# Optimized configuration of multi-layered polyurethane foams in a dissipative silencer for broadband noise reduction

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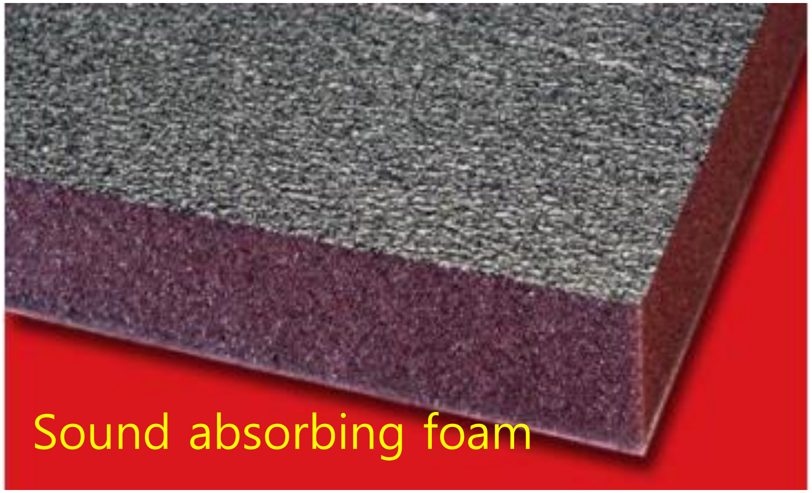
**Haesang Yang, Dongheon Kang, and Woojae Seong**

Seoul National University, South Korea

# Background (1/2)

- Silencers are indispensable elements of modern pipe-line system (e.g., automotive, aircraft & ship industry, HVAC applications).
  - **A dissipative silencer** containing absorbing materials inside has an ability of noise control by transferring acoustic/vibration energy to thermal energy.
- There are numerous models for computing sound attenuation through dissipative silencers each having advantages and drawbacks according to the configuration in hand.

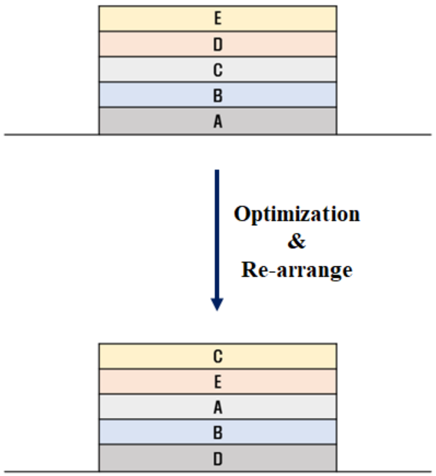



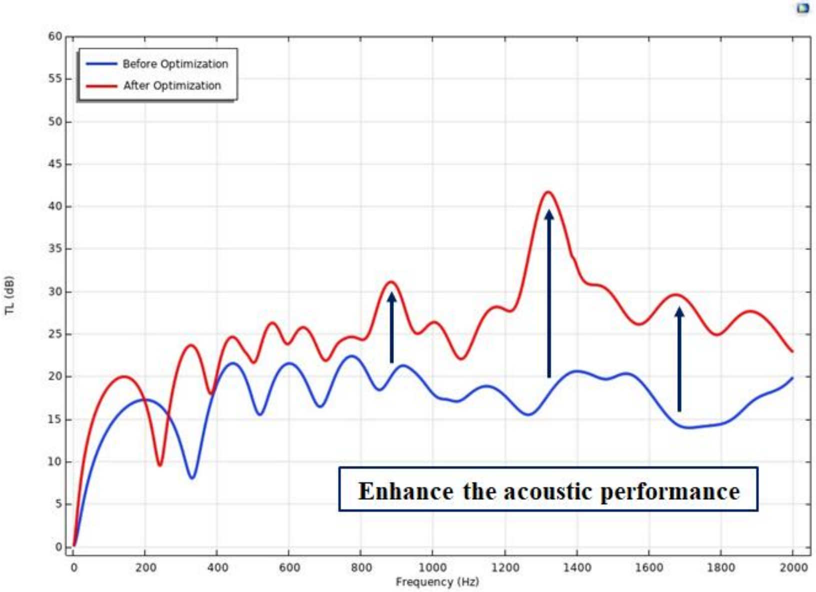
# Background (2/2)

- If the solid structure of the absorbing materials has a finite stiffness (**poroelastic materials such as foam**), it is known that three type of waves are allowed to propagate through the medium (**Biot theory**).

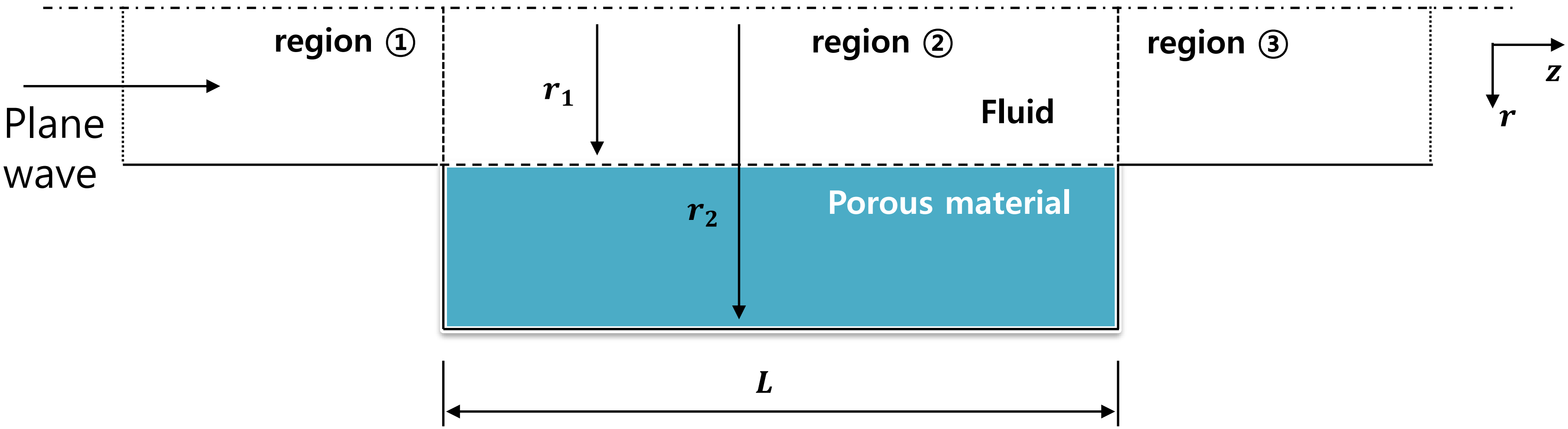
- We investigate the acoustic performance of a dissipative silencer lined with poro-elastic absorbing materials.
  - Acoustic performance: **transmission loss (TL)**
  - Optimized configuration of **multi-layered polyurethan (PU) foams**

