(\theta_i, \omega)|^2\)
Reflection coefficient under a virtual array

With a fixed microphone doublet and a mobile point source

Source position # 1: Measuring $H(\theta_1, \omega)$, ratio of the acoustic pressure at the two microphones, allows estimating $R(\theta_1, \omega)$

$$R(\theta_1, \omega) = \frac{e^{-jk_0r_{12}}}{r_{12}} - \frac{H(\theta_1, \omega)e^{-jk_0r_{11}}}{r_{11}} \cdot \frac{H(\theta_1, \omega)e^{-jk_0r'_{11}}}{r'_{11}} - \frac{e^{-jk_0r'_{12}}}{r'_{12}}.$$
Reflection coefficient under a virtual array

With a fixed microphone doublet and a mobile point source

Source position #2: Measuring $H(\theta_2, \omega)$, ratio of the acoustic pressure at the two microphones, allows estimating $R(\theta_2, \omega)$

\[
R(\theta_2, \omega) = \frac{e^{-jk_0r_{22}}}{r_{22}} - H(\theta_2, \omega)\frac{e^{-jk_0r_{21}}}{r_{21}}
\]

\[
\frac{H(\theta_2, \omega)\frac{e^{-jk_0r'_{21}}}{r'_{21}} - \frac{e^{-jk_0r'_{22}}}{r'_{22}}}{H(\theta_2, \omega)\frac{e^{-jk_0r'_{21}}}{r'_{21}} - \frac{e^{-jk_0r'_{22}}}{r'_{22}}}
\]
Reflection coefficient under a virtual array

With a fixed microphone doublet and a mobile point source

Source position $i$: Measuring $H(\theta_i, \omega)$, ratio of the acoustic pressure at the two microphones, allows estimating $R(\theta_i, \omega)$

$$R(\theta_i, \omega) = \frac{e^{-jk_0r_{i2}} - H(\theta_i, \omega)e^{-jk_0r_{i1}}}{H(\theta_i, \omega)\frac{e^{-jk_0r'_{i1}}}{r'_{i1}} - \frac{e^{-jk_0r'_{i2}}}{r'_{i2}}}$$

>a database of measured reflection coefficients at various incidence angles is generated

>a virtual array of monopoles is created in front of the material
Reflection coefficient under a virtual array

Coupling a calculated matrix of source amplitudes $S_{QQ}$ to the previously measured reflection coefficients database in a post processing phase allows estimating the absorption coefficient under a synthetic DAF.

**Measurement of** $R(\theta_i, \omega)$
(coefficients included in the $h_1$ term below)

Squared reflection coefficient under a synthetic pressure field

$$|R_{\text{synth}}(\omega)|^2 = \frac{h_1^H S_{QQ} h_1}{g_1^H S_{QQ} g_1}$$

Absorption coefficient under a synthetic pressure field

$$\alpha_{\text{synth}}(\omega) = 1 - |R_{\text{synth}}(\omega)|^2$$
Numerical simulations: summary

- **Main objective:** Studying sample size effect, and array size and height effect

- A finite element model is used to calculate the complex acoustic pressure at positions $z_1$ and $z_2$ (microphones positions), under a monopole source positioned at various heights

- Reflection coefficients for ten source positions are calculated (deduced for other source positions by simple symmetry considerations)

- A melamine foam with similar parameters as the one experimentally tested is considered

- Results are compared with TMM calculations (‘$\infty$’ material) or with experimental results for different sample sizes or array sizes
Numerical simulations: sample size effect

Material of sidelenight 0.22 m (four times smaller than the synthetic array)

FEM result ≡ numerical simulation of the method / TMM ≡ theoretical result for ∞ material

Melamine sample

\[ L_{array} \]
Numerical simulations: sample size effect

Material of sidelength 0.45 m (two times smaller than the synthetic array)

FEM result \equiv\ numerical simulation of the method – TMM \equiv\ theoretical result for \infty material

![Graph showing absorption coefficient vs. frequency for different thicknesses of Melamine sample.

\( L_{array} \)

Melamine sample

![Diagram of a Melamine sample with an array of points.](Image)
Numerical simulations: sample size effect

Material of sidelength 0.9 m (same size than the synthetic array)

FEM result $\equiv$ numerical simulation of the method / TMM $\equiv$ theoretical result for $\infty$ material

![Graph showing absorption coefficient vs. frequency for different thicknesses of Melamine sample.](image)

$L_{\text{array}}$

- FEM result - 1in. thick
- FEM result - 2in. thick
- FEM result - 3in. thick
- TMM result - 1in. thick
- TMM result - 2in. thick
- TMM result - 3in. thick

Absorption coefficient [-]

Frequency [Hz]

Melamine sample
Numerical simulations: sample size effect

Material of sidelength 1.8 m (two times larger than the synthetic array)

FEM result ≡ numerical simulation of the method / TMM ≡ theoretical result for ∞ material
Numerical simulations: sample size effect

