Sound Field Reconstruction in Low-Frequency Room Acoustics: A Benchmark Study With Simulation

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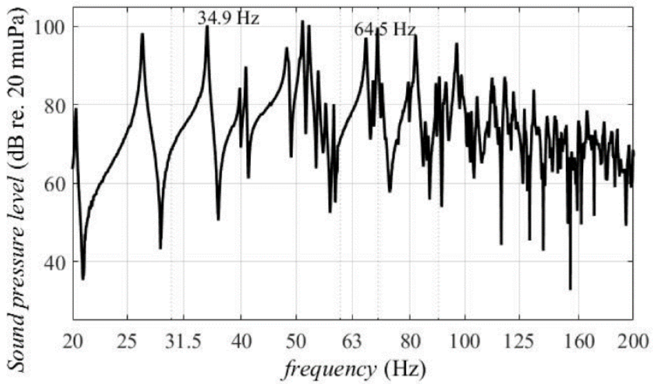
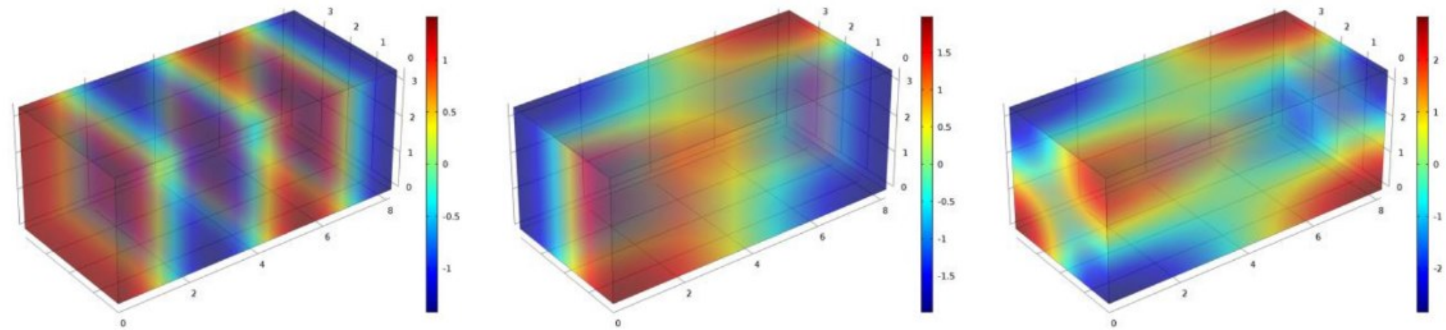
Contents

- Introduction
- Sparsities in Low-Frequency Room Acoustic
- Reconstruction procedures
- Numerical Models and Validation

Introduction:
Sound field in room at Low Frequencies (LF)



- Coupling with room by standing waves
- Uneven distribution of sound pressure in space and frequency domain



A thorough understanding of sound field in room is highly appreciated

Introduction:
Reconstruction of sound fields in room

- Standard measurement techniques: Impractically high number of measurements

- Solution
  Compressive Sensing:
  Sparsities in LF room acoustics → lower number of measurements for RIRs interpolation.

  Need an extensive test of validity

*R. Mignot, G. Chardon and L. Daudet, "Low Frequency Interpolation of Room Impulse Responses Using Compressed Sensing", in IEEE/ACM Transactions on Audio, Speech, and Language Processing, vol. 22, no. 1, pp. 205-216, Jan. 2014.