- Objective



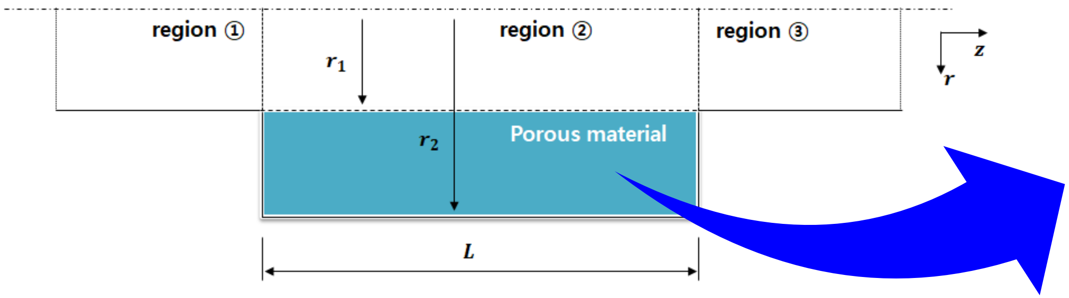
# Problem description




- Axisymmetric cylindrical chamber duct of length *L*
- Inlet and outlet pipes (regions ① and ③)
  - each having a circular cross-section with rigid walls
- Fluid domain ($0 < r < r_1$): $$\nabla^2 p - \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} = 0$$

$p$: acoustic pressure
$c_0$: sound speed in fluid

# Porous absorbing material – Biot-Allard model




<Polyurethane foam>

- Absorbing media ($r_1 < r < r_2$):
  - Wave propagation in the media is described via Biot-Allard model.[1]

Biot Model : **Saturating fluid is a liquid**, like water or oil. Only considered viscous loss.

$$\rho_{av}\frac{\partial^2}{\partial t^2}\mathbf{u}+\rho_f\frac{\partial^2}{\partial t^2}\mathbf{w}-\nabla\cdot\sigma=0$$

$$\rho_f\frac{\partial^2}{\partial t^2}\mathbf{u}+\frac{\mu_f}{\kappa}\frac{\partial}{\partial t}\mathbf{w}+\rho_f\frac{\tau}{\varepsilon_p}\frac{\partial^2}{\partial t^2}\mathbf{w}+\nabla p_f=0$$

$\longrightarrow$

$$-\left(\rho_{av}-\frac{\rho_f^2}{\rho_c(\omega)}\right)\omega^2\mathbf{u}-\nabla\cdot\left(\sigma_d(\mathbf{u})-\alpha_B p_f\mathbf{I}\right)=\frac{\rho_f}{\rho_c(\omega)}\nabla p_f$$

$$-\frac{\omega^2}{M}p_f-\nabla\cdot\frac{1}{\rho_c(\omega)}\left(\nabla p_f-\omega^2\rho_f\mathbf{u}\right)=\omega^2\alpha_B\varepsilon_{vol}$$

**Biot-Allard Model** : **Porous material is saturated by a gas, like air.**

Viscous and Thermal losses are included.

$$\mu(\omega)=\mu\left(1+\frac{4i\omega\tau_\infty^2\mu\rho_f}{R_f^2L_v^2\varepsilon_p^2}\right)^{\frac{1}{2}},\quad \chi_f(\omega)=\frac{1}{\gamma p_A}\left[\gamma-(\gamma-1)\left(1+\frac{8\mu}{i\omega L_{th}^2 Pr\rho_f}\sqrt{1+\frac{i\omega L_{th}^2 Pr\rho_f}{16\mu}}\right)^{-1}\right]$$

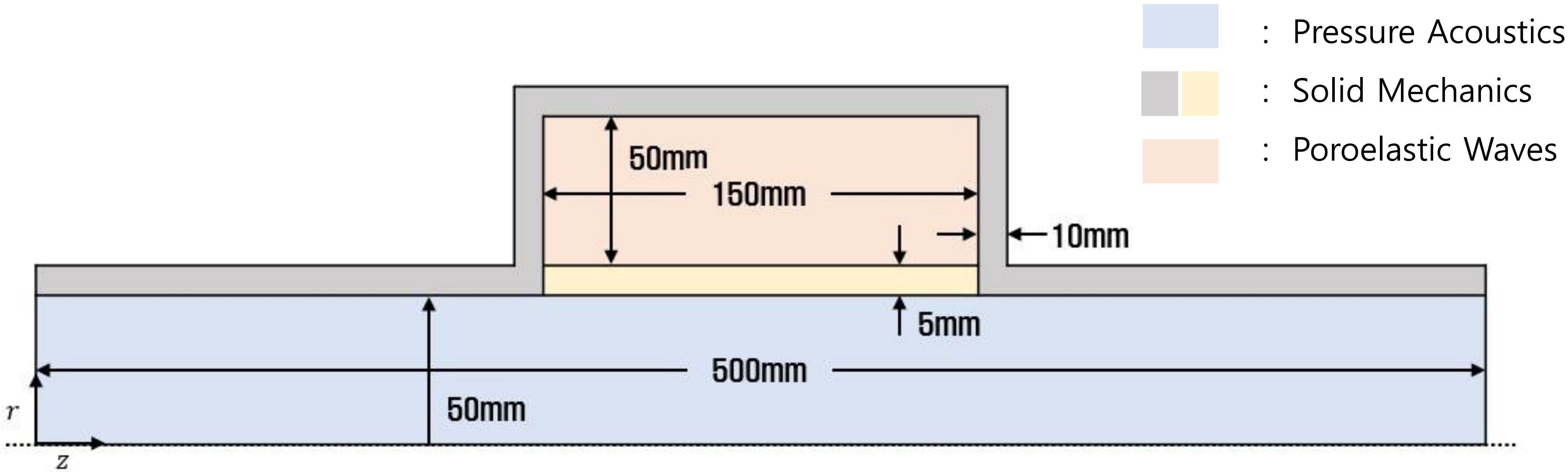


[1]Allard, *Propagation of Sound in Porous Media: Modeling Sound Absorbing Materials*. (Elsevier, New York, 1993).

# Simulation tool & configuration

- **COMSOL Multiphysics**
  - Acoustic-Solid-Poroelastic Waves Interface Physics
  - 2D Axisymmetric model

- 2D Axisymmetric Configuration
  - Cylindrical pipe and silencer with liner



# Simulation tool & configuration

- Material Properties
  - **Water** in pipe
  - **Air** in absorbing material (PU foam)
  - **Polyurethane A, B, C, D, E**
    - *Density, Shear Modulus, and Loss factor*

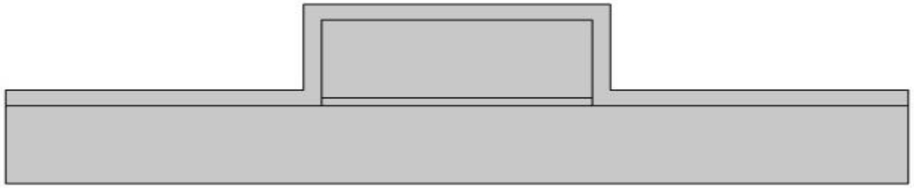
    (Standard properties of a KRAIBURG Co. (DE))
    - For the rest, random values were applied.
  - **Steel** as casing (to surround the pipe and the silencer)
  - **Rubber** as liner (to physically separate the pipe and the silencer)

| Type | Polyurethane | | | | |
|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** |
| Density [kg/m$^3$] | **652** | **770** | **828** | **915** | **992** |
| Shear Modulus [MPa] | **1.15** | **1.85** | **2.84** | **3.51** | **6** |
| Loss factor | **0.1** | **0.1** | **0.1** | **0.09** | **0.09** |
| Poisson's ratio | | | **0.4** | | |
| Porosity | | | **0.5** | | |
| Flow Resistivity [kPa*s/m$^2$] | | | **1,000** | | |
| Viscous characteristic length [um] | | | **20** | | |
| Thermal characteristic length [um] | | | **20** | | |
| Tortuosity | | | **1.5** | | |