Material of sidelong 3.6 m (four times larger than the synthetic array)

FEM result \equiv \text{numerical simulation of the method} / \text{TMM} \equiv \text{theoretical result for } \infty \text{ material}
Numerical simulations: sample size effect

Consistent results with other works

Simulation of the effect of specimen area on a glasswool (Hirosawa et al., JASA 2009)

Measurement with a plane wave synthesis on a melamine foam (Yankai et al., ICSV 2016).
Numerical simulations: array height effect

- For a fixed array size, its height is now increased
- Simulation results for a 2-inch thick melamine foam
- 9x9 source array, $h_2 > h_1$, $\theta_2 < \theta_1$

$\theta_1$ $\theta_2$

$\theta_{\text{max}} = 77^\circ$

$\theta_{\text{max}} = 46^\circ$

Sample to be tested
Numerical simulations: height/size effect

For a fixed array side length, increasing the array height has the same consequence as reducing the array side length for a fixed array height: the highest incidence angle included in the database becomes lower.

\[ \theta_1 = \theta_2 \]

Sample to be tested

![Graph showing absorption coefficient vs frequency for different heights and source array configurations.](image)
Tested materials

1: melamine foam
2: fiberglass
3: high-density fiberglass board
4: PU foam
5: ceiling tiles

But 6: Mineral wool was also tested

Initially five...
Tested materials

Materials were characterized at GAUS laboratory

<table>
<thead>
<tr>
<th>Material</th>
<th>Tortuosity $\alpha_\infty$ [-]</th>
<th>Porosity $\phi$ [-]</th>
<th>Resistivity $\sigma$ [Nm$^{-4}$s]</th>
<th>Viscous length $\Lambda$ [$\mu$m]</th>
<th>Thermal length $\Lambda'$ [$\mu$m]</th>
<th>Foam mass density $\rho_1$ [kg.m$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melamine foam</td>
<td>1</td>
<td>0.98</td>
<td>7920</td>
<td>132</td>
<td>149</td>
<td>6.1</td>
</tr>
<tr>
<td>Fiberglass</td>
<td>1</td>
<td>0.99</td>
<td>4860</td>
<td>225</td>
<td>388</td>
<td>10</td>
</tr>
<tr>
<td>HDFB</td>
<td>1</td>
<td>0.96</td>
<td>22200</td>
<td>57</td>
<td>115</td>
<td>66</td>
</tr>
<tr>
<td>PU foam</td>
<td>2.95</td>
<td>0.96</td>
<td>9770</td>
<td>123</td>
<td>227</td>
<td>29.8</td>
</tr>
<tr>
<td>Tiles</td>
<td>&gt; 4</td>
<td>0.82</td>
<td>&gt; 1e6</td>
<td>25</td>
<td>60</td>
<td>210</td>
</tr>
</tbody>
</table>

Measurements made using reverberant room and proposed method
Tested materials

The final setup:
- A 7 x 7 virtual array, with sources spaced by 0.15 m in both directions
- A source translated at a height 0.2 m to include large incidence angles
- A microphone triplet, instead of a doublet, in order to cover the whole frequency range (a microphone spacing of 50 mm up to 3150 Hz [1 -> 3], and a microphone spacing of 25 mm above [1 -> 2])
- The microphone permutation technique is used to improve accuracy at low frequency (phase mismatch reduction)
- A swept sine signal is used to improve signal to noise ratio
Laboratory measurements

Comparative results for the rigid fiberglass panel
Laboratory measurements

Comparative results for the polyurethane foam

![Graph showing comparative results for the polyurethane foam. The graph compares sound absorption coefficient across different frequencies for Reverberant room method, Proposed method, and TMM simulation (infinite material).]
Laboratory measurements

Comparative results for the glass wool

![Graph showing sound absorption coefficient vs. frequency for different methods: Reverberant room method, Proposed method, TMM simulation (infinite material).]
Laboratory measurements

Comparative results for the mineral wool

[Graph showing sound absorption coefficient vs frequency for different methods: Reverberant room method, Proposed method, TMM simulation (infinite material).]
Laboratory measurements

Comparative results for the ceiling tiles

![Graph showing sound absorption coefficient vs frequency for two methods: Reverberant room method and Proposed method. The graph illustrates the performance of ceiling tiles across different frequency ranges.](image-url)
**In situ measurements**

Two out-of-laboratory spaces were considered *(tests were only made once)*:

1. A small workspace of 100 m³ volume — small reverberation time, many reflective surfaces close to the measurement zone.
2. A large fabrication shop of 3500 m³ volume — large reverberation time, reflective surfaces are away from measurement zone.