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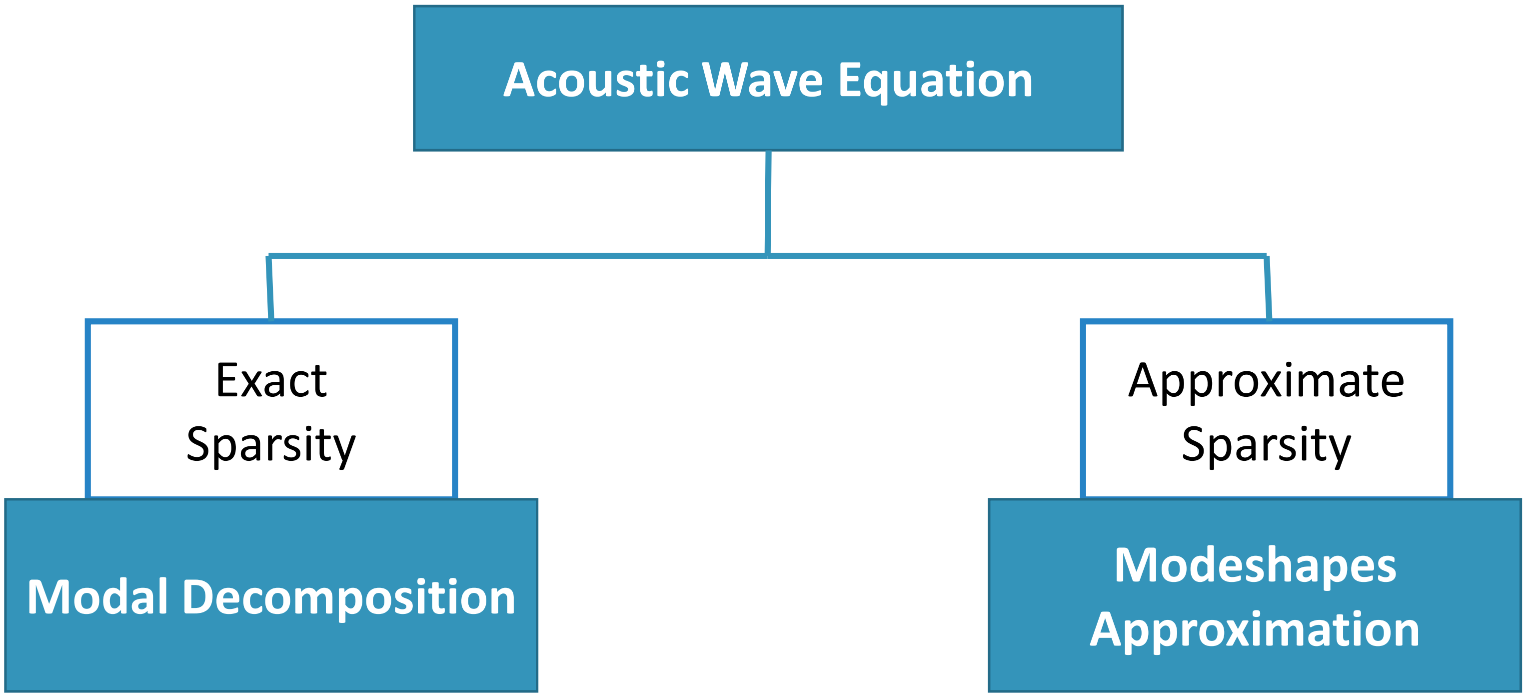

Acoustic Wave Equation
Exact Sparsity
Modal Decomposition
Approximate Sparsity
Modeshapes Approximation

A. Modal decomposition

- In LF room acoustic, the solution of the wave equation can be decomposed as discrete sum of damped harmonic eigenmodes

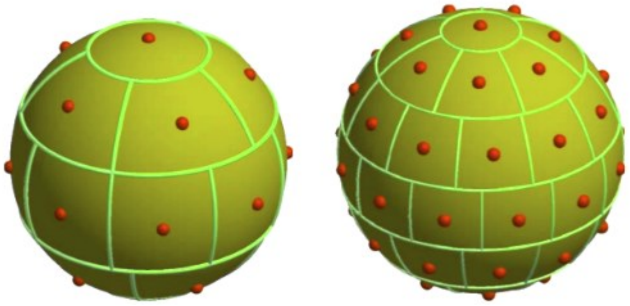
$$p(t,\vec{X}) = \sum_{n\in\mathbb{Z}^*} A_n \Phi_n(\vec{X}) e^{jk_n c_0 t}$$

c_0: speed of sound
A_n: Expansion coeff.
$k_n = (\omega_n + j\delta_n)/c_0$: wavenumber of eigenmode
ω_n: eigenfrequency δ_n: damping coeff.

B. Modeshapes Approximation

Plane waves spherical sampling approximation of modeshapes

$$\Phi_n(\vec{X}) \approx \sum_{r=1}^{R} B_{n,r} e^{j\vec{k}_{n,r}\cdot\vec{X}}$$

