Low frequency sound field reconstruction in a non-rectangular room

Hervé Lissek

EPFL – LTS2 / Acoustic Group

SGA SSA

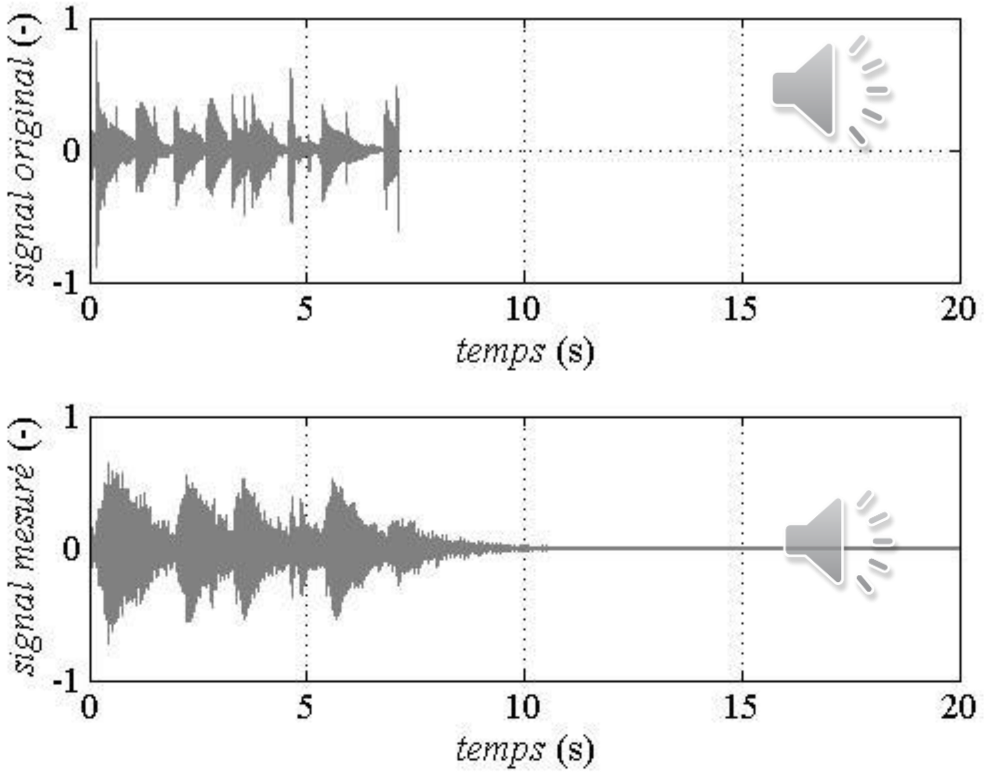
Journées d'automne 2023

Simulations acoustiques des locaux et des bâtiments – possibilités et limites

22. & 23. novembre 2023 Trafo Baden

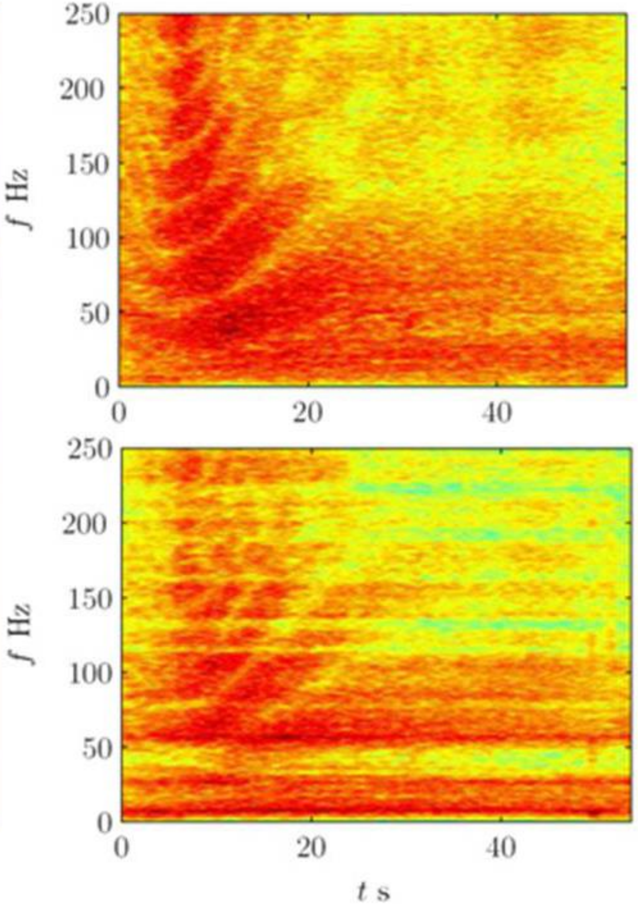
CONTEXT

- Music rendering at low-frequencies



CONTEXT

- Transportation noise immissions in inhabitations

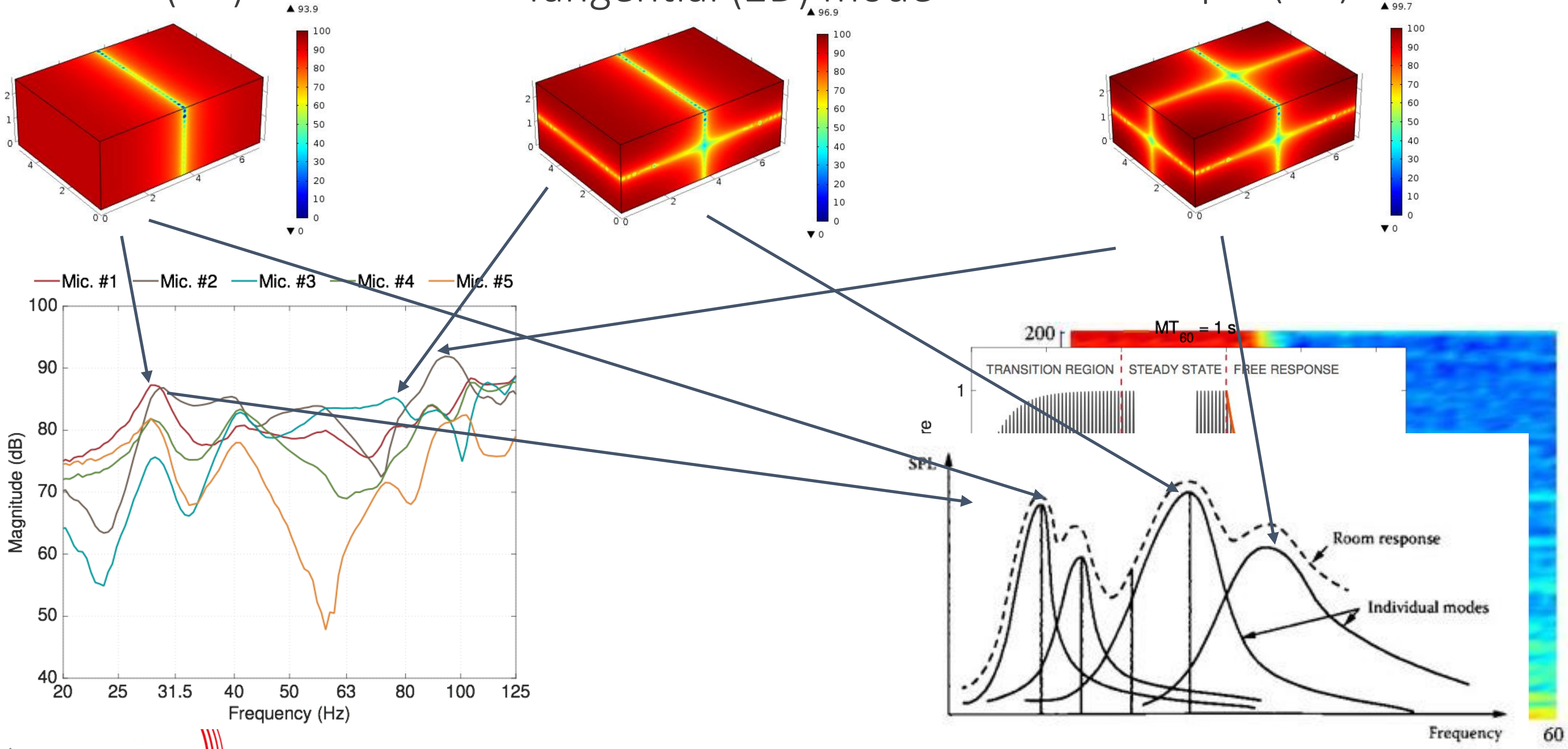


outside

inside

Room resonances at low-frequencies

Axial (1D) mode　　Tangential (2D) mode　　Oblique (3D) mode



Room resonances due to standing waves: **in 1 D**

Ex in 1D, with 2 hard walls: pressure distribution follows eigenmodes $\Phi_n(x) = \cos\left(\frac{n\pi x}{L}\right)$

- Eigenvalues (wavelengths, frequencies)

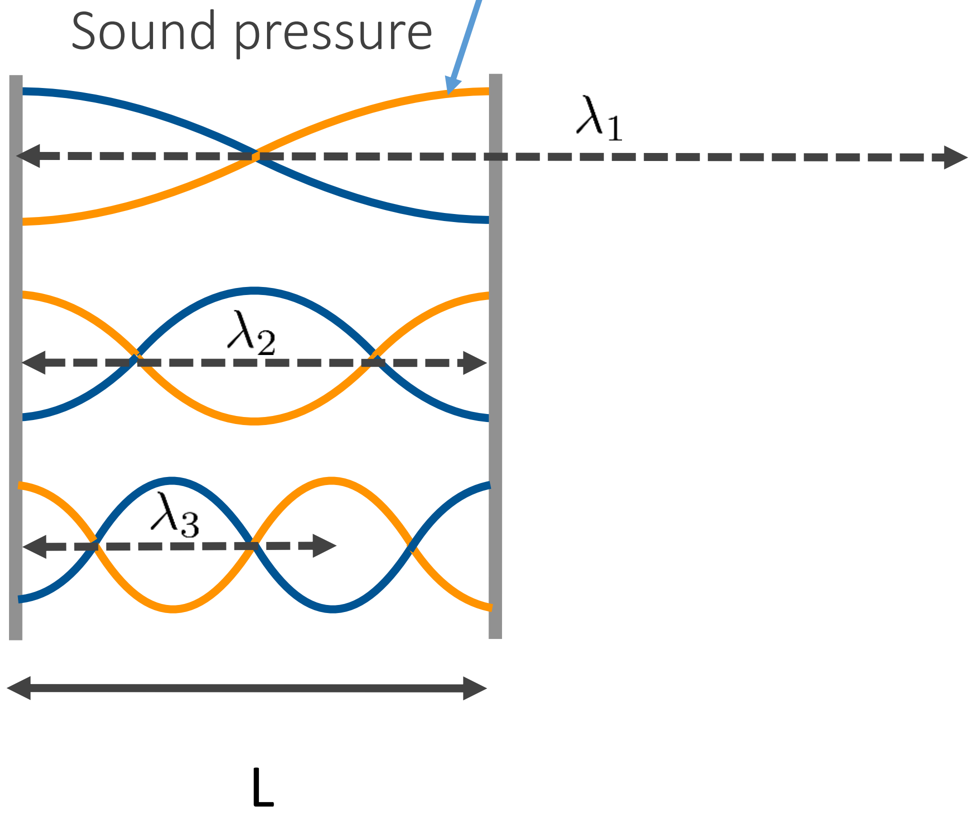
Mode 1 $\lambda_1 = 2L, f_1 = \frac{c}{2L}$