Control microphone to monitor SPL, estimate reverberation time and an additional perturbation sound source (for one material).
**In situ measurements**

- **Background noise (hemi-anechoic room)**
- **Background noise (room #1)**
- **Background noise (room #2)**

Measured reverberation times

<table>
<thead>
<tr>
<th>1/3 octave band</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1 kHz</th>
<th>2 kHz</th>
<th>4 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room #1</td>
<td>0,47 s</td>
<td>0,37 s</td>
<td>0,47 s</td>
<td>0,32 s</td>
<td>0,46 s</td>
<td>0,39 s</td>
</tr>
<tr>
<td>Room #2</td>
<td>-</td>
<td>1,1 s</td>
<td>1,29 s</td>
<td>0,83 s</td>
<td>0,66 s</td>
<td></td>
</tr>
</tbody>
</table>
In situ measurements

Comparative results for the rigid fiberglass panel

![Graph showing sound absorption coefficient vs frequency for different environments.](image)

- Hemi-anechoic room
- Room #1 (no additional noise)
- Room #1 (additional noise)
- Room #2
- TMM simulation

Additional noise effect
In situ measurements

Comparative results for the polyurethane foam

Some calculation errors due to unwanted acoustic reflections provide large negative values at specific frequencies.
In situ measurements

Comparative results for the polyurethane foam
In situ measurements

Comparative results for the melamine foam

Some calculation errors due to reflections or large background noise provide large negative values at specific frequencies.
In situ measurements

Comparative results for the melamine foam

Effect of a strong tonal noise from a fan
In situ measurements

Comparative results for the glass wool

![Graph showing sound absorption coefficient vs. frequency for different conditions: Hemi-anechoic room, Room #1, Room #2, and TMM simulation. The graph displays data points and curves indicating the absorption coefficients across various frequencies.]
Improvement of the method?

The simplified sound propagation model is the main source of discrepancies at low frequency, at low frequency and for small source heights -> provide values of $|R| > 1$ then $\alpha < 0$

Dragonetti et al., Applied Ac. 2015

$\alpha = \frac{h}{\theta} = 0.75$ m

Such a low frequency limit is also met in other in situ works

Ducourneau et al., Applied Ac. 2009

Directional 13 microphone array
Improvement of the method?

- The **Nobile-Hayek model** is used with an estimation of the reflection coefficient following an **acoustic power balance**, and compared with the classical spherical wave hypothesis and a sound pressure ratio.
- Measurements were post-processed for two point source positions: 1 = (0 cm, 0 cm); 2 = (15 cm, 15 cm)

![Rigid fiberglass panel](image)
Improvement of the method?

- The Nobile-Hayek model is used with an estimation of the reflection coefficient following an acoustic power balance, and compared with the classical spherical wave hypothesis and a sound pressure ratio.
- Measurements were post-processed for two point source positions: 1 = (0 cm, 0 cm); 2 = (15 cm, 15 cm).

**Polyurethane foam**

![Graphs showing absorption coefficient against frequency for two positions](image.png)

<table>
<thead>
<tr>
<th>Position</th>
<th>Polyurethane foam</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
Conclusion

- A method for the estimation of the absorption coefficient of an absorbing material under a synthesized DAF excitation in free-field conditions was presented.

- Concerning laboratory measurements: the method allows testing smaller samples than with the standard method, and always provides physical values ($\alpha \leq 1$) – no specific preparation of samples is needed.

- Concerning in situ measurements: the great majority of the obtained results are in line with those measured in lab conditions – the presence of close reflective surfaces is more crucial than an important background noise level.

- Perspectives:
  1. Improving the post-processing step to solve the low-frequency issue.
  2. Adding automatic source and microphone translation systems to improve accuracy, repeatability, and reduce measurement time.
• Thank you for your attention
• Questions?
• Funding from IRSST is greatly acknowledged
• Enjoy SAPEM 2017
Laboratory measurements

Case of ceiling tiles with and without plenum
Laboratory measurements

Comparative results for the ceiling tiles with and without plenum
Numerical simulations: array size effect

- Array size is reduced at post-processing with fixed height, which reduces the highest incidence angle $\theta_{\text{max}}$

- Satisfactory agreement between results and simulations above the 1/3 octave band that nearly corresponds to the lowest frequency that could be reproduced ($\approx c_0/L_{\text{array}}$, see).

Using a database including the highest incidence angle, the absorption coefficient under a DAF excitation with other incidence angles can be then computed.
- Is the synthesis effective?
Tested materials

Simulation results following Transfer Matrix Method (infinite material)
Laboratory measurements

Measurements in reverberant room results (following ASTM C423), samples of minimum 6.7 m² area (72 sq ft)
Laboratory measurements

Measurements in anechoic room following the proposed method, using samples of 1.4 – 1.7 m²

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**Diagram Description:**
- **Y-axis:** Coefficient d'absorption
- **X-axis:** Frequency (Hz)
- **Graphs:**
  - Melamine foam
  - Polyurethane foam
  - Rigid fiberglass panel
  - Ceiling tiles
  - Glasswool
  - Rockwool

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Additional notes or details (if any):
Numerical simulations: height/size effect

- For a fixed array side length, increasing the array height has the same consequence as reducing the array side length for a fixed array height: the highest incidence angle included in the database becomes lower.