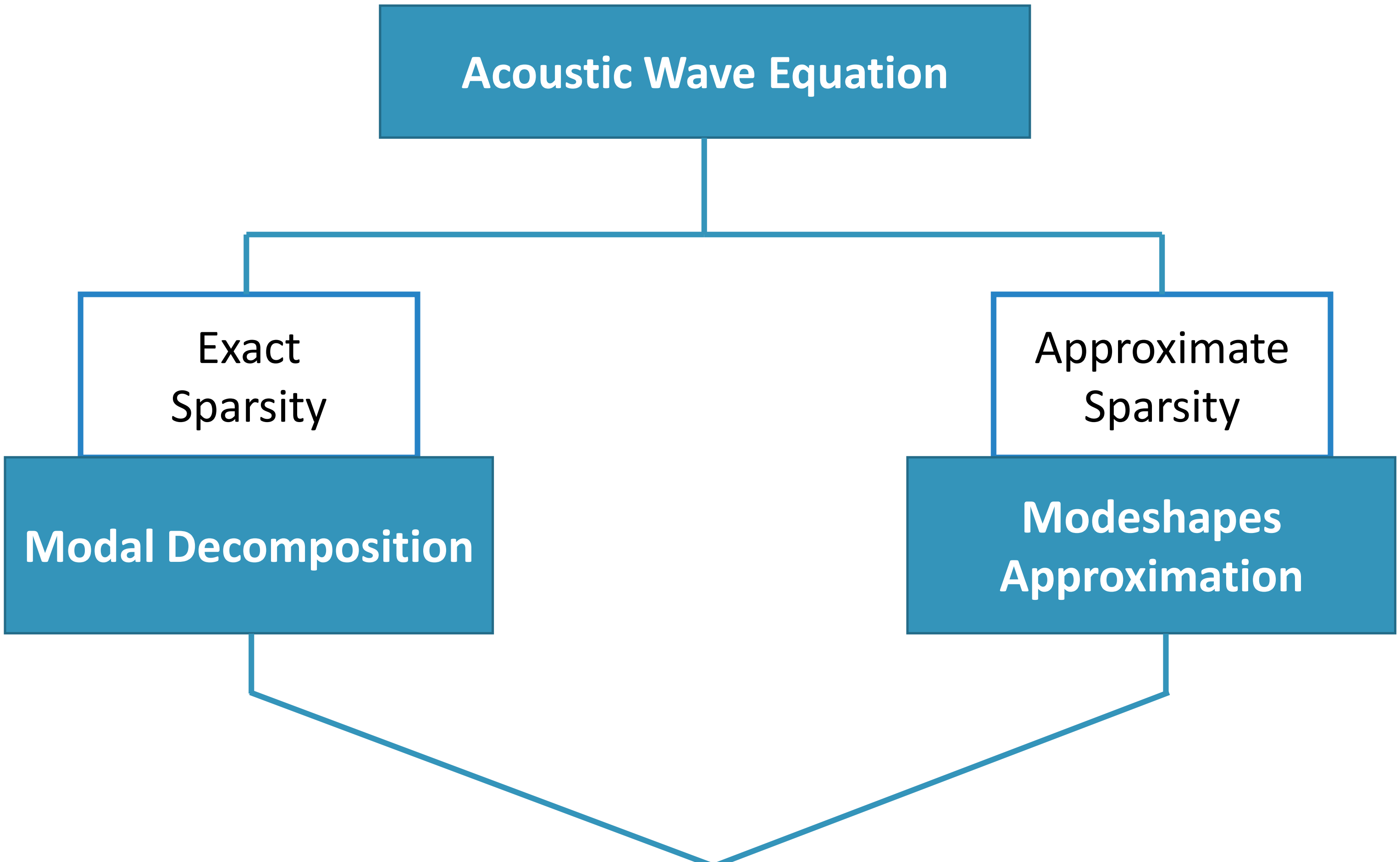


$R = 25$ $R = 50$

$B_{n,r}$: Expansion coeff.

$\vec{k}_{n,r}$ wave vector with $\|\vec{k}_{n,r}\|_2 = |k_n| \ \forall\, r \in R$

Well adapted to non-rectangular rooms



$$p(t,\vec{X}) = \sum_{n,r} C_{n,r} e^{jk_n c_0 t} e^{j\vec{k}_{n,r} \cdot \vec{X}}$$