Mode 2 $\lambda_2 = L, f_2 = \frac{c}{L}$

Mode 3 $\lambda_3 = \frac{2L}{3}, f_3 = \frac{3c}{2L}$

⋮

Mode n $\lambda_n = \frac{2L}{n}, f_n = \frac{nc}{2L}$



Room resonances due to standing waves: **in 3 D**

In 3D, for simple shoebox shapes and 6 hard walls, pressure distribution follows eigenmodes

$$\Phi_{n_x n_y n_z}(x,y,z) = \cos\left(\frac{n_x \pi x}{l_x}\right)\cos\left(\frac{n_y \pi y}{l_y}\right)\cos\left(\frac{n_z \pi z}{l_z}\right)$$

where $(n_x,\, n_y,\, n_z) \in \mathbb{N}^3$ are non-simultaneously equal to zero

- **Eigenfrequencies:**

$$f_n = \frac{c}{2}\sqrt{\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2} \qquad n = [n_x n_y n_z]$$

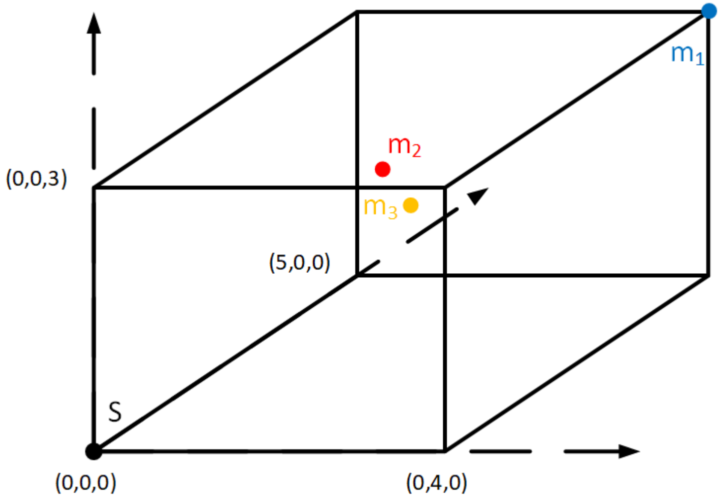
Room resonances due to standing waves

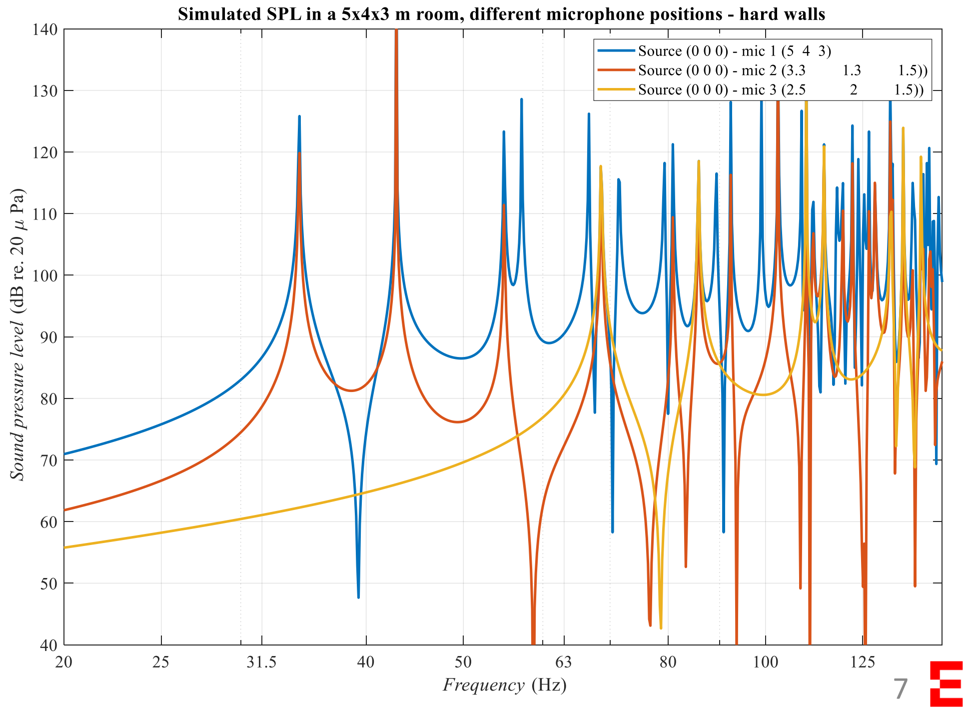
- **In 3D, for simple shoebox shapes and 6 hard walls, f_n are real values.**

For a source with flow velocity $\boldsymbol{q_0}$ located at position $\vec{r}_0(x_0, y_0, z_0)$

The measured pressure at receiver position $\vec{r}(x, y, z)$ is

$$p_\omega(\mathbf{r}) \propto \sum_n \frac{\Phi_n(\mathbf{r})\Phi_n(\mathbf{r}_0)}{({f_n}^2 - f^2)}$$





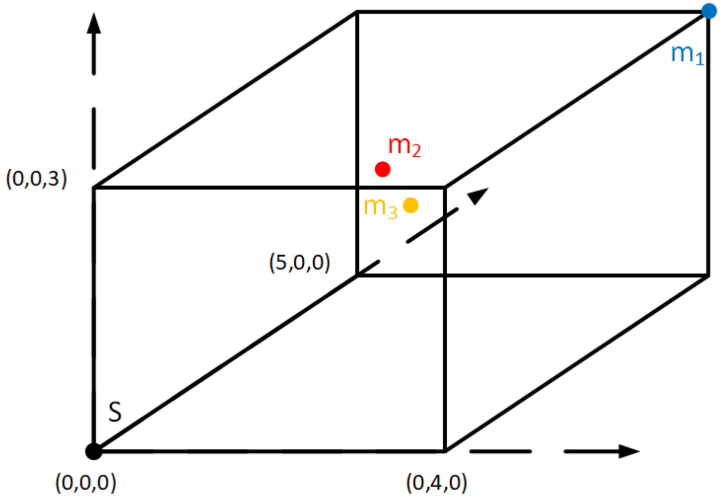
Room resonances due to standing waves

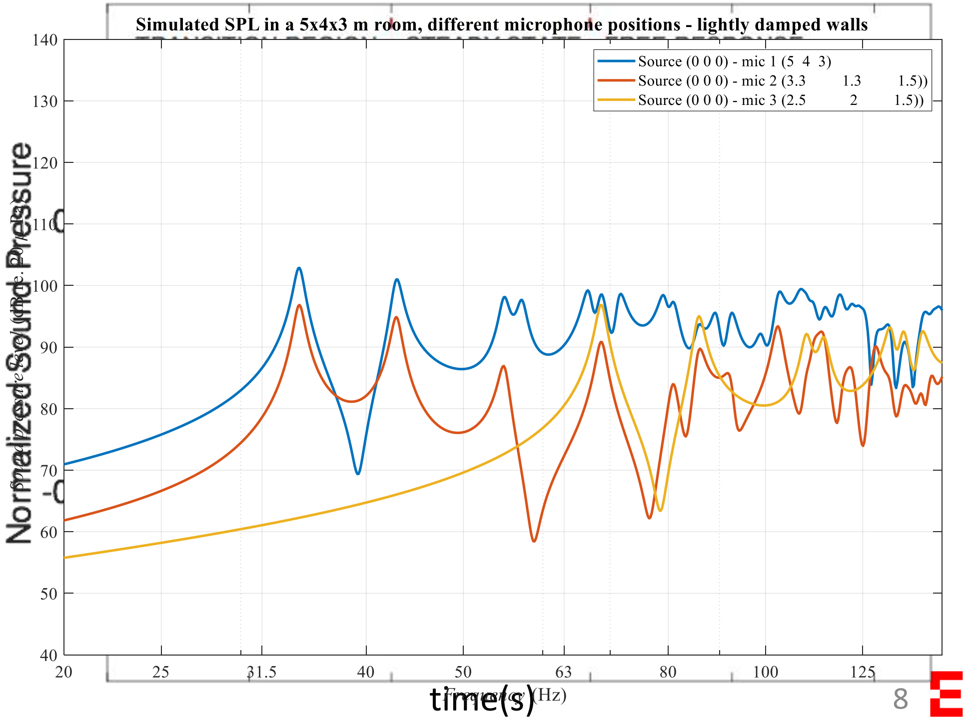
- In 3D, for simple shoebox shapes and 6 lightly damped walls, f_n are complex values

For a source with flow velocity $\boldsymbol{q_0}$ located at position $\vec{r}_0(x_0, y_0, z_0)$

The measured pressure at receiver position $\vec{r}(x, y, z)$ is $p_\omega(\mathbf{r}) \propto \sum_n \frac{\Phi_n(\mathbf{r})\Phi_n(\mathbf{r}_0)}{j\frac{\delta_n}{\pi}\operatorname{Im}(f_n) + \left(\operatorname{Re}(f_n)^2 - f^2\right)}$

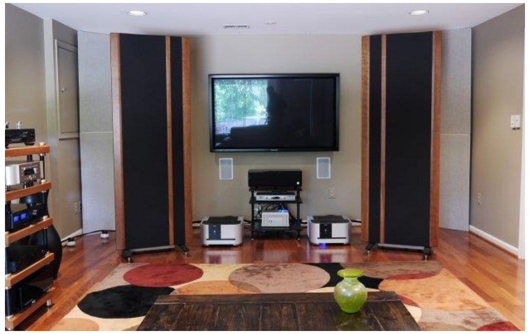
$$MT_{60_n} = \frac{3\ln(10)}{2\pi\operatorname{Im}(f_n)}$$





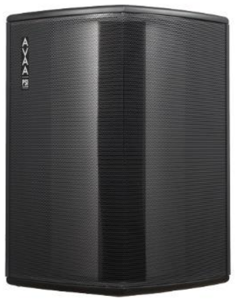
Limits of analytical models

- Limitations of analytical models of rooms at low frequencies
  - shoebox shapes➔ not suited for most rooms
  - Only lightly-damped walls
  - Only 6 independant wall impedance/absorption properties
  - Not suited for **discrete sound absorbers**, such as bass traps or active sound absorbers



