Acoustic absorption applied to materials

« Exotic » acoustic resonators

F. Simon, "Low frequency sound absorption of resonators with flexible tubes", ICA 2013
Context

Noise radiated by aircraft engines

Acoustic absorption of fan noise using porous liners in engine nacelle in presence of grazing flow and high noise level (frequencies above 2000 Hz)

Future Ultra High Bypass Ratio (UHBR) engines with shorter and thinner nacelles (frequencies around 500 Hz)

New types of liner needed
### Porous liner for aircraft engine

Classically: Perforated plate / wiremesh above honeycomb (SDOF/ 2DOF liners)

<table>
<thead>
<tr>
<th>Resistive plate</th>
<th>$\sigma$ (%)</th>
<th>$l$ (mm)</th>
<th>$d$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perforated plate</td>
<td>5 - 20</td>
<td>0.5 – 2.5</td>
<td>1 - 2</td>
</tr>
<tr>
<td>Micro-perforated plate</td>
<td>2 - 5</td>
<td>0.8 – 1.5</td>
<td>0.1 – 0.4</td>
</tr>
<tr>
<td>Honeycomb</td>
<td></td>
<td></td>
<td>L = 15 - 30 mm / Cells 3/8 inch</td>
</tr>
</tbody>
</table>

Absorption around 2 to 3 kHz

Alternative: Perforated plate **with flexible hollow tubes** above honeycomb

– to shift the resonance frequency to a lower frequency by a prolongation of air column length

**Liner with hollow tubes in cavity**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Plate thickness</th>
<th>Plate porosity</th>
<th>Number of tubes</th>
<th>Inner radius of tubes</th>
<th>Outer radius of tubes</th>
<th>Tube length</th>
<th>Cavity filling factor</th>
<th>Cavity thickness</th>
<th>Cavity radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>$l_p$</td>
<td>$\sigma_p$</td>
<td>$n$</td>
<td>$r_i$</td>
<td>$r_e$</td>
<td>$l_t$</td>
<td>$\sigma_t$</td>
<td>$h$</td>
<td>$r_c$</td>
</tr>
</tbody>
</table>

Diagram: Incident waves and Reflected waves through the cavity with perforated plate and flexible tubes.
Proposed theory

- Pressure field along tubes (x direction):

\[ p(x, r) = A \cos(q_r r) \left( e^{iqx} + e^{-iqx} \right) \]

with \( q_r \) and \( q \) the transverse and axial propagation constants

- If \( q_r r_i << 1 \): \[ q_r^2 = \left( \frac{\omega}{c} \right)^2 = -\frac{(\gamma - 1)F(k_h r_i) + F(k_v r_i)}{1 - F(k_v r_i)} \]

where \( F(X) = \frac{\tan(X)}{X} \)

\[ \begin{align*}
  k_h &= \frac{1+i}{\delta_h} \quad \text{where} \quad \delta_h = \sqrt{\frac{2K}{\rho C_p \omega}} \quad \text{(thermal boundary layer thickness)} \\
  k_v &= \frac{1+i}{\delta_v} \quad \text{where} \quad \delta_v = \sqrt{\frac{2\mu}{\rho \omega}} \quad \text{(viscous boundary layer thickness)}
\end{align*} \]

Average axial velocity:

\[ u_x = \frac{A q}{\omega p} \left( 1 - F(k_v r_i) \right) (e^{iqx} - e^{-iqx}) \]

For narrow channels:

\[ q = \left( \frac{\omega}{c} \right) \sqrt{\frac{1 + (\gamma - 1)F(k_h r_i)}{1 - F(k_v r_i)}} \quad (*) \]

* For circular tubes, Bessel functions instead of \( F(X) \)
Proposed theory

Hypotheses:
• All holes connected
• Continuity of pressure and mass flow between narrow channels and the surrounding cavity
• Transmitted waves in cavity, without loss, in the direction of thickness
• Total length: tube length + cavity thickness

Main parameters:
• Cavity filling factor \( \sigma_t = \frac{\text{Total surface of mass flow}}{\text{Air cavity area}} \)
• Cavity thickness \( h \)