Finite weighted sum of damped harmonic plane waves

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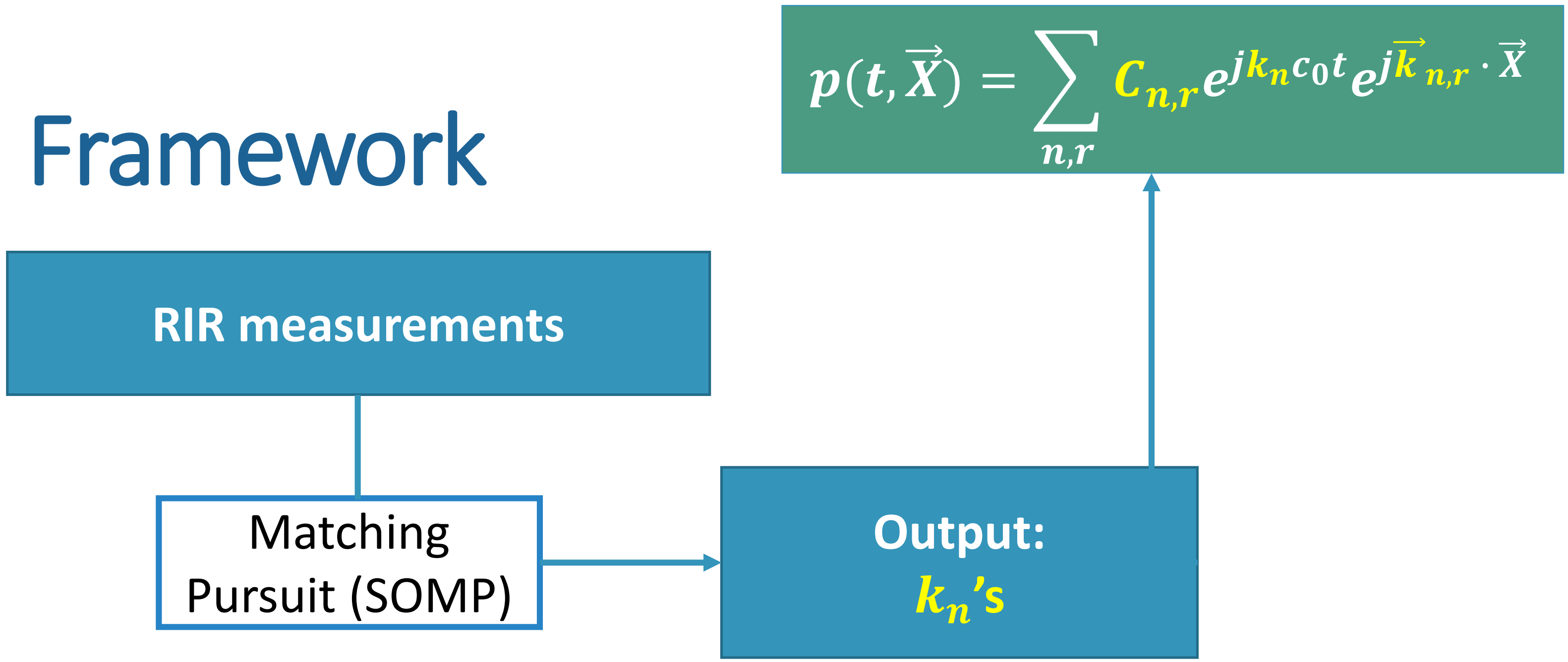
Reconstruction framework

$$p(t,\vec{X}) = \sum_{n,r} C_{n,r} e^{jk_n c_0 t} e^{j\vec{k}_{n,r}\cdot\vec{X}}$$

Objective: Through M measurements

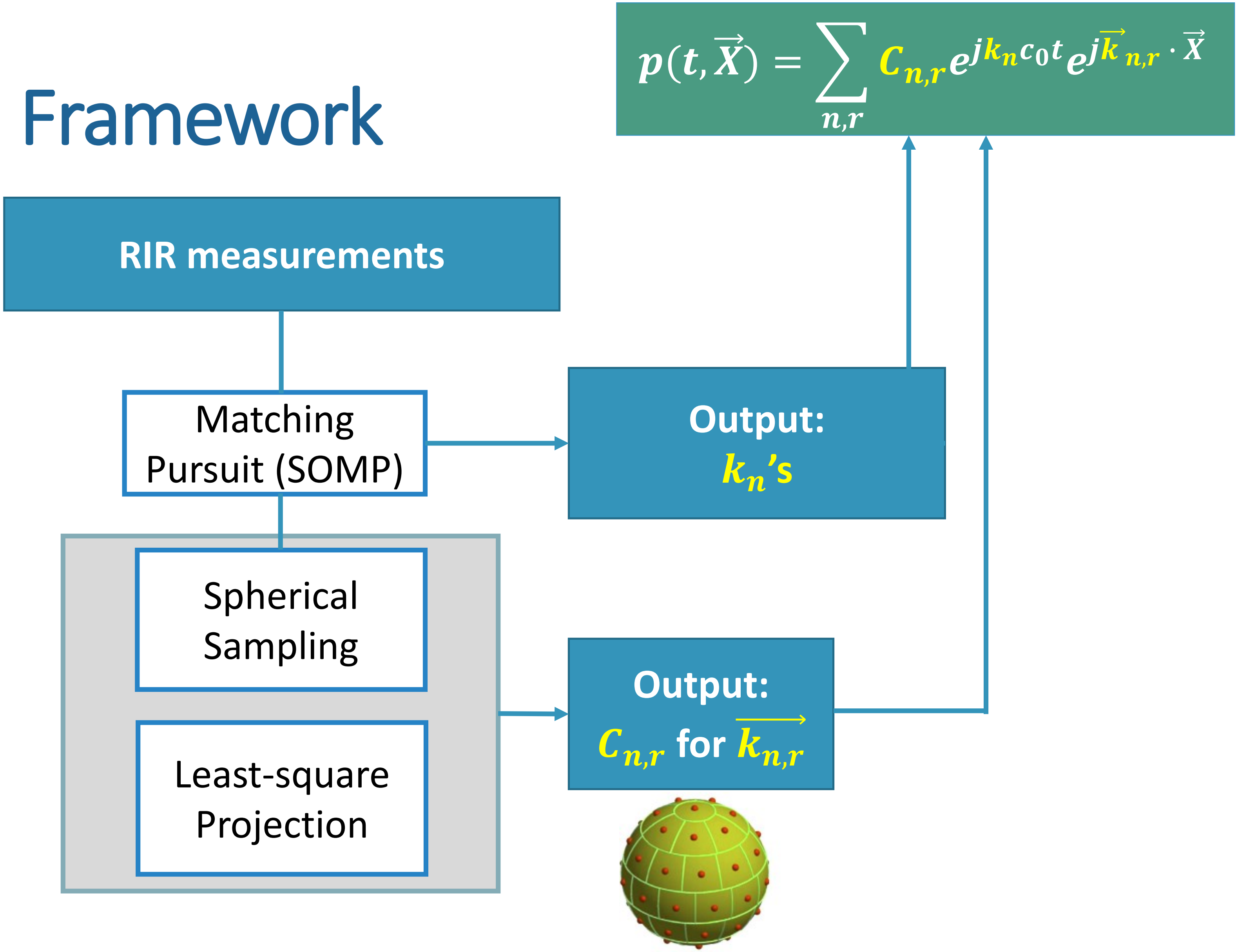
- Estimate k_n's for N modes
- For each mode n, define $\vec{k}_{n,r}$'s as spherical sampling vectors
- Find $C_{n,r}$ for each $\vec{k}_{n,r}$