GIK Acoustics
Corner Bass traps

EPFL - Active
Electroacoustic absorber



PSI Audio AVAA C20
Active sound absorber

PSI Audio AVAA C214
Active sound absorber

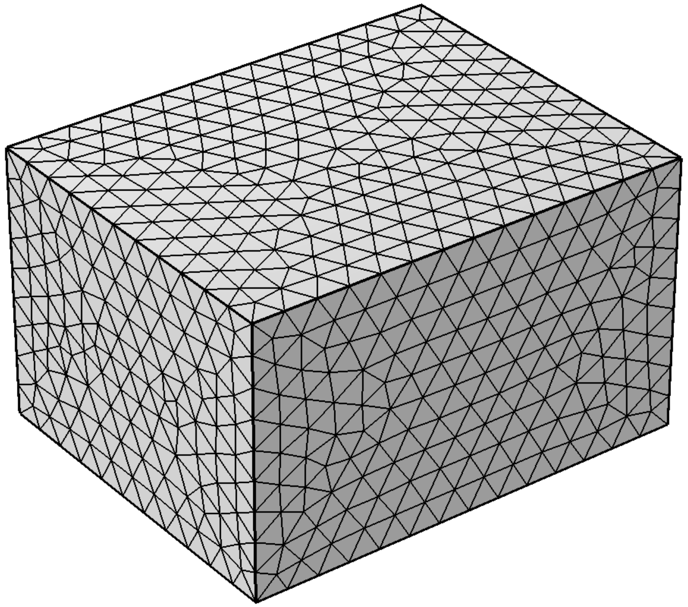
FEM models (COMSOL Multiphysics) for rooms at LF

- Requires 3D models
  - Pressure Acoustics, Frequency Domain

  - Possible studies:
    - **Eigenfrequency**: solving the eigenvalues problem (eigenfrequencies and eigenmodes)
    - **Frequency domain**: simulating room responses with the presence of source(s)
    - **Time domain**: also possible, but not shown here

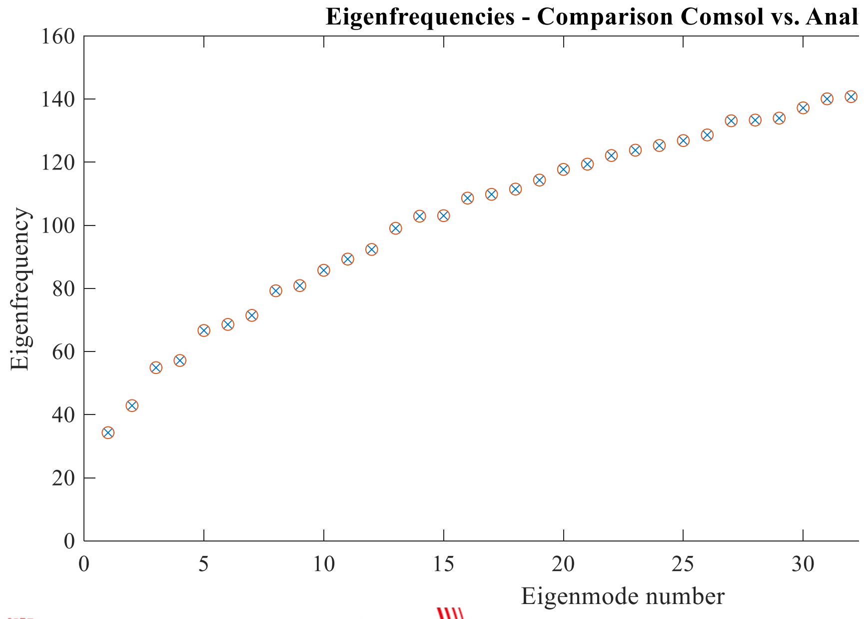
Model design

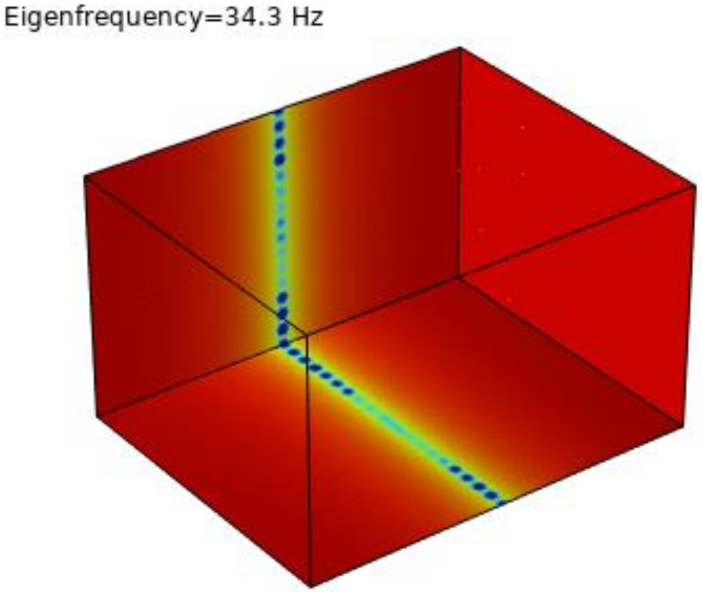
- Ex: shoebox of 5x4x3 m
  - Simulations up to 160 Hz ➔ max. mesh size $d_{mesh} = \frac{c}{6 f_{max}} = 35.7\text{cm}$
  - Find eigenfrequencies between 0 Hz and 160 Hz
  - Number of nodes:
    - 21’431 domain elements
    - 1’852 boundary elements
    - 136 edge elements

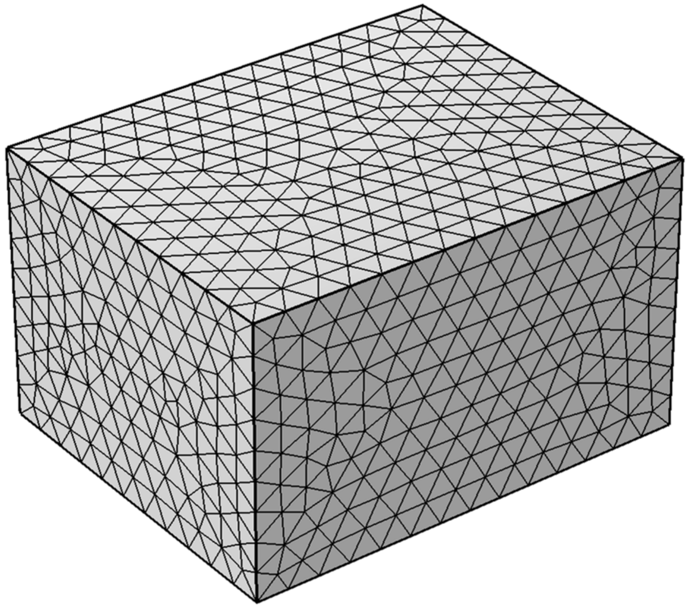


1. Eigenfrequency

- Compute 45 first resonances (~160 Hz)
- Model set in less than 5 minutes
- Computation time:
  - **2 minutes** (!) (COMSOL 6.1 on a laptop / Windows 10 64 bits / Intel(R) Core(TM) i7-8650U / 16 GB RAM)
  - 31 s (COMSOL 6.1 on PC / Windows 11, 64 bits / 11th Gen Intel(R) Core(TM) i9-11900 / 32 GB RAM)



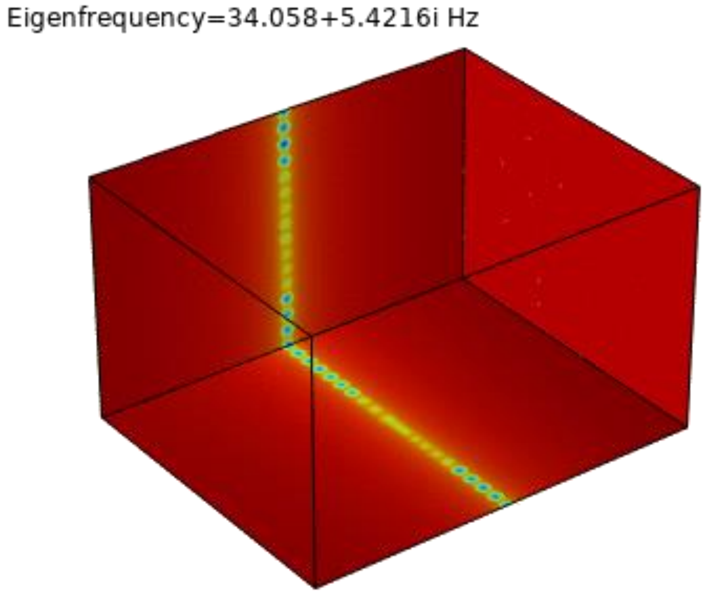


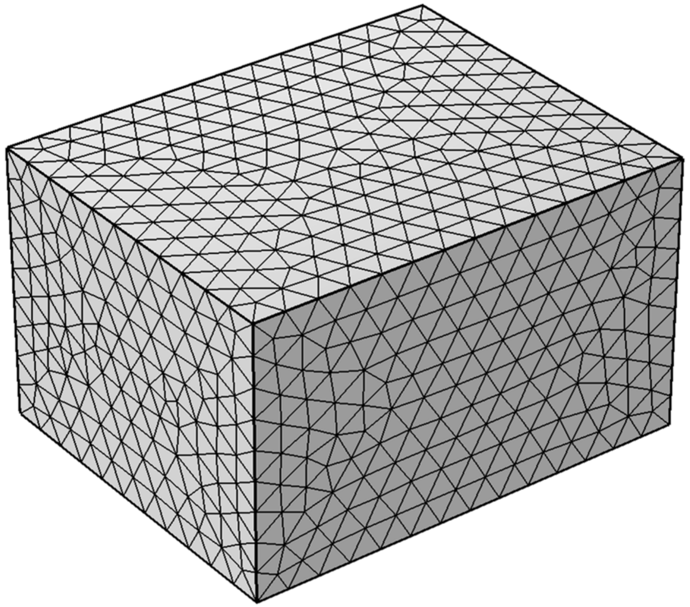


1. Eigenfrequency

- Accounting for slightly-damping walls (eg. Z_{walls}=100.Z_c)
  - Complex eigenfrequencies
  - Possibility to derive modal decay times