# Simulation – parameter study

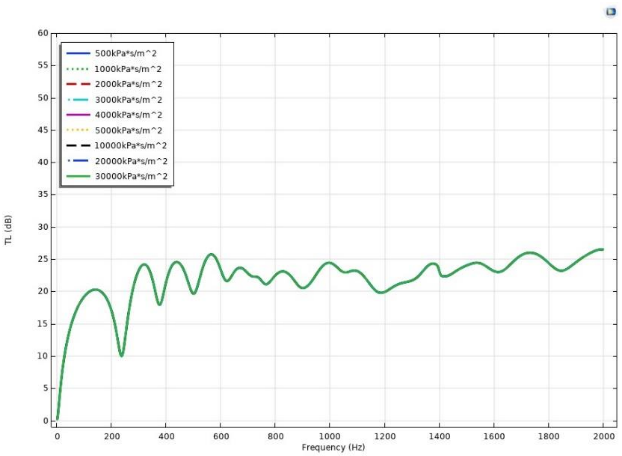
- **1-layer PU foam**
  - Acoustic performance according to changes in each material properties
  - Based on Standard polyurethan B

| | |
|---|---|
| Density | **600 ~ 1,000kg/m³** |
| Shear Modulus | **2 ~ 10MPa** |
| Loss factor | **0.06 ~ 0.14** |
| Porosity | **0.2 ~ 0.8** |
| Flow Resistivity | **500 ~ 30,000 kPa*s/m²** |