Output:
• Specific reactance \( x_s = \text{Im} \left( \frac{Z_c}{\rho c} \right) = \text{Im} \left( \frac{Z_t}{\rho c \sigma_p} \right) \) with \( Z_t \) impedance at the opening of narrow channels
## Configurations of tested liners

### « Flexible » tubes

```
<table>
<thead>
<tr>
<th>Parameter</th>
<th>( l_p (\text{mm}) )</th>
<th>( \sigma_p (%) )</th>
<th>( n )</th>
<th>( r_i (\text{mm}) )</th>
<th>( r_e (\text{mm}) )</th>
<th>( l_t (\text{mm}) )</th>
<th>( \sigma_t )</th>
<th>( H (\text{mm}) )</th>
<th>( r_c (\text{mm}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>1</td>
<td>1.92</td>
<td>73</td>
<td>0.35</td>
<td>0.55</td>
<td>Variable: 2</td>
<td>35.9</td>
<td>43.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10-20-30-60-90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

### « Mansart » project

### « Rigid » tubes

```
<table>
<thead>
<tr>
<th>Parameter</th>
<th>( l_p (\text{mm}) )</th>
<th>( \sigma_p (%) )</th>
<th>( n )</th>
<th>( r_i (\text{mm}) )</th>
<th>( r_e (\text{mm}) )</th>
<th>( l_t (\text{mm}) )</th>
<th>( \sigma_t )</th>
<th>( H (\text{mm}) )</th>
<th>( r_c (\text{mm}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>/</td>
<td>5.2</td>
<td>/</td>
<td>0.5</td>
<td>0.91</td>
<td>17</td>
<td>/</td>
<td>30</td>
<td>43.2</td>
</tr>
<tr>
<td></td>
<td>10-20-30-60-90</td>
<td></td>
<td></td>
<td></td>
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</tr>
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</table>
```

### « Coralie » project
“Mansart” samples: Effect of SPL (dB) on absorption coefficient

Experimentation

Non-linearity

Linearity

<table>
<thead>
<tr>
<th>Non-linearity</th>
<th>Linearity</th>
</tr>
</thead>
<tbody>
<tr>
<td>133.0 dB (100-2500 Hz)</td>
<td>163.0 dB (100-2500 Hz)</td>
</tr>
<tr>
<td>123.0 dB (100-2500 Hz)</td>
<td>123.5 dB (100-2500 Hz)</td>
</tr>
<tr>
<td>113.0 dB (100-2500 Hz)</td>
<td>114.0 dB (100-2500 Hz)</td>
</tr>
<tr>
<td>104.5 dB (100-2500 Hz)</td>
<td>104.8 dB (100-2500 Hz)</td>
</tr>
</tbody>
</table>

36 mm

36 mm
“Mansart” samples vs. classical resonator: Effect of tube length on absorption coefficient

- To increase the tube length to decrease the frequency range of absorption
  - But reduction of absorption coefficient
“Mansart” and “Coralie” samples: Simulation / experimentation of reactance
```
“Equivalent” classical resonators: Simulation of reactance

- Simu. "Mansart Classical resonator" 130 mm
- Simu. "Mansart Classical resonator" 220 mm
- Simu. "Mansart Classical resonator" 280 mm
- Simu. "Coralie Classical resonator" 130 mm