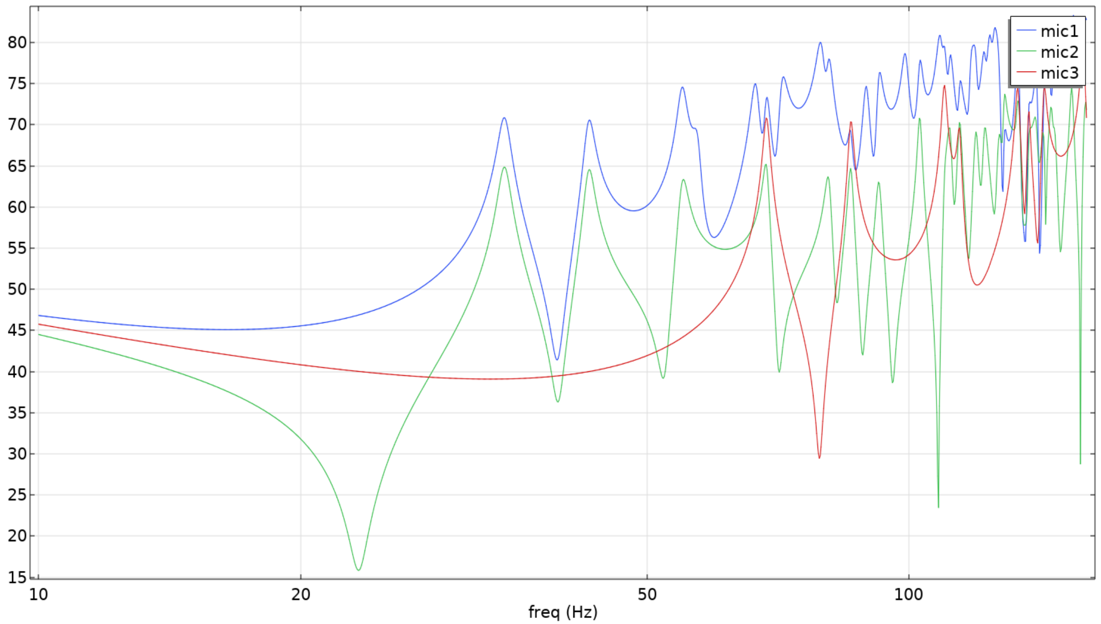
Re(fn)	Im(fn)	MT60n
34.058	5.422	1.274
42.731	5.694	1.213
54.806	6.800	1.016
57.149	6.148	1.124
66.662	7.255	0.952
68.655	5.401	1.279
71.479	7.527	0.918
79.286	8.638	0.800
80.958	6.782	1.019
85.897	5.667	1.219
89.386	7.238	0.954
92.502	6.776	1.020
99.143	8.625	0.801
…	…	…

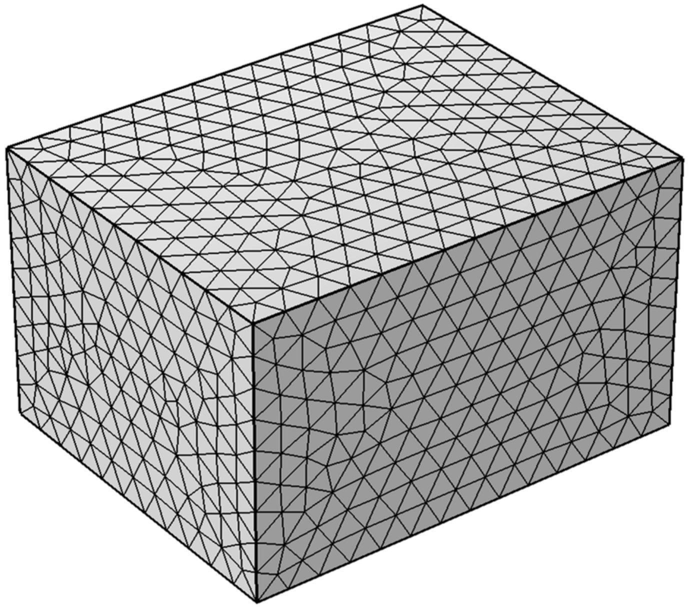




2. Frequency domain: frequency response

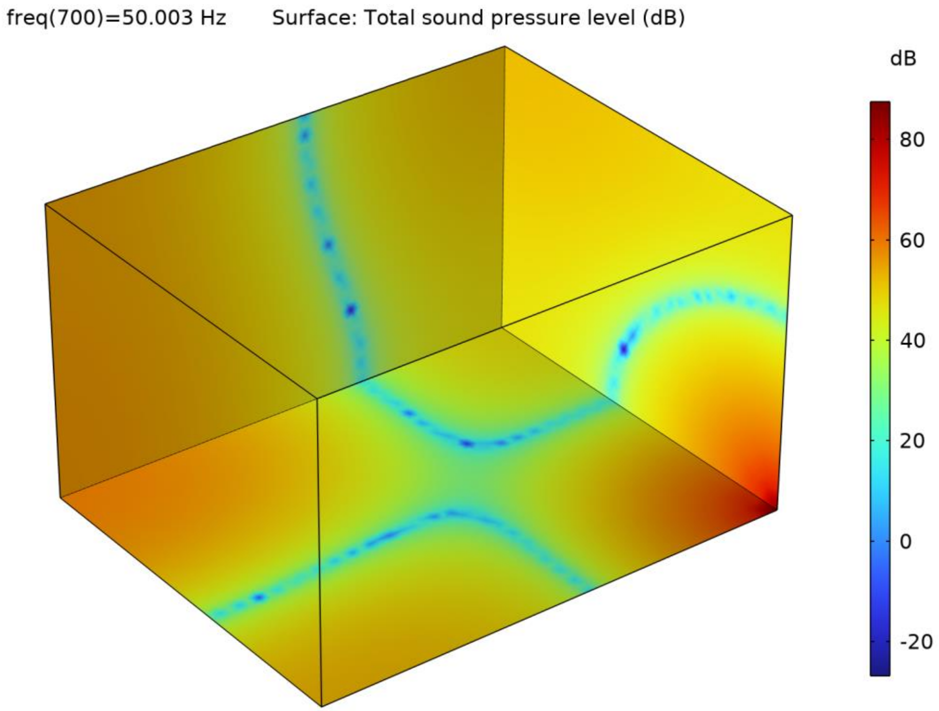
- Simulate frequency response from source at position (000) and 3 microphones positions
- Model set in less than 5 minutes
- Computation time:
  - **12 minutes** (!) (COMSOL 6.1 on a laptop / Windows 10 64 bits / Intel(R) Core(TM) i7-8650U / 16 GB RAM)
  - 5 minutes (COMSOL 6.1 on PC / Windows 11, 64 bits / 11th Gen Intel(R) Core(TM) i9-11900 / 32 GB RAM)

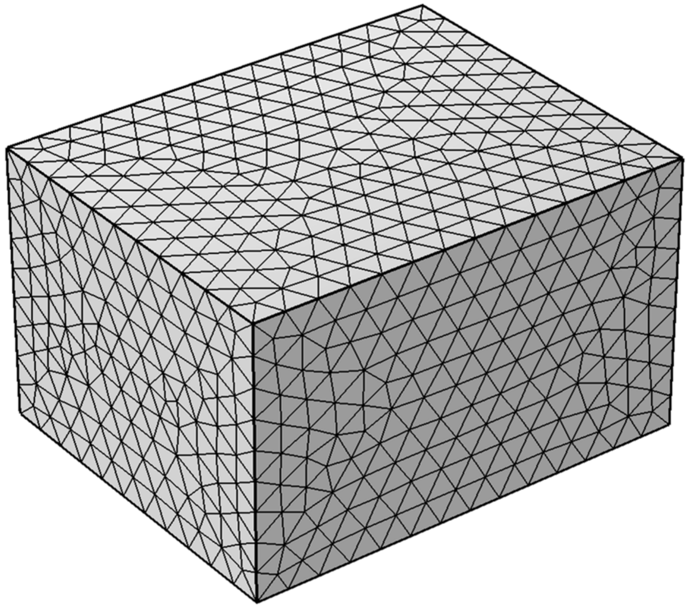




2. Frequency domain: spatial response

- Unique way to have access to sound field distribution throughout the room



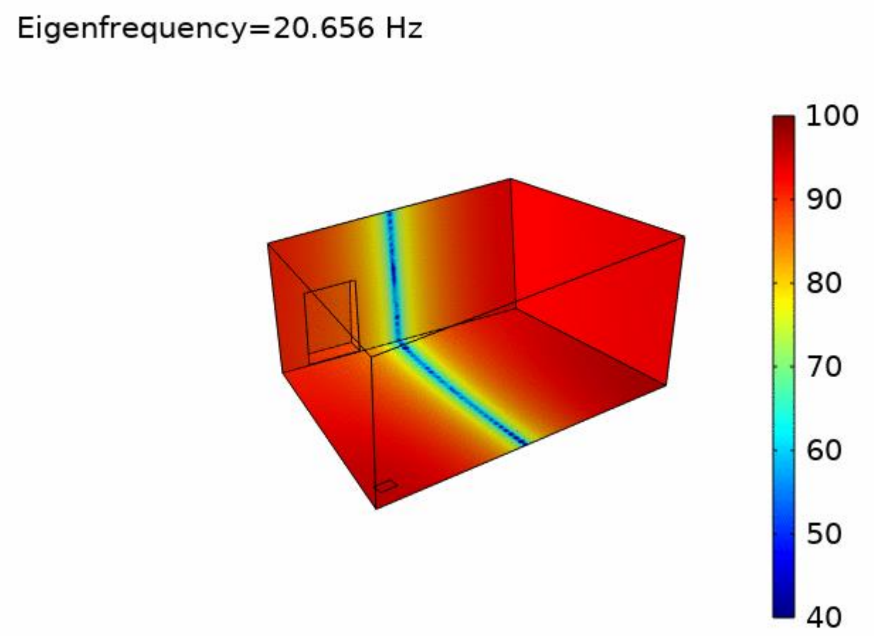


Example 1:
Simulation of arbitrary shapes

Complex rooms: reverberant chamber

- Not accessible through analytical model
- Example 1: Hard-walls
  - Only 4 minutes of computing (with PC / windows11-64 bits / Intel i9 / 32 GB RAM)
  - Hardwalls ➔ real eigenfrequencies

f_n (Hz)
20.66
26.67
35.16
40.56
40.88
45.25
49.16
51.41
53.27
55.07
56.97
59.19
60.83
65.61
67.64
69.57
…



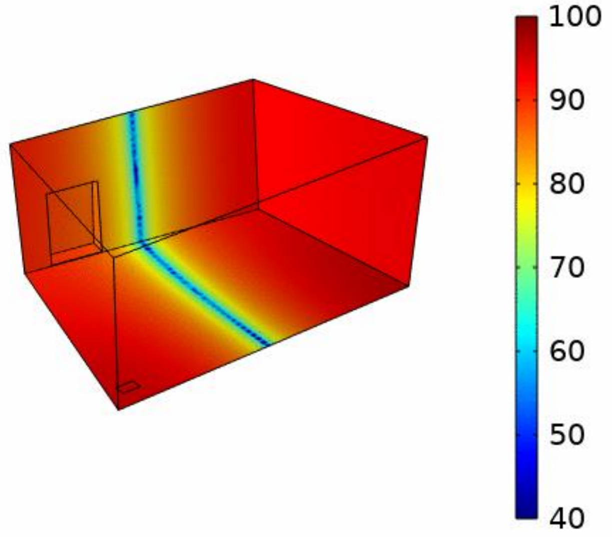
Complex rooms: reverberant chamber

- Not accessible through analytical model
- Example 2: Slightly damped walls
  - Complex eigenfrequencies
  - Possibility to derive modal decay times $MT_{60_n} = \dfrac{3\ln(10)}{2\pi\,\mathrm{Im}(f_n)}$

$\mathrm{Re}(f_n)$ (Hz)	$\mathrm{Im}(f_n)$ (Hz)	$MT60_n$ (s)
20.65	0.36	19.10
26.67	0.39	17.71
35.16	0.44	15.80
40.56	0.41	16.94
40.88	0.40	17.35
45.25	0.50	13.70
49.16	0.49	14.09
51.41	0.44	15.79
53.27	0.43	16.01
55.07	0.53	12.98
56.97	0.51	13.46
59.19	0.42	16.55
60.83	0.40	17.24
65.61	0.55	12.59
67.64	0.53	13.05
69.57	0.46	14.92
…	…	…