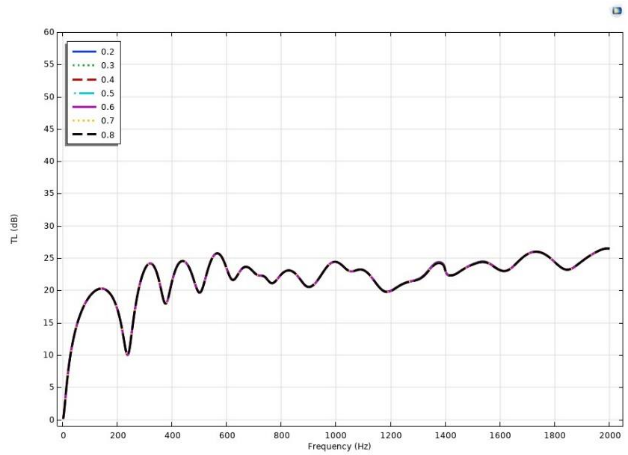


1-layer PU foam

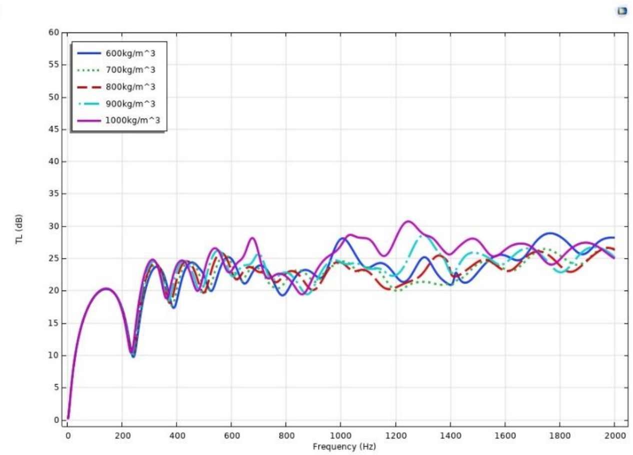
# Simulation results – parameter study



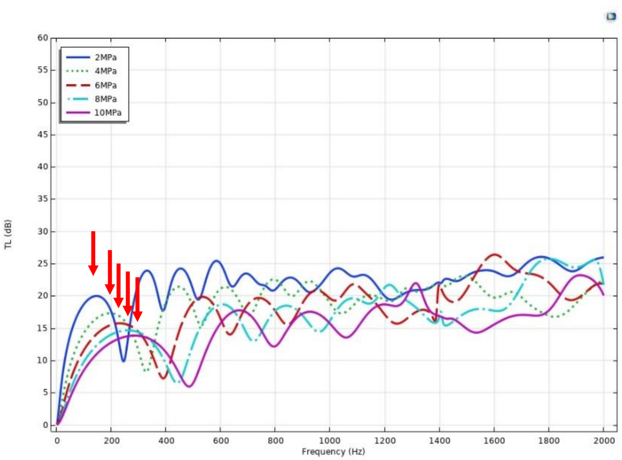

**Flow Resistivity**



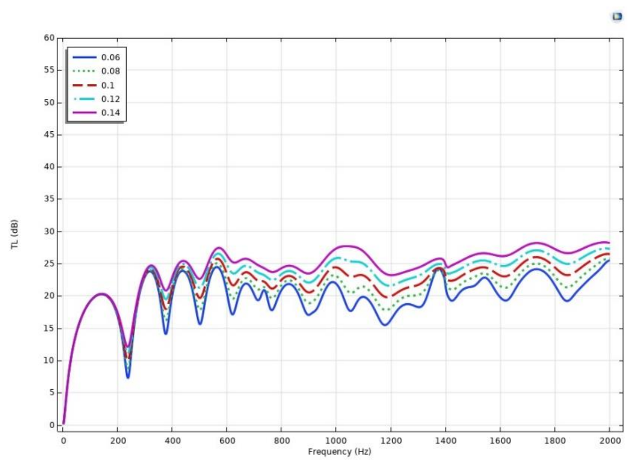

**Porosity**




**Density**




**Shear modulus**

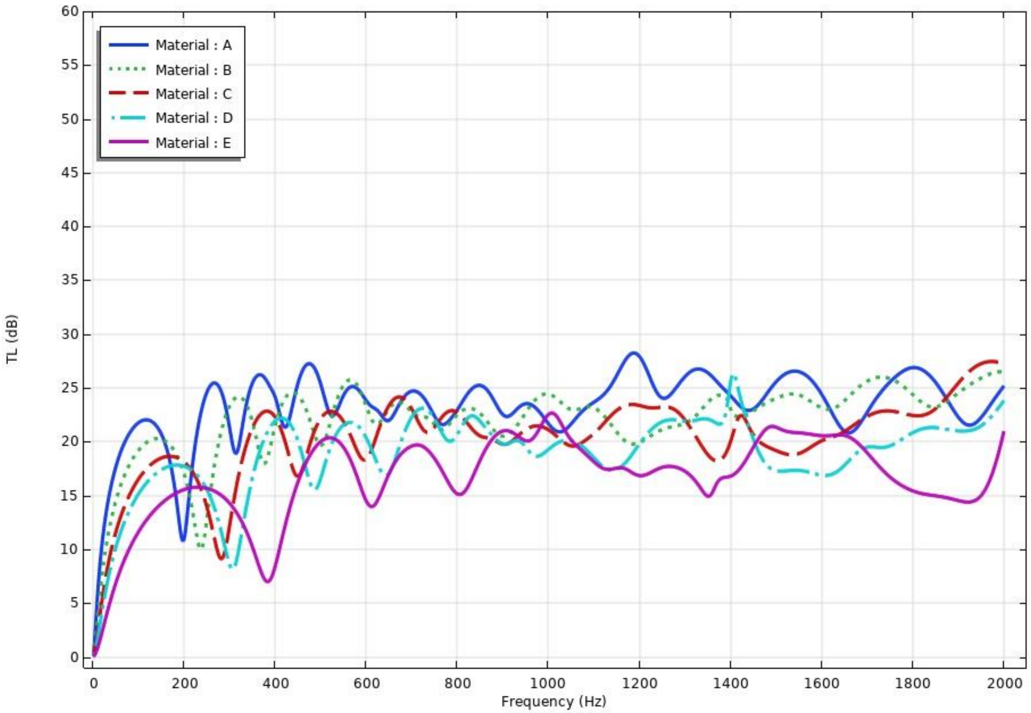



**Loss factor**

**⇒ Shear modulus & Loss factor have great influence on TL.**

# Simulation results – baseline model

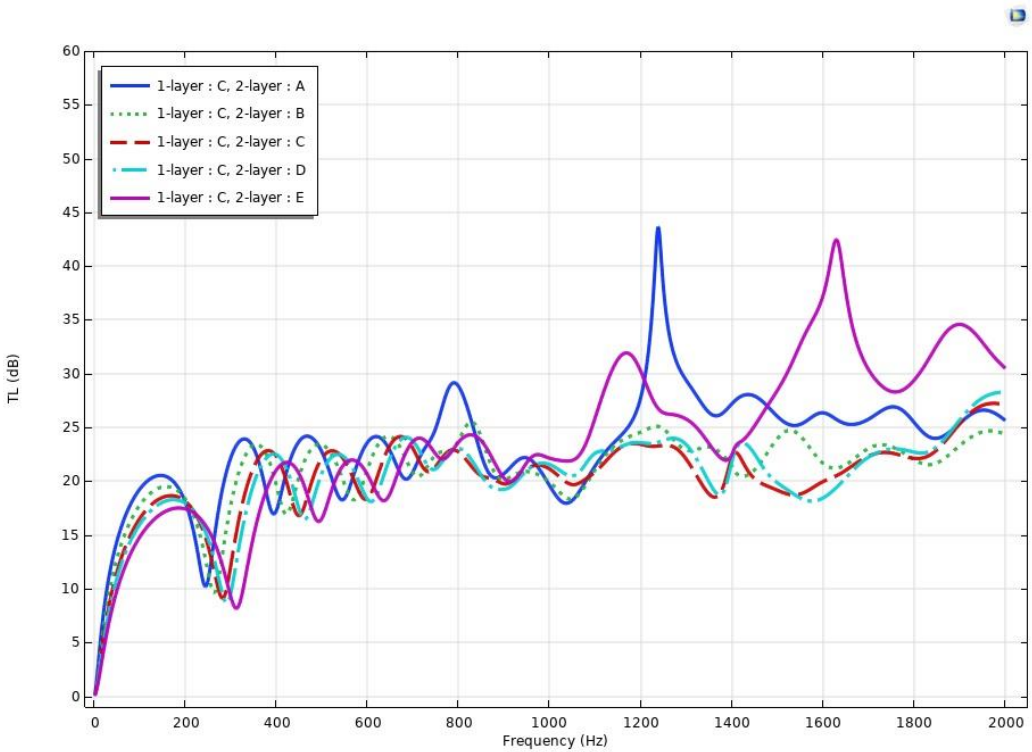
- **1-layer PU foam**



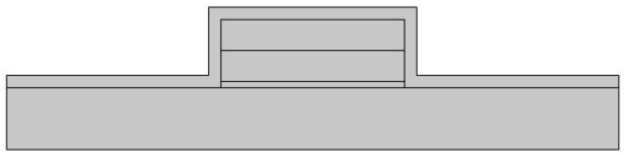

| Type | Polyurethane | | | | |
|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** |
| Density [kg/m$^3$] | **652** | **770** | **828** | **915** | **992** |
| Shear Modulus [MPa] | **1.15** | **1.85** | **2.84** | **3.51** | **6** |
| Loss factor | **0.1** | **0.1** | **0.1** | **0.09** | **0.09** |
| **Avg. TL [dB]** | **23.33** | **22.06** | **20.41** | **18.92** | **16.69** |

# Simulation results – baseline model

- **2-layer PU foams (1/2)**



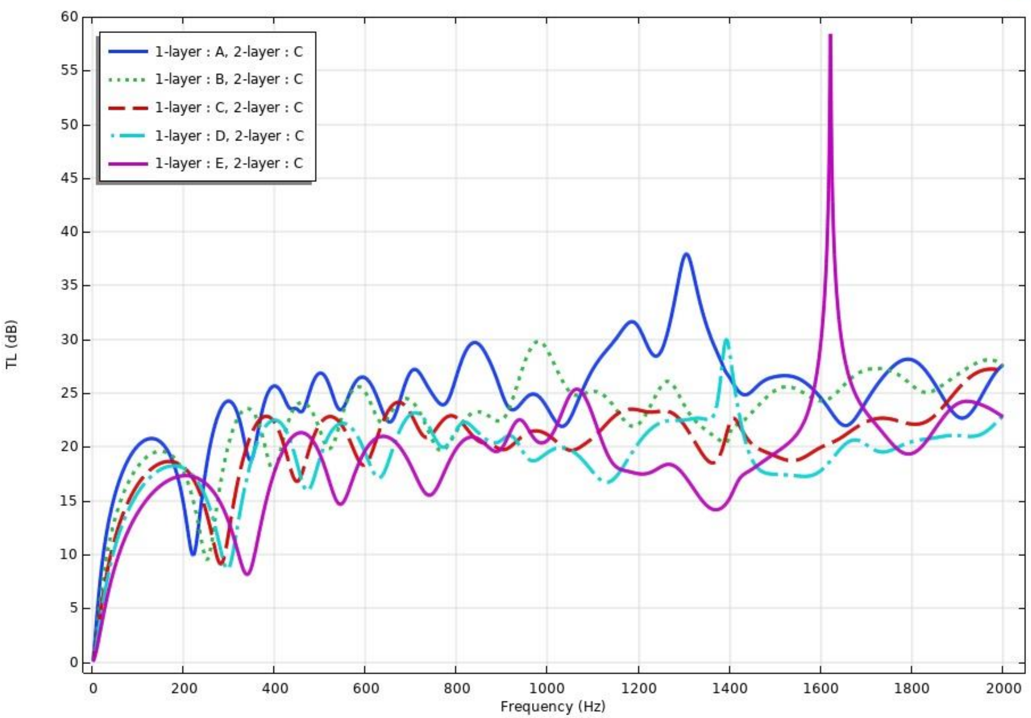

| Case | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Arrangement of Absorbing materials | **CA** | **CB** | **CC** | **CD** | **CE** |
| **Avg. TL [dB]** | **23.28** | **21.11** | **20.40** | **20.47** | **23.76** |