Framework



$$k_n = (\omega_n + j\delta_n)/c_0$$

Framework


$p(t, \vec{X}) = \sum_{n,r} C_{n,r} e^{jk_n c_0 t} e^{j\vec{k}_{n,r} \cdot \vec{X}}$
RIR measurements
Matching Pursuit (SOMP)
Output: k_n's
Spherical Sampling
Least-square Projection
Output: $C_{n,r}$ for $\vec{k_{n,r}}$

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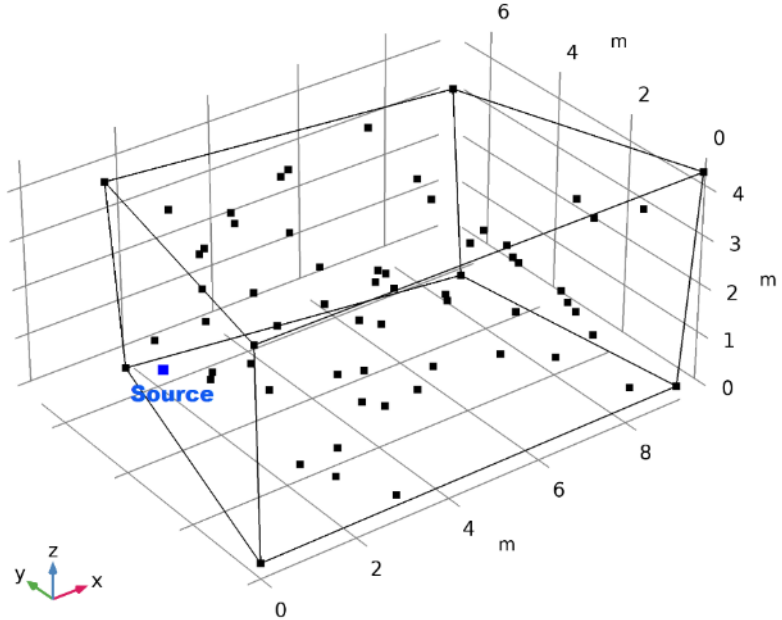
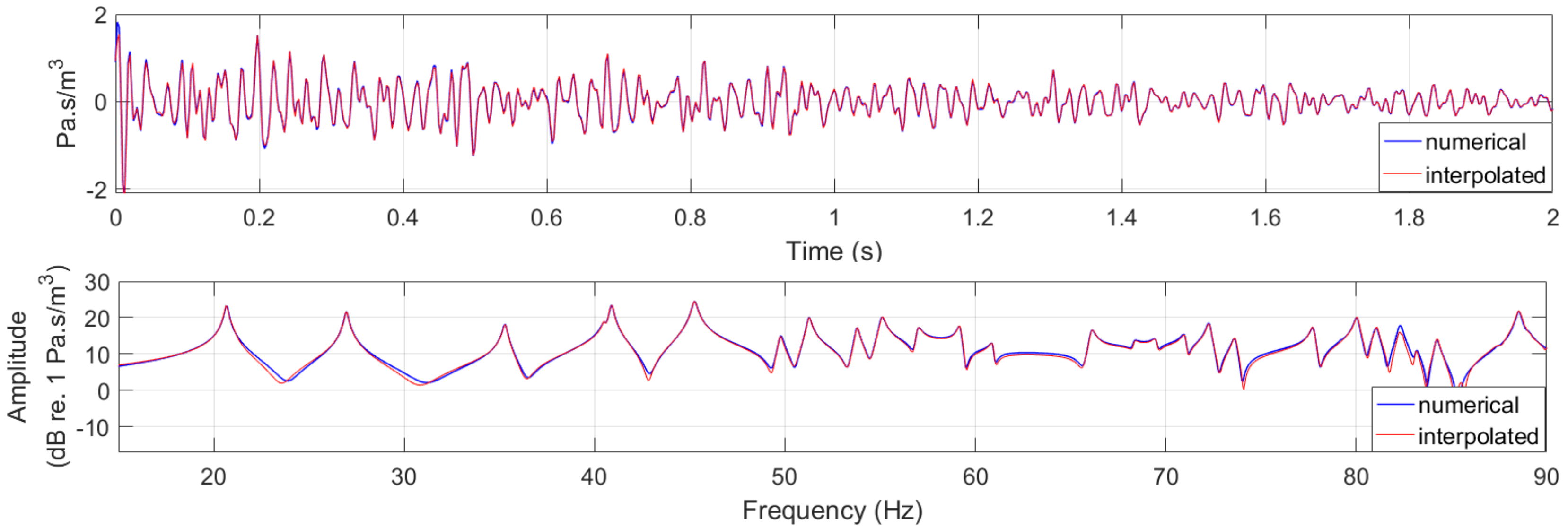
Numerical model