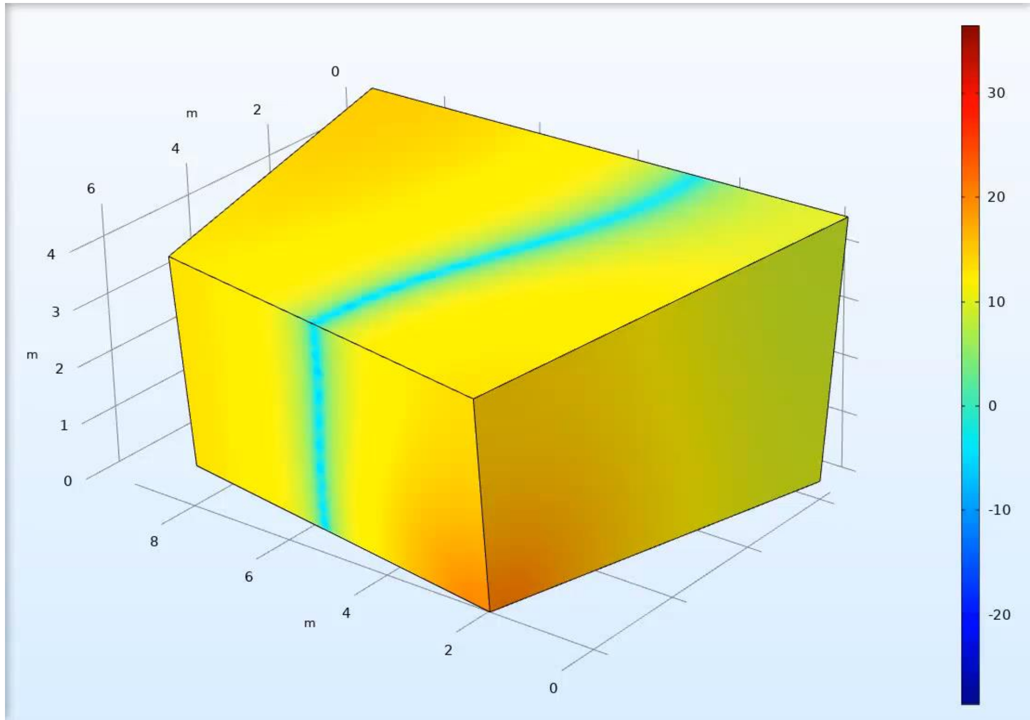
Eigenfrequency=20.654+0.36165i Hz

$\mathrm{Re}(f_n)$ $\mathrm{Im}(f_n)$



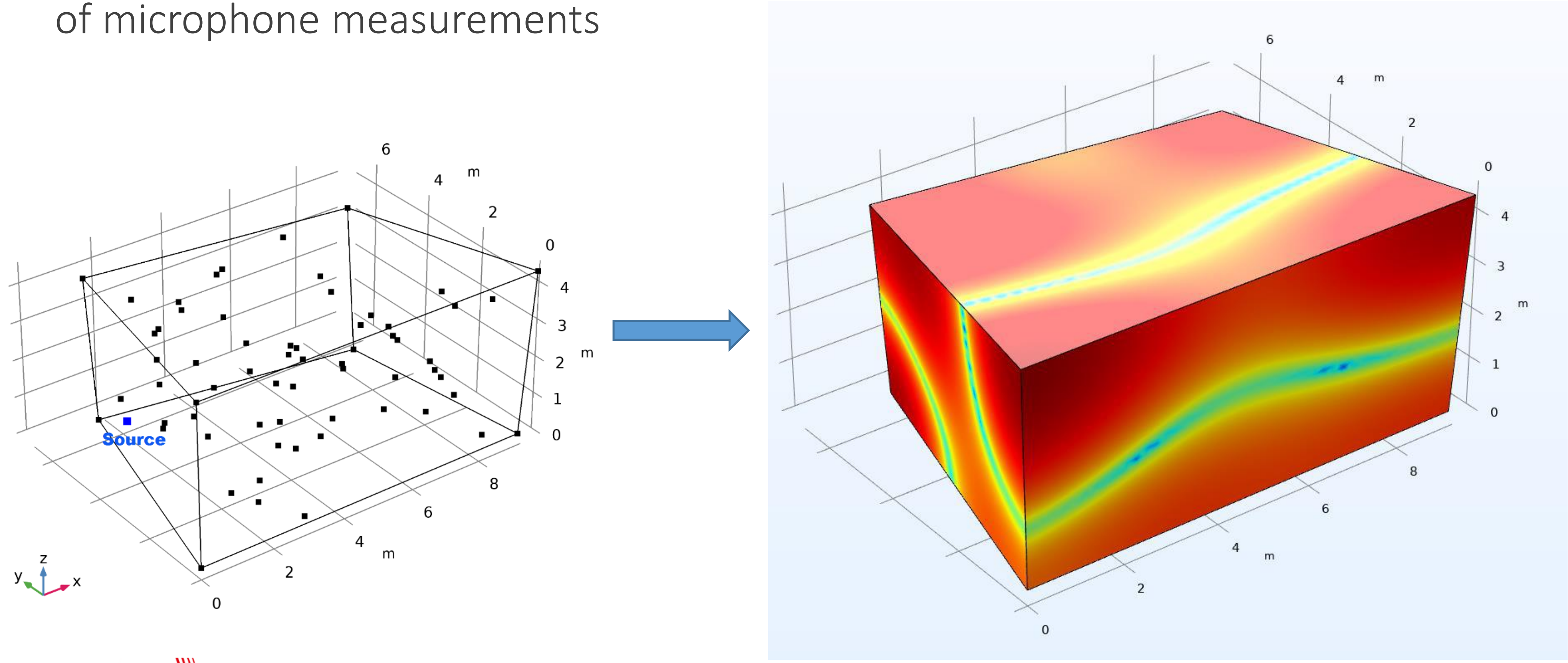
Sound pressure field simulation at low-frequencies

- Goal: visualize the complex sound pressure distribution (nodes / antinodes) in a room
  - Mode shapes are more complex and unpredictable
  - Identification of hot spots and zones of silences
  - Optimal location of compact low-frequency sound absorbers



Sound pressure field reconstruction at low-frequencies

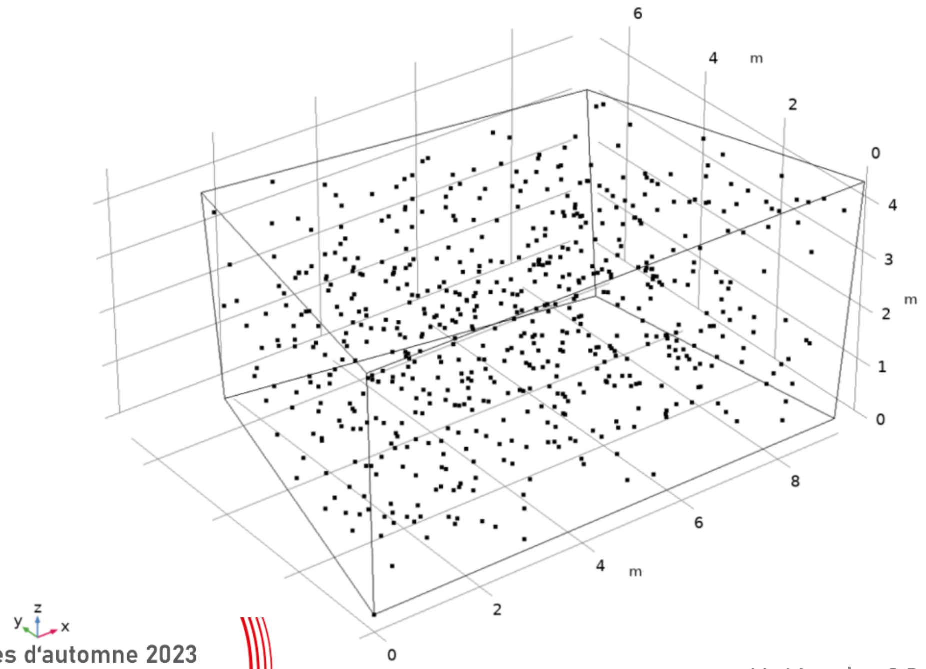
- Benchmark for an experimental method of Sound Field Reconstruction at LF
  - Possibility to reconstruct the sound field spatial distribution out of a limited number of microphone measurements

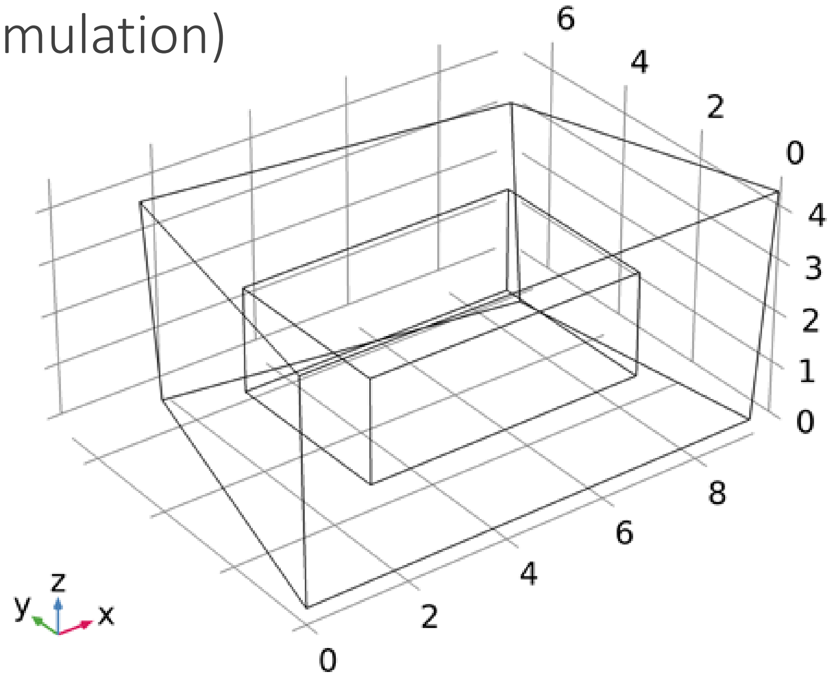


Sound pressure field reconstruction at low-frequencies

- FEM Analysis of a non-rectangular room model
  - Lightly-damped walls with α_{wall}=0.01
  - 600 randomly-spaced «virtual» microphones – 30 used as input the remaining for validation
  - Sound field estimation in a rectangular-shaped volume inside the room (1 m away from walls)

Compare with «real» sound field distribution (full COMSOL simulation)