2-layer PU foams

# Simulation results – baseline model

- **2-layer PU foams (2/2)**

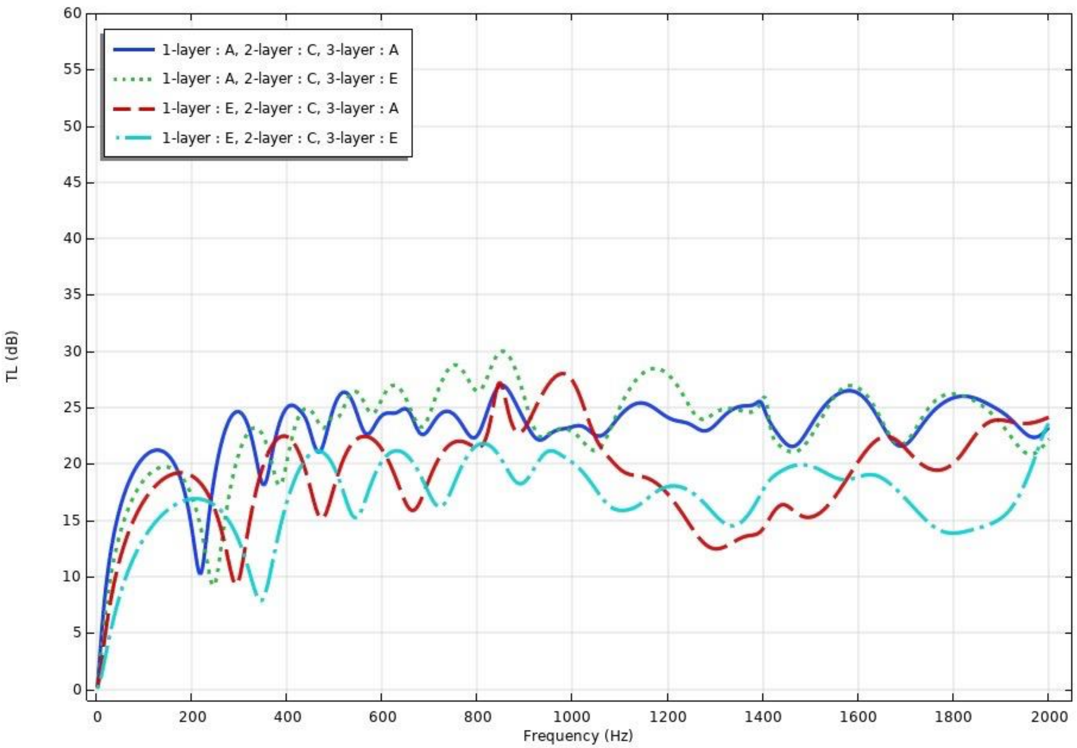



| Case | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| Arrangement of Absorbing materials | **AC** | **BC** | **CC** | **DC** | **EC** |
| **Avg. TL [dB]** | **24.73** | **22.86** | **20.40** | **19.22** | **19.07** |

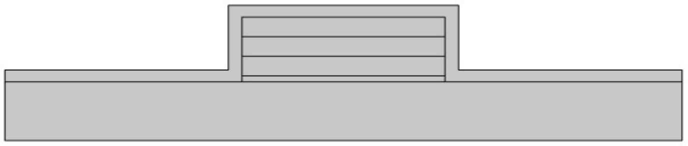
⇒ Material properties located at **lower levels** have a **dominant influence on TL**

# Simulation results – baseline model

- **3-layer PU foams**



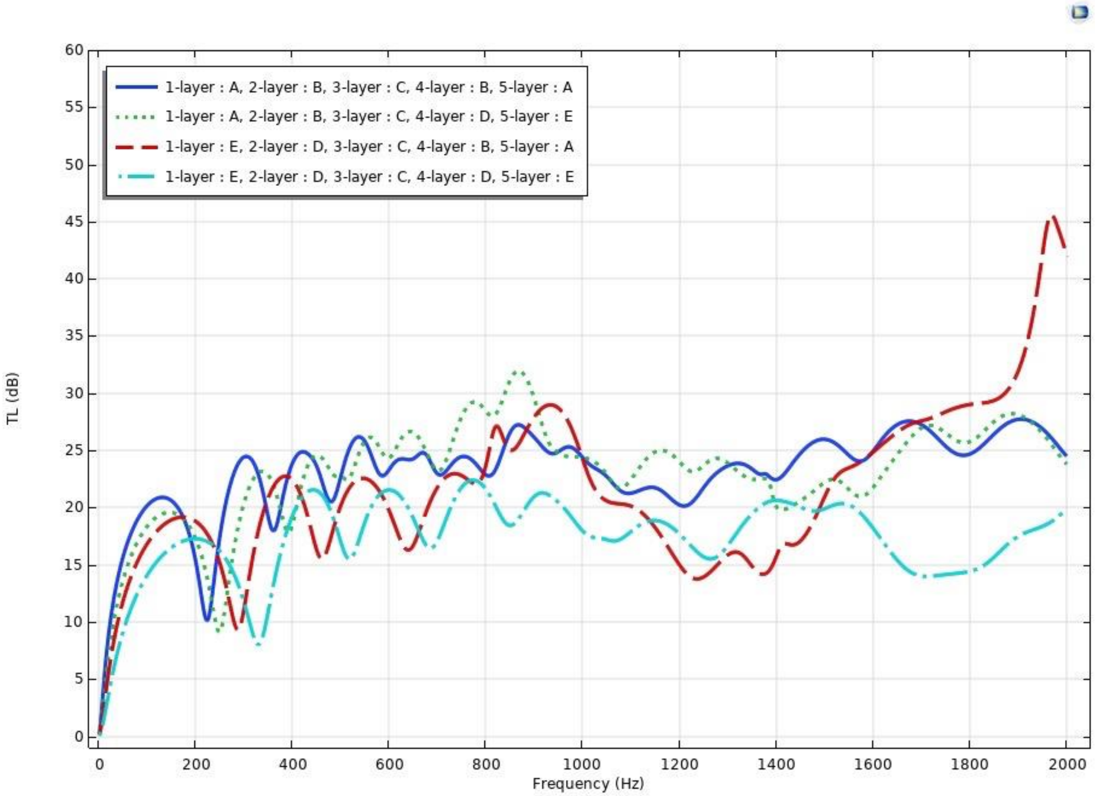

| Case | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Arrangement of Absorbing materials | **ACA** | **ACE** | **ECA** | **ECE** |
| **Avg. TL [dB]** | **22.97** | **23.19** | **19.10** | **16.95** |



3-layer PU foams

# Simulation results – baseline model

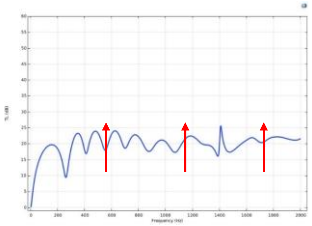
- **5-layer PU foams**

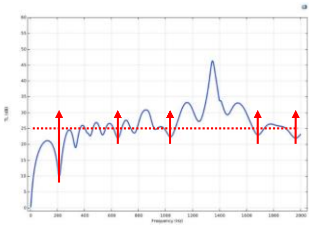



| Case | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| Arrangement of Absorbing materials | **ABCBA** | **ABCDE** | **EDCBA** | **EDCDE** |
| **Avg. TL [dB]** | **23.12** | **23.13** | **21.63** | **17.33** |

5-layer PU foams

# Optimization





- ✓ **Two kinds of objective function** $f_1$ & $f_2$

  1. **Maximize TL :** $\min_{\sigma} f_1(\sigma)$ , $f_1(\sigma) = \sum(-TL)$
  2. **Uniformize TL :** $\min_{\sigma} f_2(\sigma)$, $f_2(\sigma) = \sum|TL - \overline{TL}|$