- FEM Analysis of a non-rectangular room model
- Lightly damped walls with $\alpha_{wall} = 0.01$
- 50 randomly placed measurement points
- Simulation data used for both input and validation
- Use broad-band response as input for the algorithm



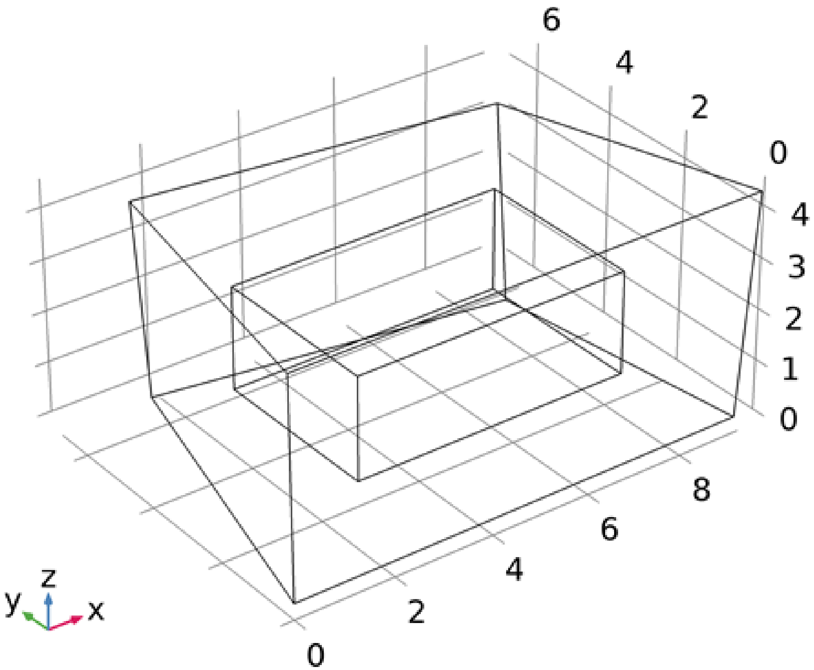
Numerical Validation:
1. Time – Frequency response comparison



This is only for one interpolated position in the room → not enough to assess the validity of the framework!