Thickness "classical resonator" \( \frac{\text{Thickness }"\text{new resonator}"}{\text{Thickness }"\text{new resonator}"} = 4 \text{ to } 8 \).
```
“Coralie” sample with “closed tubes”:
Effect of SPL (dB) on absorption coefficient

- Non-linearity in low frequency band
- High absorption in high frequency band
“Coralie” sample with “closed tubes”:
Simulation / experimentation of reactance

Non-linearity

- Exp. 117 dB (100-6400 Hz)
- Exp. 127 dB (100-6400 Hz)
- Exp. 137 dB (100-6400 Hz)
- Simu. "closed tube"
Conclusion

• Introduction of tubes in a cavity of a conventional resonator generates a significant shift of the frequency range of absorption towards lower frequencies
  – Effect of prolongation of air column length

• Determination of resonance frequency with dimensional parameters as for conventional resonator
  – Unsuitable Lu et al. and Helmholtz formulation

• Applied for an aeronautical liner:
  – Resonance frequency decreases of about 1/5
  – Linear behavior (no dependence in SPL)
Acoustic absorption applied to materials

« Thermoacoustic » materials
Fluctuation of pressure linked to fluctuation of temperature

Problème : Pour 20 Pa : ΔT=0.02 °C (air)
« It is possible to produce a sound by a gradient of temperature »

Tube de Rijke (1859)

Historical experiment

Practical cases

In our days: thermoacoustic heat engine
Principle of thermoacoustic heat engine with Stirling engine (1816)
"It is possible to produce a gradient of temperature by a sound."

Principle of "acoustic refrigerator"

\[ \Delta T = \left( \dot{P}_0 T_0 \beta T / \rho_0 C_p \right) \Delta P \]

(Le Châtelier law)
Acoustic refrigerator

\[ \Delta T(x) > 0 \text{ si } \Delta p(x) > 0 \]
\[ \Delta T(x) < 0 \text{ si } \Delta p(x) < 0 \]
(hypothesis: \( L < \lambda/4 \))

« To use acoustic power for pumping heat »

\( \Delta T : \) thermal gradient in structure
Examples of Acoustic refrigerators
Acoustic absorption with thermoacoustic gradient (experiment)

<table>
<thead>
<tr>
<th>Dimensions du régénérateur</th>
<th>Diamètre des canaux (mm)</th>
<th>Epaisseur inter-canaux (mm)</th>
<th>Diamètre du régénérateur</th>
<th>Longueur du régénérateur (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>0,34</td>
<td>39,8</td>
<td>50</td>
</tr>
</tbody>
</table>

- Montage expérimental:

Haut-parleur

microphones

thermocouples

Porte-échantillon

Tube à impédance
Acoustic absorption with thermoacoustic gradient (experiment)

Acoustic absorption

Gradient of temperature
Porous metamaterials as « noise barriers »

**Context**

- Concept of "metamaterial" developed initially in the electromagnetic field
- Recent extension in acoustic domain:
  Artificial structures to reproduce various phenomena: barrier, cloaking, Lens


Cloaking: « F. Delrieu – Stage Master Onera 2012 »

• Most studies are "Sonic Crystals" (SC):
  – composed of a periodic lattice:

  ![Diagram of Sonic Crystals](image)

  i.e. cylinders distributed symmetrically and embedded in a fluid

  – Effect:
    • Attenuation of noise in a large frequency range (stop band) by interferences of scattered waves
    • Moving and increase of frequency range thanks to vacancies in the periodicity or by using quasi-fractal structures

• Generally: numerical studies (MST approach, FEM)

• Topic:
  – To generate a **numerical & experimental acoustic database** for different types of synthetic material including some typical fractals based on an initial metamaterial
**Fractal concept**

**Geometric shape** that can be split into parts, each of which is a **reduced-size copy of the whole** (self-similarity)

- i.e. Sierpinski-Menger carpet
- i.e. Vicsek fractal

- Acoustic or vibration effect as a local focus of energy (contrary to a global modal behavior)
Comparison of configurations

Simulated pressure field (dB) at 9000 Hz

- Cylinder
  - Porosity: 47%

- Classical meta
  - Porosity: 58%

- Sierpinsky fractal
  - Porosity: 58%

- Vicsek fractal
  - Porosity: 84%
Validation by experiments

Metamaterial with loudspeaker and intensity probe in anechoic room
Validation by experiments

Experimental pressure fields (dB) behind metamaterials at 6000 Hz

Same beam area whatever configuration
Validation by experiments

- With Vicsek fractal, shift of stop-band towards high frequencies
Conclusions

• Experimental validation of MST approach to represent the effect of 2D metamaterials as acoustic barriers
  – Classical metamaterial as sonic crystal: Stop-band around \( f = \frac{c}{2T} \)

• Interest of fractals to modify initial frequency range of reduction:
  – Fractal based on Sonic Crystal as Sierpinsky carpet: \textit{expansion} of stop-band
  – Vicsek fractal: shift toward high frequencies

• Perspective:
  – Test of other types of fractal (i.e. Cantor dust, H-fractal…)
  – Application of metamaterial in duct (effect of boundary conditions, mean flow, vortex shedding…)
Elastic materials as « acoustic cloak »

Context

- infinite rigid cylinder
- plane acoustic wave
- no scattering

Magnitude of the pressure field $|p_{ext}|$ around a cylinder excited by a unit plane wave
Different approaches

- Transformation method
  - anisotropic and inhomogeneous fluid
  - metamaterials

- Scattering cancellation
  - Multiple scattering

- Multilayered elastic coating


Scattering cancellation: multiple scattering

V. M. García-Chocano

- Obstacle: $\phi$ 22.5 cm
- 125 Cylinders : $\phi$ 1.5 cm
- F=3060 Hz

F. Delrieu
Master Onera 2012

- Obstacle: $\phi$ 30 cm
- 80 Cylinders : $\phi$ 2 cm
- F=3060 Hz
A passive device for acoustic scattering reduction using **layers of elastic materials**?

- infinite rigid cylinder
- acoustic plane wave
- orthotropic viscoelastic materials

- layers $\Rightarrow$ minimization of $p_{scat}$?
  $\Rightarrow$ optimization
Objective: evaluate the scattered pressure field in the exterior fluid

\[ p(r, \theta, \omega) = e^{-i\omega t} \sum_{n=0}^{\infty} \left[ p_0 i^n \epsilon_n J_n(kr) + A_n H_n(kr) \right] \cos(n\theta) \]

\[ A_n = -p_0 i^n \epsilon_n \frac{J_n'(kb)}{H_n'(kb)} + \rho c^2 k_b \frac{u_{r,n}^N(b)}{H_n'(kb)} \]

\[ u_{r,n}^N(b) \Rightarrow \text{Modeling of the vibrations of the multilayered coating} \]

\[ \Rightarrow \text{Development of semi-analytic vibro-acoustic models adapted to orthotropic multilayers} \]
Vibration of the elastic coating

Stress components on a cylindrical element

\[
\begin{pmatrix}
\sigma_{rr}^j \\
\sigma_{\theta\theta}^j \\
\sigma_{r\theta}^j
\end{pmatrix}
= \frac{1}{\rho_0 c_0^2}
\begin{pmatrix}
c_{11}^j & c_{12}^j & 0 \\
c_{12}^j & c_{22}^j & 0 \\
0 & 0 & c_{66}^j
\end{pmatrix}
\begin{pmatrix}
\varepsilon_{rr}^j \\
\varepsilon_{\theta\theta}^j \\
2\varepsilon_{r\theta}^j
\end{pmatrix}
\]