     $if \ (TL - \overline{TL}) \geq 0, \ then \ 0$

- ✓ **Control variables**

  Standard PU foams : **A, B, C, D, E**

  **Density($\sigma$)** **: 652 ~ 992 kg/m³**

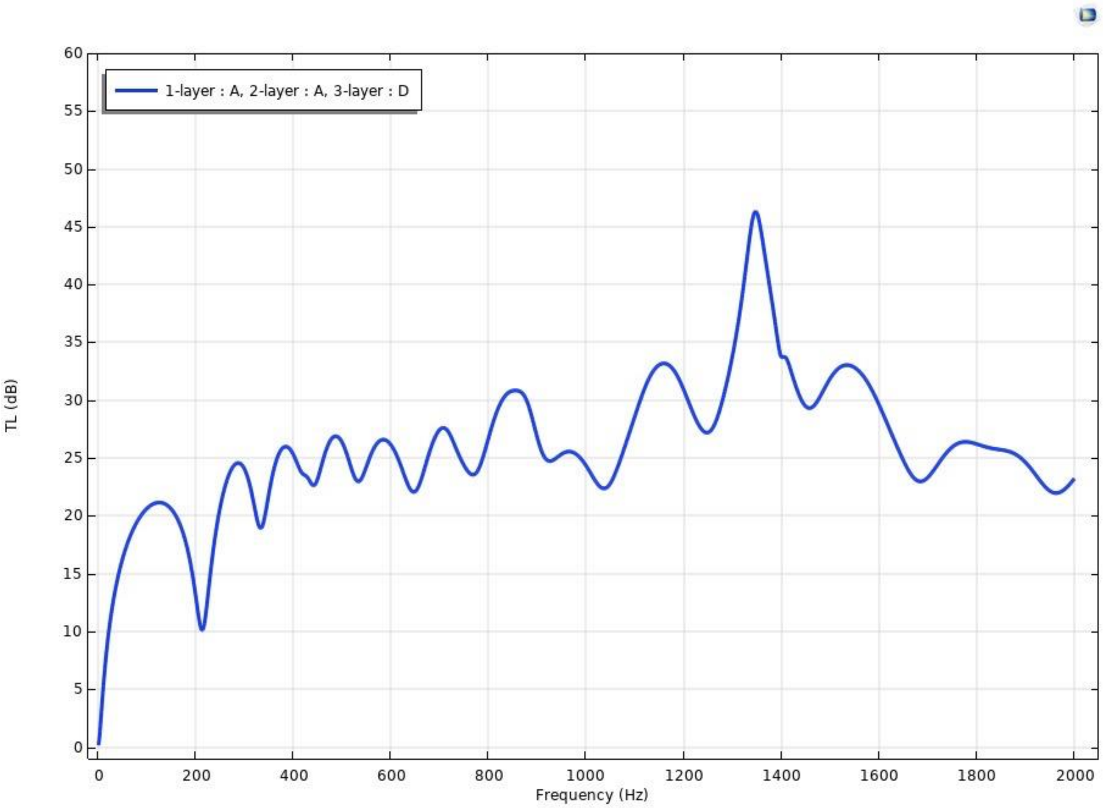
  - Shear modulus : 1.15 ~ 6 MPa
  - Loss factor : 0.09 ~ 0.1

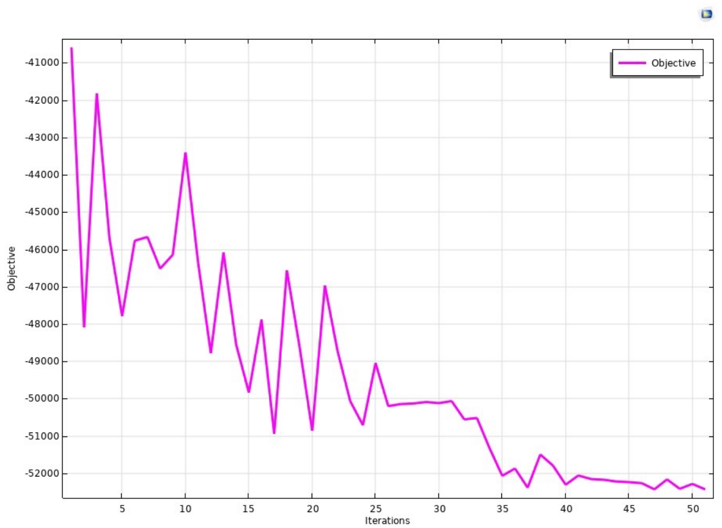
- ✓ **Solver**

  Nelder-Mead (NM) method (downhill simplex method)