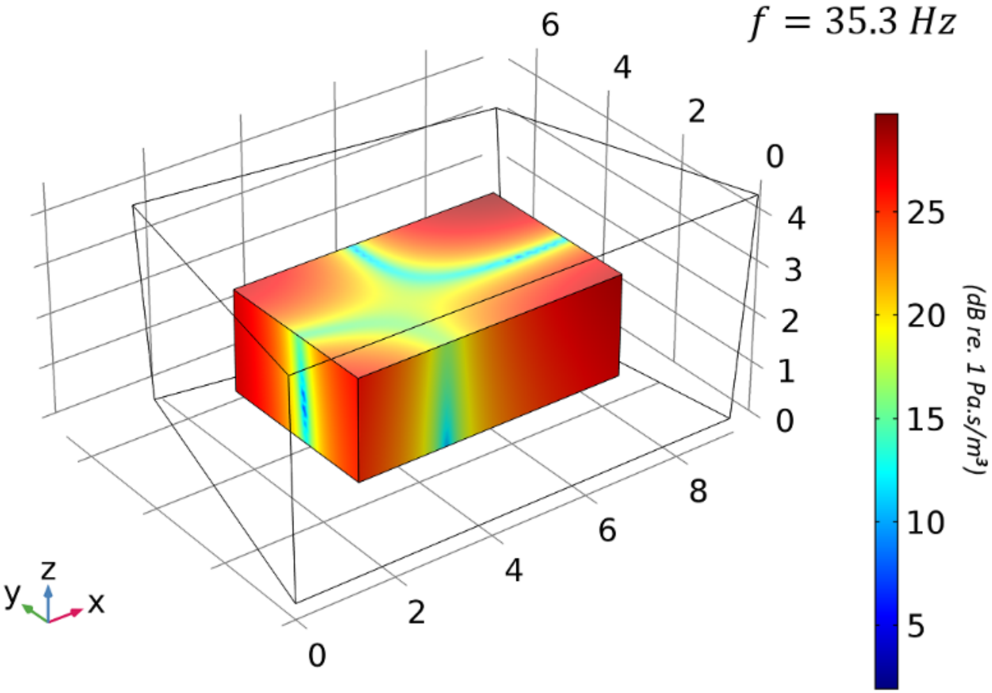
→ Lack of spatial information

Numerical Validation:
2. Spatial Sound Field Reconstruction



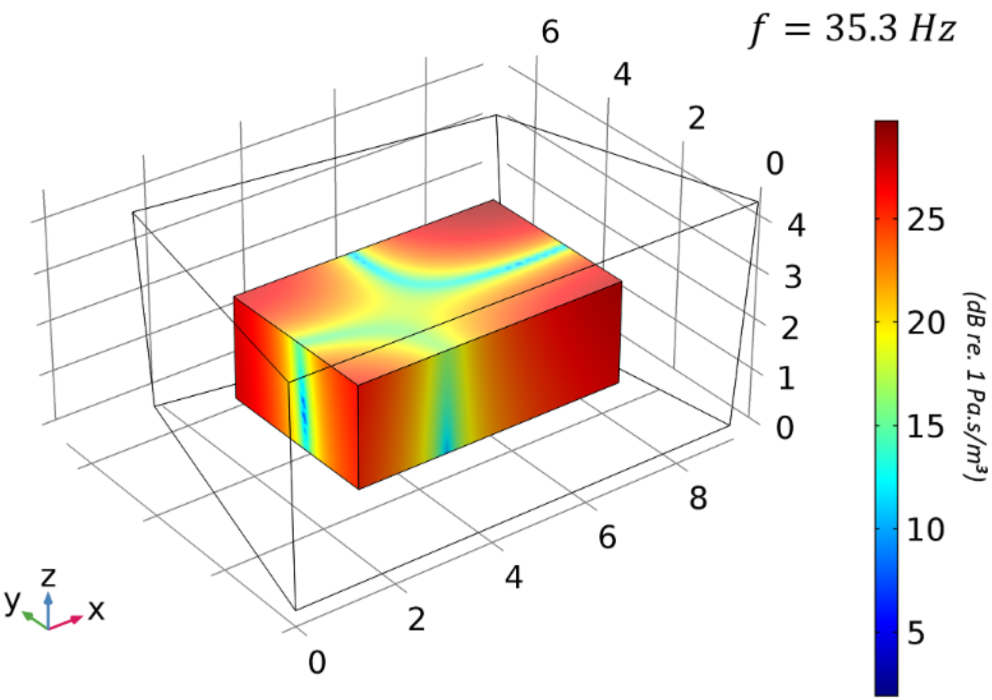
- Sound field reconstruction of a rectangular-shaped area inside the room with distance at least 1m from each walls
- Avoid non-orthogonality of modeshapes near the walls