State space formulation

\[
\frac{\partial Y^j}{\partial r} = M^j Y^j
\]

with the state vector
\[
Y^j = \begin{pmatrix}
    u^j_q \\
    u^j_r \\
    \sigma^j_{rr} \\
    \sigma^j_{r\theta}
\end{pmatrix}
= \sum_{n=0}^{\infty}
\begin{pmatrix}
    u^j_{\theta,n}(r) \sin(n\theta) \\
    u^j_{r,n}(r) \cos(n\theta) \\
    \sigma^j_{r,n}(r) \cos(n\theta) \\
    \sigma^j_{r\theta,n}(r) \sin(n\theta)
\end{pmatrix}
\]

and the matrix
\[
M^j = \begin{pmatrix}
    \frac{1}{r} & -\frac{1}{r} \frac{\partial}{\partial \theta} & 0 & \frac{\rho_0 c_0^2}{c_{66}} \\
    -\frac{c_{12}^j}{c_{11}^j} \frac{1}{r} \frac{\partial}{\partial \theta} & -\frac{1}{r} \frac{c_{12}^j}{c_{11}^j} & \frac{\rho_0 c_0^2}{c_{66}} & 0 \\
    \frac{c_{12}^j}{r^2} \frac{\partial^2}{\partial \theta^2} & \frac{c_{12}^j}{r^2} \frac{\partial}{\partial \theta} & \frac{1}{r} \left( \frac{c_{12}^j}{c_{11}^j} - 1 \right) & -\frac{1}{r} \frac{\partial}{\partial \theta} \\
    -\frac{c_{12}^j}{r^2} \frac{\partial}{\partial \theta} & -\frac{c_{12}^j}{r^2} \frac{\partial^2}{\partial \theta^2} & \frac{c_{12}^j}{r} \frac{\partial}{\partial \theta} & -\frac{2}{r}
\end{pmatrix}
\]
Modal state space formulation

\[ \frac{dV^j_n}{dr} = P^j_n V^j_n \]

with the modal state vector \( V^j_n = (u^j_{\theta,n}, u^j_{r,n}, \sigma^j_{rr,n}, \sigma^j_{r\theta,n})^T \)

and the modal matrix

\[
P^j_n = \begin{pmatrix}
0 & \frac{n}{r} & \frac{\rho_0 \sigma_0^2}{c_{66}} \\
-\frac{c_{12}^j n}{c_{11}^j r} & \frac{1}{r} & \frac{\rho_j c_0^2}{c_{11}^j} \\
-\frac{c_{22}^j n}{r^2} & -\frac{\rho_j}{\rho_0} \omega^2 & \frac{1}{r} \left( \frac{c_{12}^j}{c_{11}^j} - 1 \right) \\
\frac{c_{22}^j n^2}{r^2} - \frac{\rho_j}{\rho_0} \omega^2 & \frac{c_{22}^j n}{r^2} & -\frac{2}{r}
\end{pmatrix}
\]

\[ \Rightarrow \quad V^j_n(r_j) = \exp \left[ \frac{h_j}{a} P^j_n(r_{j-1}) \right] V^j_n(r_{j-1}) \]

Continuity of displacements and stresses at the interfaces between the \( N \) layers.
Minimization of the scattering

Objective: find the mechanical and dimensional parameters of the elastic layers that provide omnidirectional scattering reduction

Optimization

- Objective function:

\[
\sigma_{\text{gain}} = 10 \log \left( \frac{\int_{(C)} l_{\text{sc}}^{(\text{cloak})} d\theta}{\int_{(C)} l_{\text{sc}}^{(\text{ref})} d\theta} \right)
\]

\[\rightarrow -\infty\]

- Variables:

\[ka, (h/a, \rho_s, E_r, E_\theta, \nu_r, \theta, G_r, \eta)_{j=1,N}\]

- Genetic algorithm (DAKOTA)
Optimization

Conditions on the variables:
- Exterior fluid: air
- Constraints: variable range $\rightarrow$ realistic materials
- Spring-mass analogy

Tested cases:
- Isotropic
- Orthotropic
- No $\sigma_{\text{gain}} < 0$ within the imposed range

light
compact
Bi-layer coating: orthotropic / isotropic

Best result for $a = 0.15$ m, $freq = 380$ Hz ($ka \approx 1.05$)

<table>
<thead>
<tr>
<th>layer</th>
<th>$h$ (mm)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$E_r$ (MPa)</th>
<th>$E_\theta$ (MPa)</th>
<th>$\nu_{r\theta}$</th>
<th>$G_{r\theta}$ (MPa)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>internal</td>
<td>2.4</td>
<td>100</td>
<td>0.1</td>
<td>0.8</td>
<td>0.4</td>
<td>0.25</td>
<td>0.5</td>
</tr>
<tr>
<td>external</td>
<td>0.6</td>
<td>1200</td>
<td>800</td>
<td>800</td>
<td>0.3</td>
<td>308</td>
<td>1</td>
</tr>
</tbody>
</table>

![Graph showing frequency response](image)