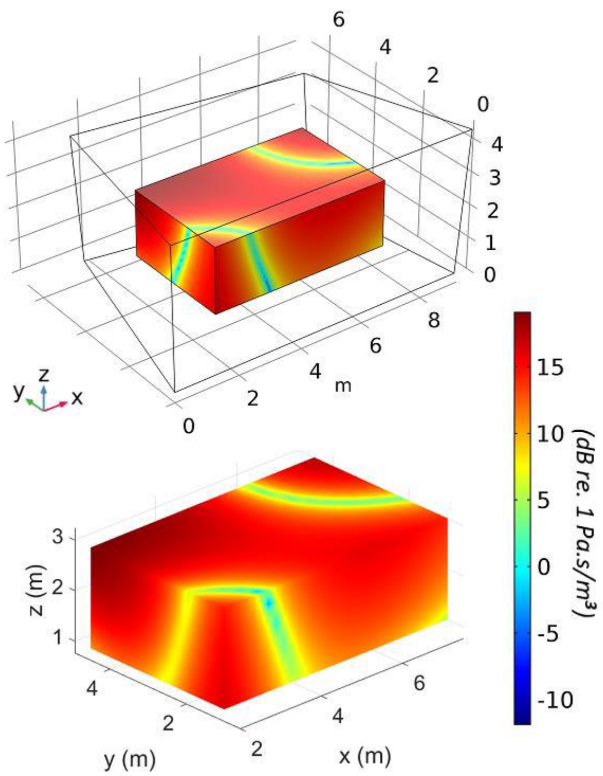




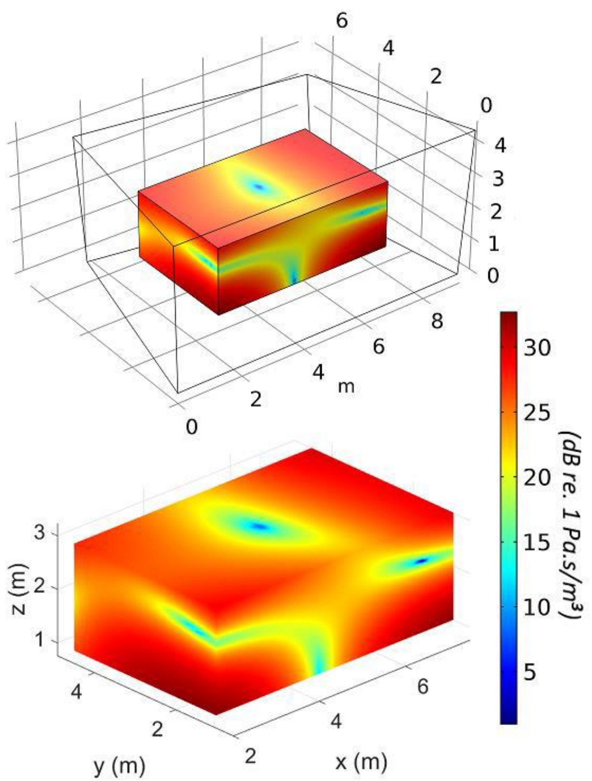
Sound pressure field reconstruction at low-frequencies

Reference sound field
(full simulation)

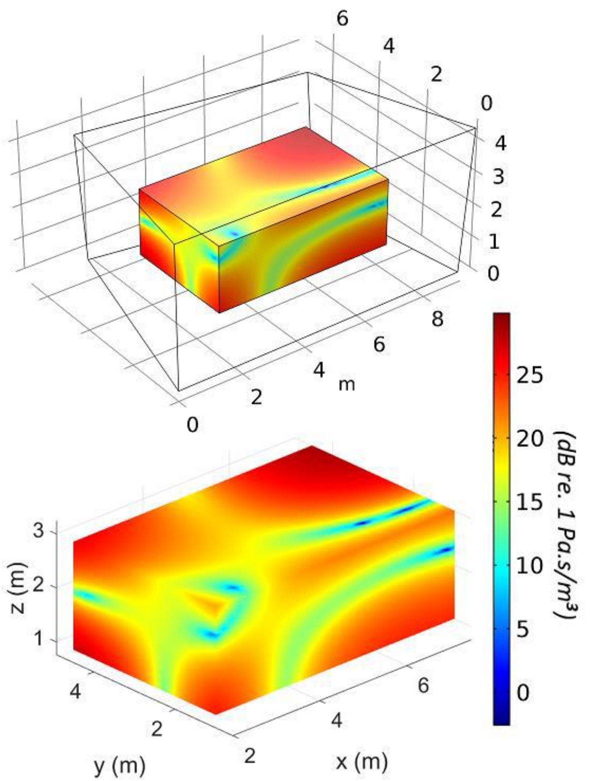
Reconstructed sound field
(out of 30 of microphones)



$f = 38.00\ Hz$



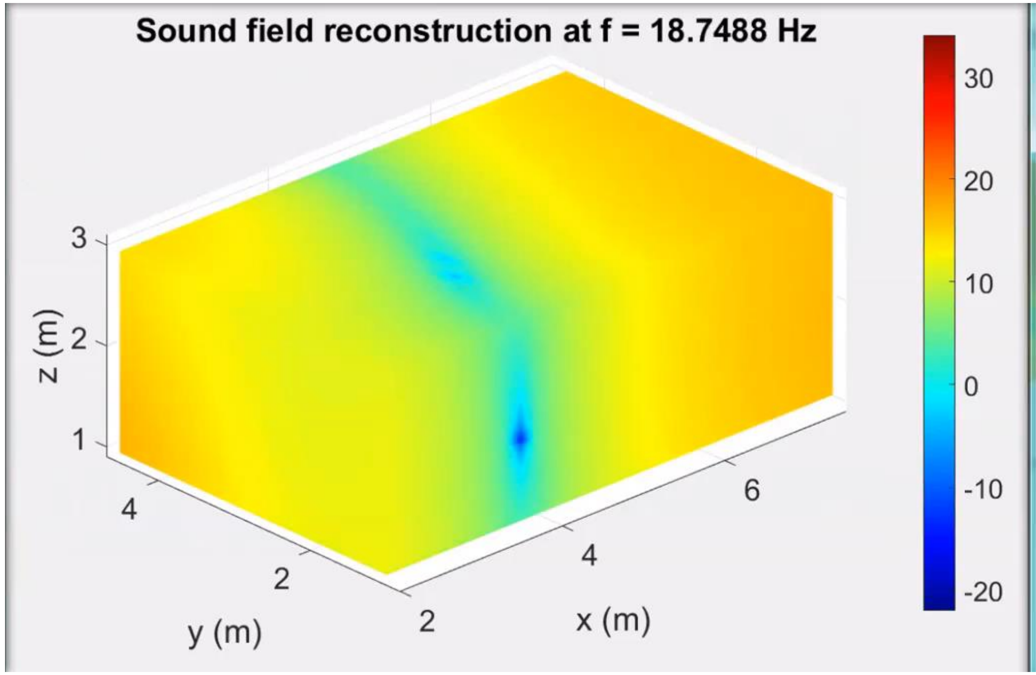
$f = 45.25\ Hz$

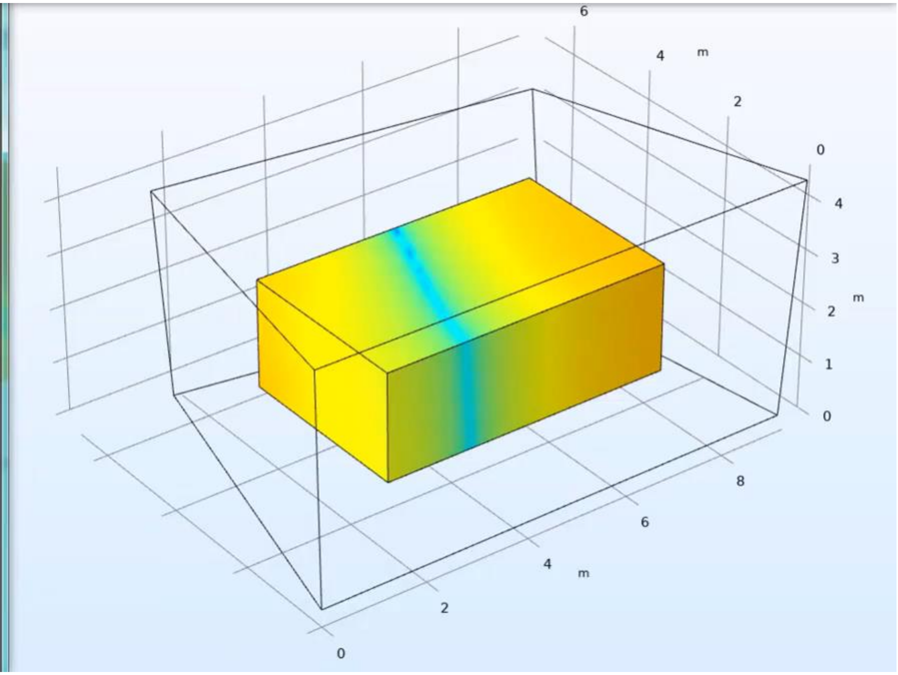


$f = 55.08\ Hz$

Numerical validation

- Broadband performance





Reconstructed sound field
(out of 30 microphones)

Reference sound field (full simulation)

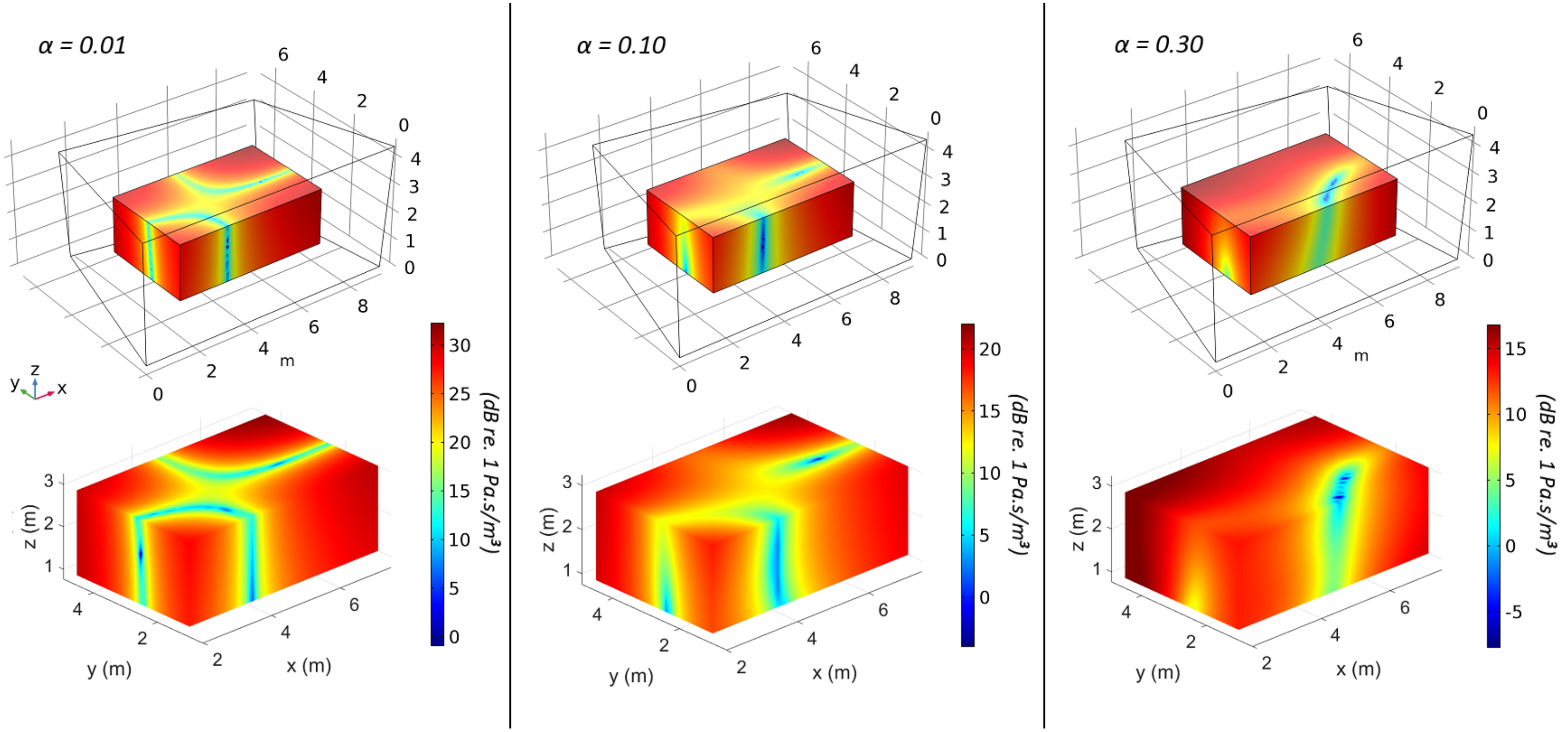
Thach Pham Vu, Hervé Lissek ,Low frequency sound field reconstruction in a non-rectangular room using a small number of microphones, Acta Acust. 4 (2) 5 (2020)
DOI: 10.1051/aacus/2020006