# Optimization results

- **3-layer PU foams (using objective function $f_1$ : maximize TL)**

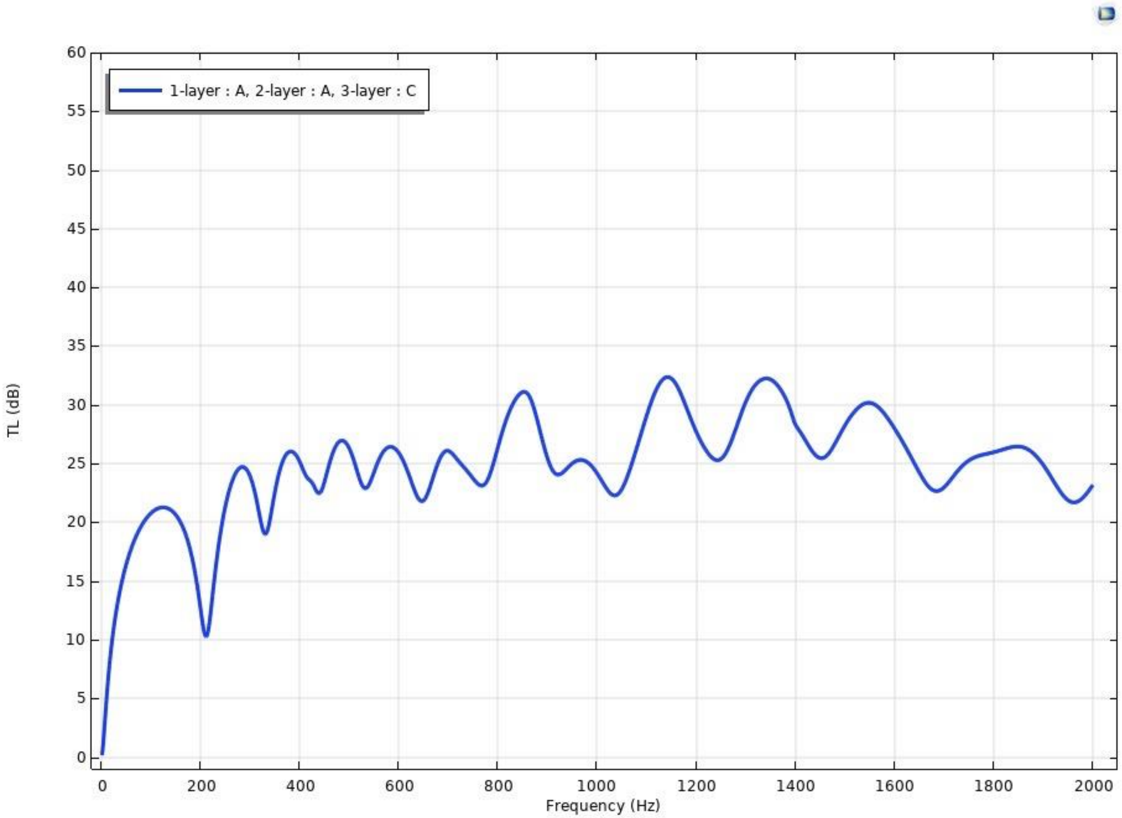


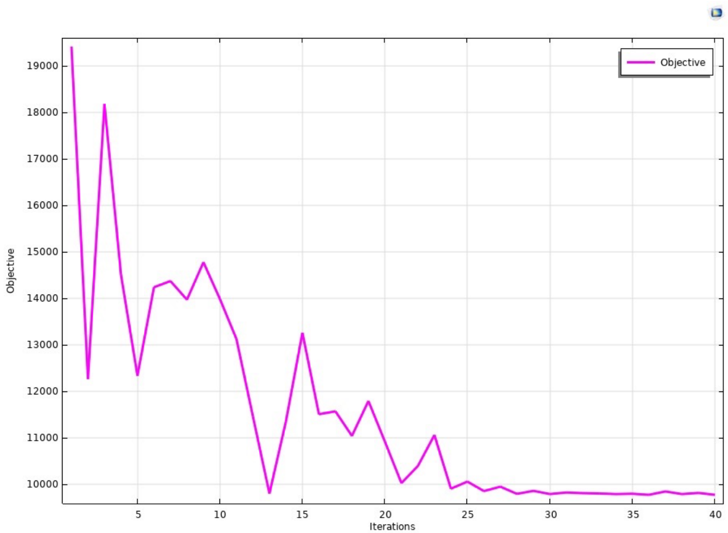




| Case | Objective function 1 (Maximize TL) |
|---|---|
| Arrangement of Absorbing materials | **AAD** |
| **Avg. TL [dB]** | **25.91** |
| **Increased TL [dB] (Compared to TL before optimization)** | **Abt. 3 ~ 9** |

# Optimization results

- **3-layer PU foams (using objective function $f_2$ : uniformize TL)**

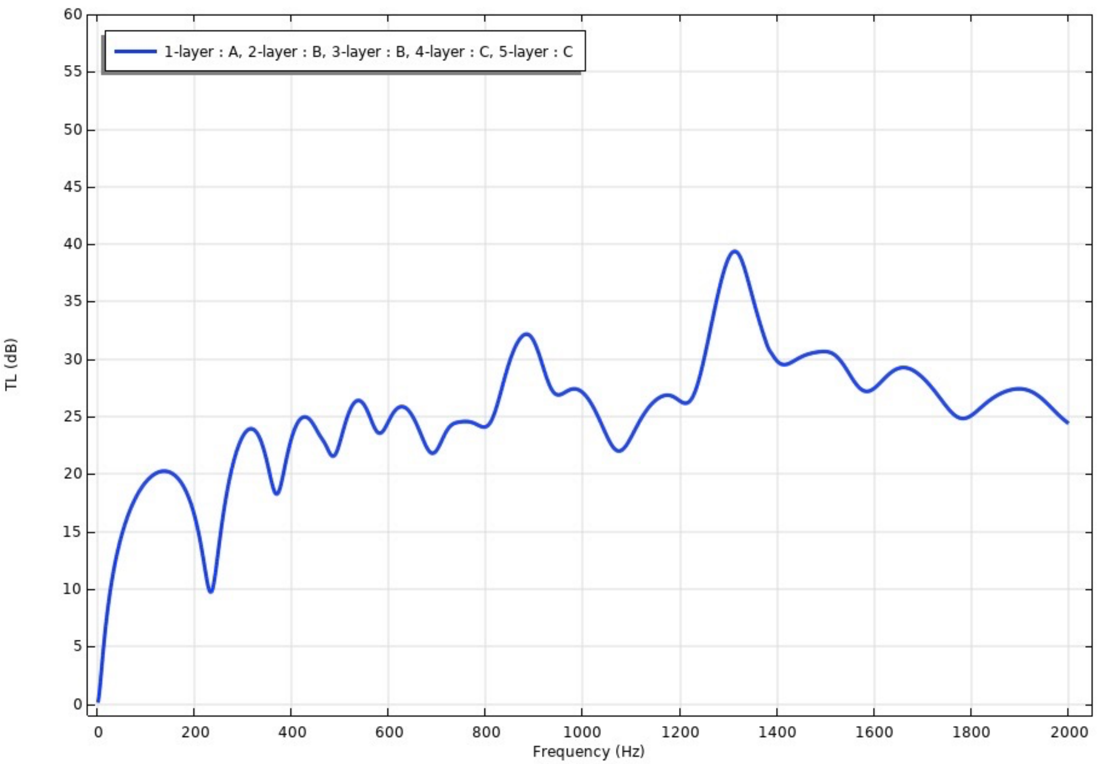


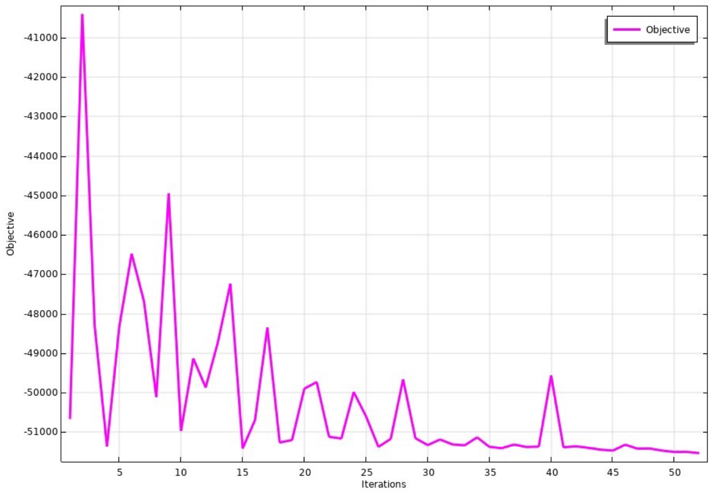




| Case | **Objective function 2 (Uniformize TL)** |
|---|---|
| Arrangement of Absorbing materials | **AAC** |
| **Avg. TL [dB]** | **24.80** |
| **Increased TL [dB] (Compared to TL before optimization)** | **Abt. 2 ~ 7** |