Bi-layer coating: orthotropic / isotropic

Pressure field $|p_{ext}|$, $a = 0.15$ m, $freq = 380$ Hz

<table>
<thead>
<tr>
<th>layer</th>
<th>$h$ (mm)</th>
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</table>
Bi-layer coating: orthotropic / isotropic
Bi-layer coating: orthotropic / isotropic

\[ f_0 = 380 \text{ Hz} \]

Without obstacle

With obstacle + cloak

Radial acoustic intensity

Radial structural intensity
A realizable bi-layer coating

- internal layer: orthotropic polyethylene foam
- external isotropic layer?

External layers allowing scattering reduction at $ka \approx 1.5$

$\sigma_{\text{gain}} < -3\text{dB}$

- $h_2/a=0.004$
- $h_2/a=0.008$
- $h_2/a=0.012$
- $h_2/a=0.016$
A realizable bi-layer coating: PE / PMP

Rigid cylinder of radius $a = 0.13$ m

<table>
<thead>
<tr>
<th>layer</th>
<th>$h$ (mm)</th>
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<th>$E_r$ (MPa)</th>
<th>$E_\theta$ (MPa)</th>
<th>$\nu_{r\theta}$</th>
<th>$G_{r\theta}$ (MPa)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>internal</td>
<td>13</td>
<td>89</td>
<td>1.2</td>
<td>14</td>
<td>0.3</td>
<td>0.1</td>
<td>11</td>
</tr>
<tr>
<td>external</td>
<td>1</td>
<td>835</td>
<td>1500</td>
<td>1500</td>
<td>0.3</td>
<td>577</td>
<td>9</td>
</tr>
</tbody>
</table>
A realizable bi-layer coating: PE / PMP

Pressure field $|p_{ext}|$, $a = 0.13$ m, $freq = 525$ Hz ($ka \simeq 1.26$)

<table>
<thead>
<tr>
<th>layer</th>
<th>$h$ (mm)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$E_r$ (MPa)</th>
<th>$E_\theta$ (MPa)</th>
<th>$\nu_{r\theta}$</th>
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<tr>
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<tr>
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<td>835</td>
<td>1500</td>
<td>1500</td>
<td>0.3</td>
<td>577</td>
<td>9</td>
</tr>
</tbody>
</table>

Uncloaked cylinder

Cloaked cylinder
Optimisation on a wider frequency range

Exemple : air, $a = 0.15$ m, $\Delta f = 450$ Hz

<table>
<thead>
<tr>
<th>cas</th>
<th>$E_2$ (MPa)</th>
<th>$\rho_2$ (kg/m$^3$)</th>
<th>$\nu_{r\theta,1}$</th>
<th>$\nu_{\theta z,1}$</th>
<th>$\nu_{rz,1}$</th>
<th>$G_{r\theta,1}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1249</td>
<td>660</td>
<td>0.36</td>
<td>0.34</td>
<td>0.25</td>
<td>0.971</td>
</tr>
<tr>
<td>B</td>
<td>1318</td>
<td>660</td>
<td>0.36</td>
<td>0.34</td>
<td>0.25</td>
<td>0.583</td>
</tr>
<tr>
<td>C</td>
<td>1665</td>
<td>660</td>
<td>0.21</td>
<td>0.25</td>
<td>0.38</td>
<td>0.749</td>
</tr>
</tbody>
</table>
Configuration with 4 layers

Exemple : eau, \( a = 4, 4 \) m, 4 couches isotropes

<table>
<thead>
<tr>
<th>couche</th>
<th>( h ) (mm)</th>
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<tr>
<td>2 et 4 : acier</td>
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<td>210.10(^3)</td>
<td>7820</td>
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Gain on diffraction \( \sigma_{gain} \) (dB)

Fréquence (kHz)
Configuration with 4 layers

Exemple : eau. \( a = 4 \), 4 m. 4 couches isotropes

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Gain en diffraction \( \sigma_{\text{gain}} \) (dB)

Fréquence (kHz)

Gain en diffraction \( \sigma_{\text{gain}} \) (dB)

Fréquence (kHz)
Configuration avec 4 couches

Exemple : eau, $a = 4, 4$ m, 4 couches isotropes

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