Numerical validation

- We can even play with wall damping

Reference sound field

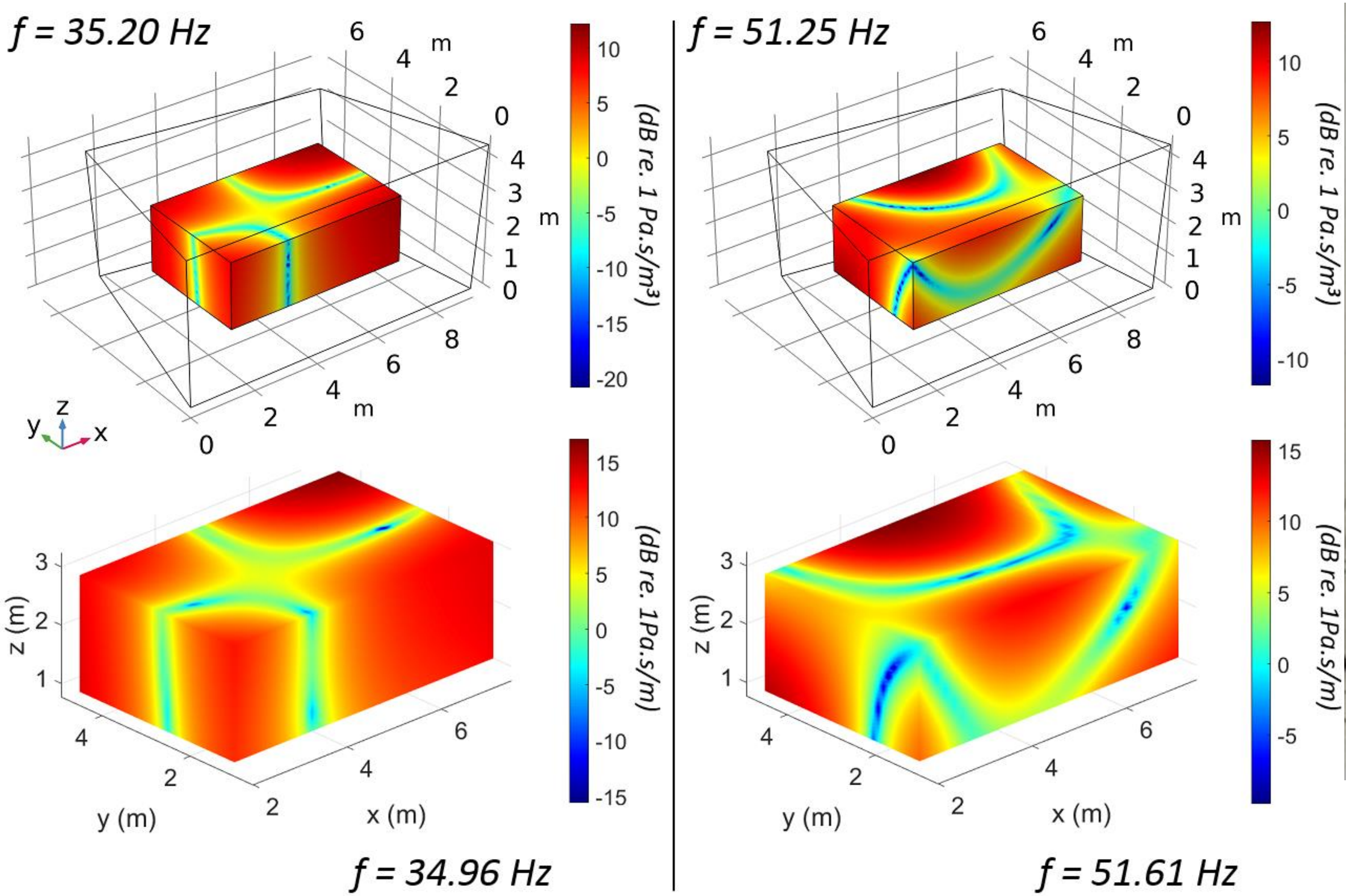
Reconstructed sound field



Numerical model to benchmark experimental data

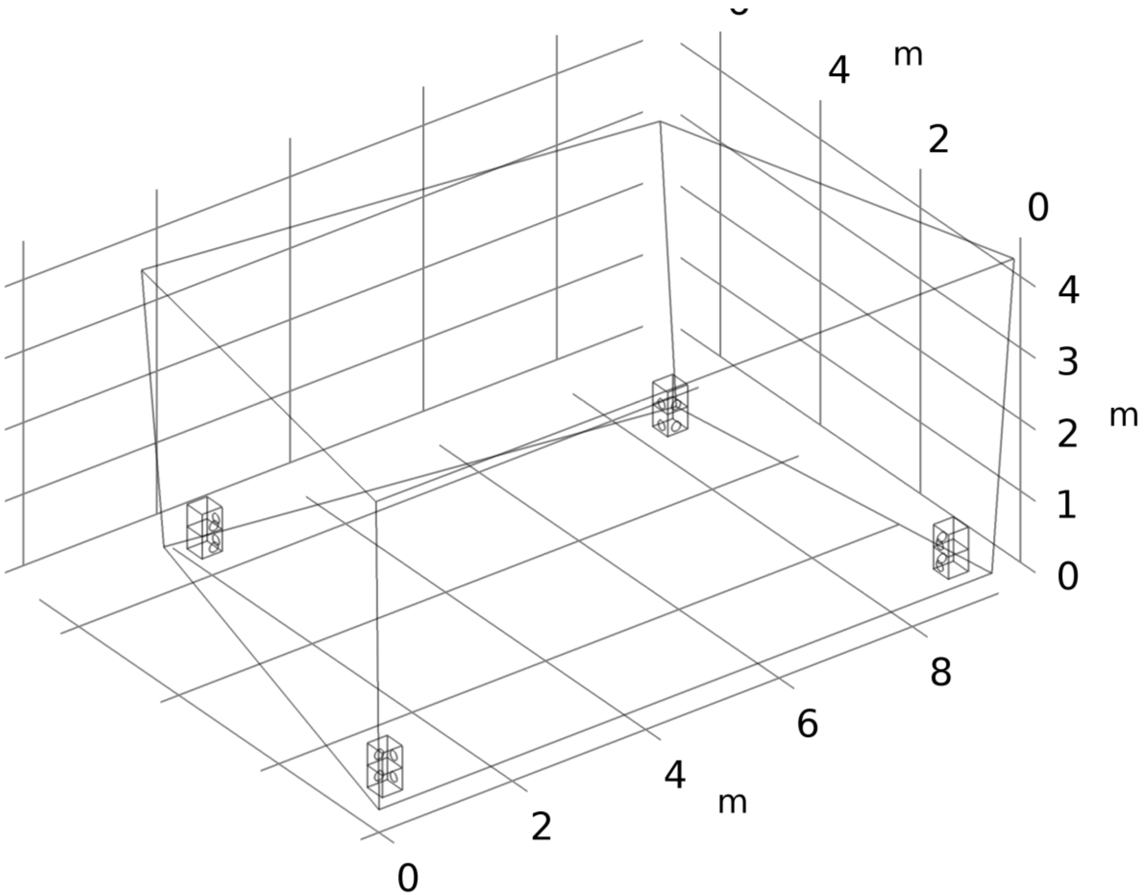
Reference sound field
(COMSOL simulations)

Reconstructed sound field
(with experimental data)



Example 2:
Application to active sound absorbers

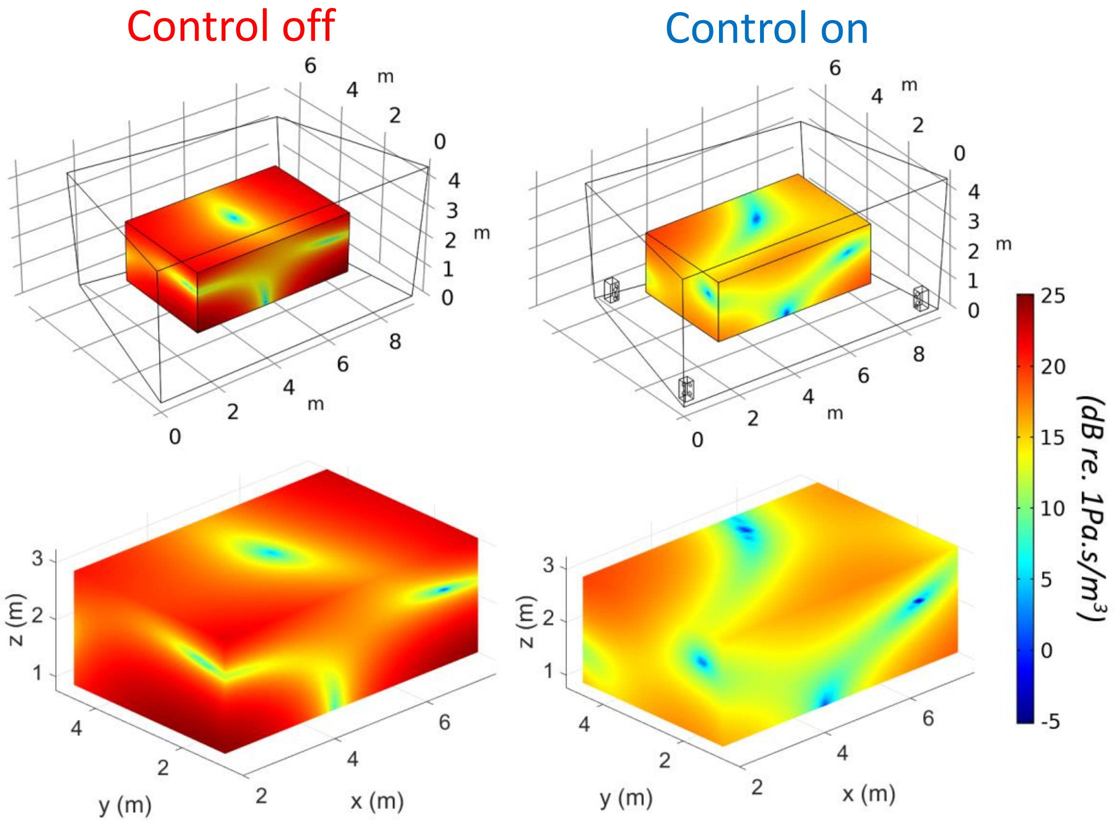
Model of discrete active sound absorbers