# Optimization results

- **5-layer PU foams (using objective function $f_1$ : maximize TL)**

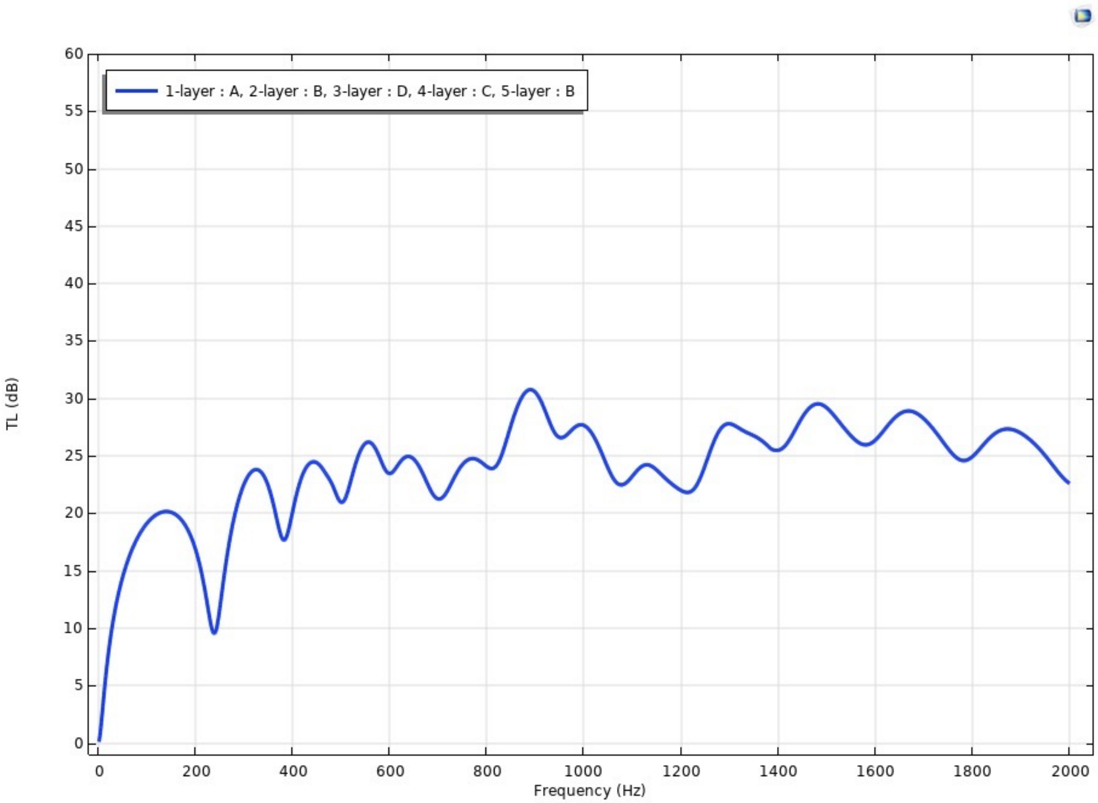


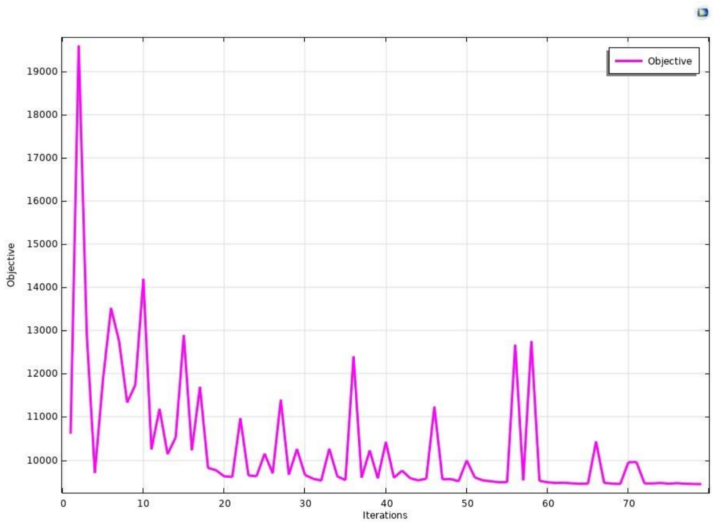




| Case | **Objective function 1 (Maximize TL)** |
|---|---|
| Arrangement of Absorbing materials | **ABBCC** |
| **Avg. TL [dB]** | **25.32** |
| **Increased TL [dB] (Compared to TL before optimization)** | **Abt. 2 ~ 8** |

# Optimization results

- **5-layer PU foams (using objective function $f_2$ : uniformize TL)**

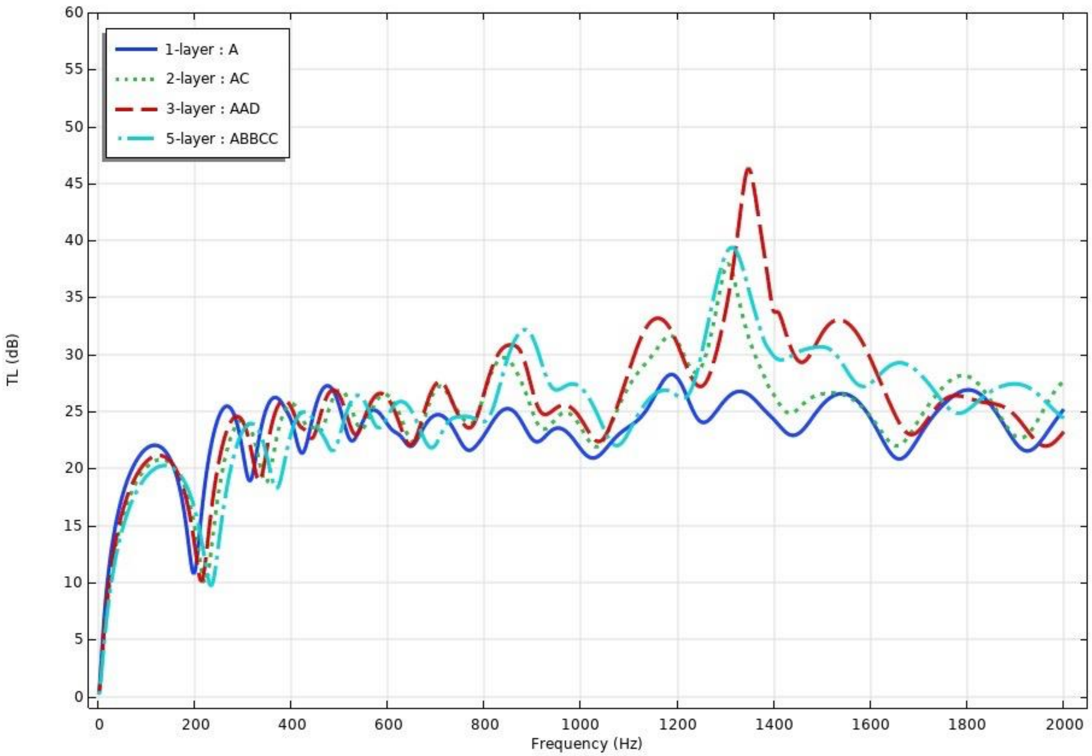



| Case | Objective function 2 (Uniformize TL) |
|---|---|
| Arrangement of Absorbing materials | **ABDCB** |
| **Avg. TL [dB]** | **23.93** |
| **Increased TL [dB] (Compared to TL before optimization)** | **Abt. 1 ~ 7** |

# Optimization results

- **Enhancement of the acoustic performance of a dissipative silencer with multi-layered PU foams**




| Case | 1-layer | 2-layer | 3-layer | 5-layer |
|---|---|---|---|---|
| Arrangement of Absorbing materials | A | AC | AAD | ABBCC |
| **Avg. TL [dB]** | 23.33 | 24.73 | 25.91 | 25.32 |

# Conclusions

1. We verify material properties that affect the acoustic performance of dissipative silencer.
   - ❖ **Shear modulus** & **loss factor** → great influence on acoustic performance

2. We show to enhance the acoustic performance by **optimizing the arrangement sequence of absorbing materials.**

| Case | 3-layer | | 5-layer | |
|---|---|---|---|---|
| | Objective function 1 (Maximize TL) | Objective function 2 (Uniformize TL) | Objective function 1 (Maximize TL) | Objective function 2 (Uniformize TL) |
| Arrangement of Absorbing materials | AAD | AAC | ABBCC | ABDCB |
| Avg. TL [dB] | 25.91 | 24.80 | 25.32 | 23.93 |
| Increased TL [dB] (Compared to TL before optimization) | 3 ~ 9 | 2 ~ 7 | 2 ~ 8 | 1 ~ 7 |

→ A relatively low increment at applying $f_2$ focusing on enhancing only below-average TL

# Thank You