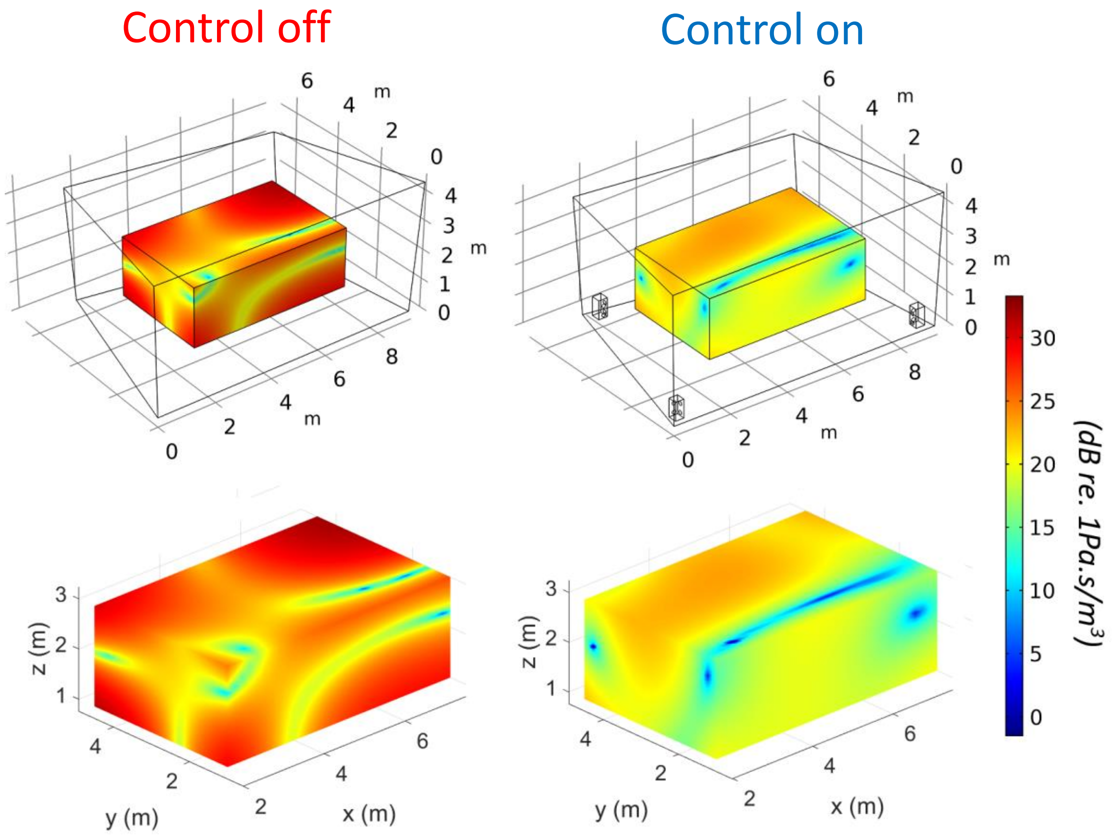
Model of discrete active sound absorbers

- Impact on eigenmodes and eigenfrequencies

Mode @ 45.25 Hz

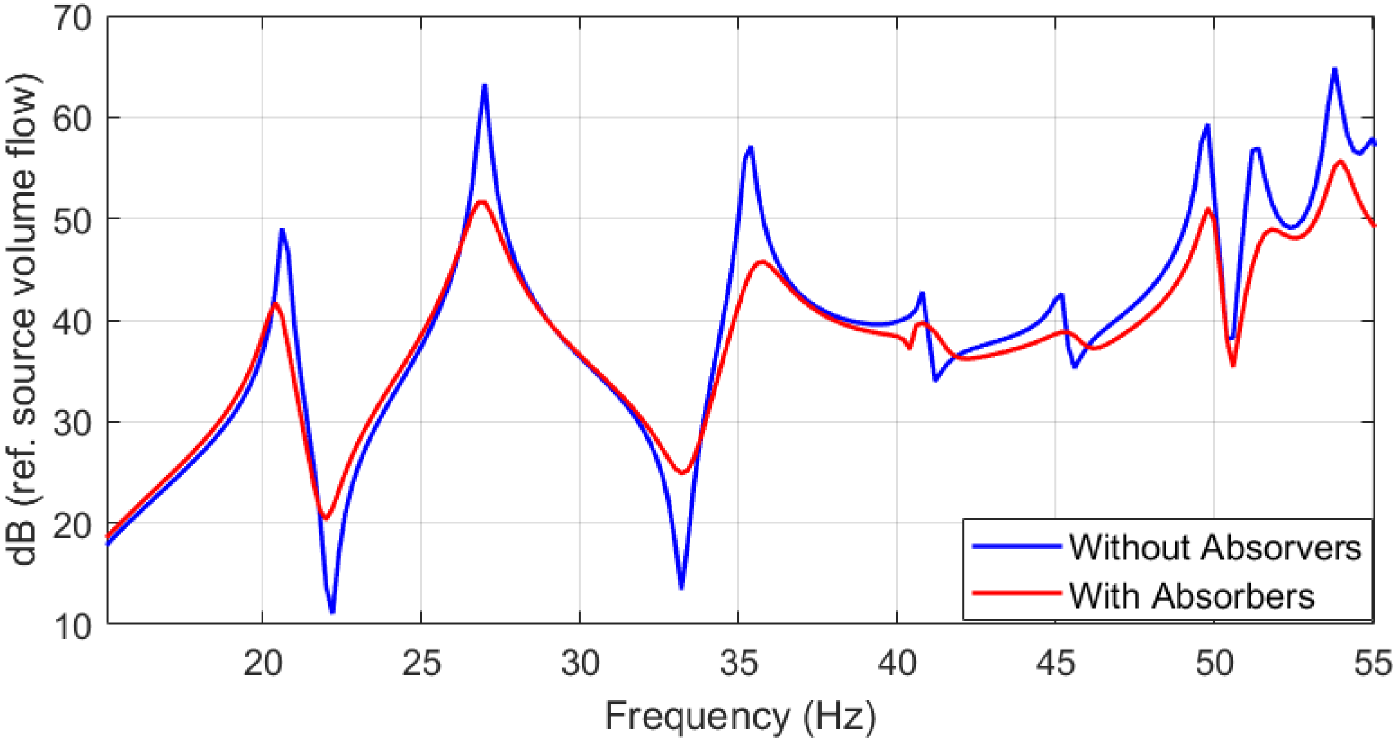


Mode @ 55.07 Hz



Model of discrete active sound absorbers

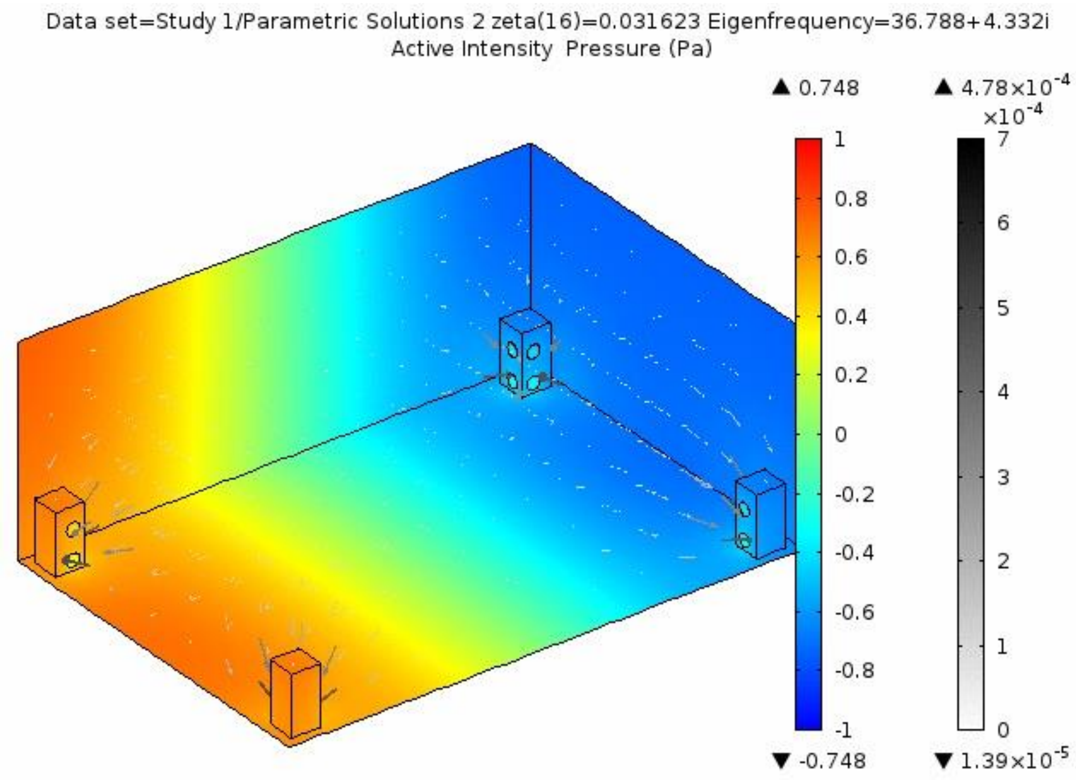
- Frequency responses
  - with 4 active electroacoustic absorbers,
  - one source at one corner
  - one microphone at another corner



Optimization of active absorbers settings

- Test different values of active impedance $Z_{target} = \zeta Z_c$

and visualize the effect on intensity streams and sound pressure distribution



Conclusions

- COMSOL takes more time to compute room acoustics at low frequencies for simple room shapes
  - Not necessarily more complex to build a model (for expert, less than 5 minutes to set up)
  - But the FEM processing takes more time than simple analytical models

- But indispensable for
  - complex-shaped rooms:
    - eigenfrequencies, mode shapes, modal decay time
    - Frequency response of the room
  - simulating the effect of discrete sound absorbers
  - optimizing their settings and placement

Thank you for your attention