Numerical Validation:
2. Spatial Sound Field Reconstruction

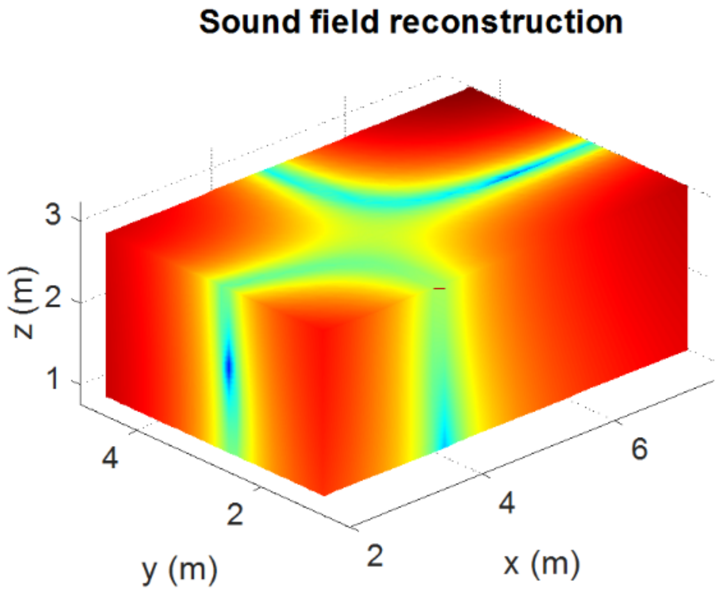


Reference sound field

Numerical Validation:
2. Spatial Sound Field Reconstruction



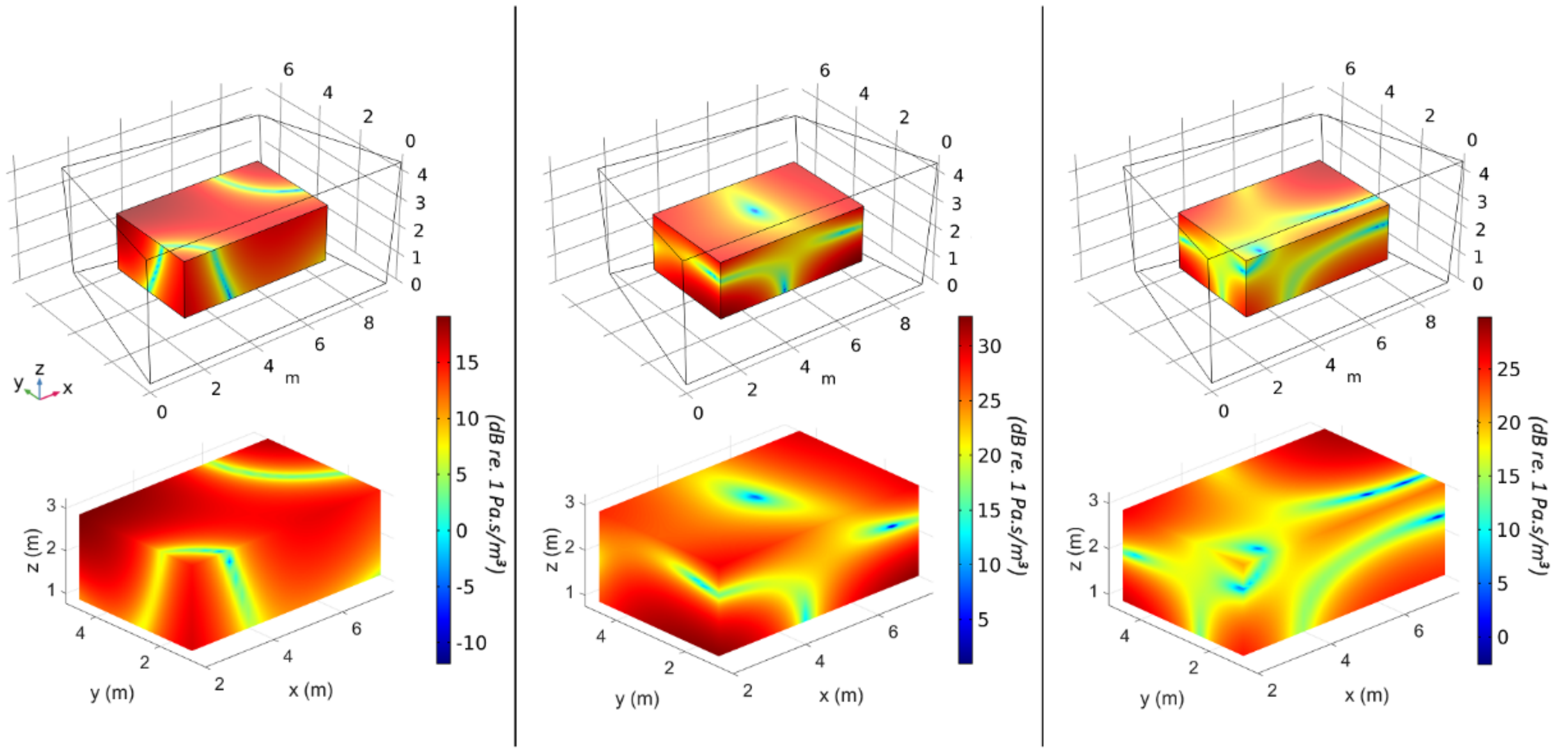
Reference sound field



Numerical Validation:
2. Spatial Sound Field Reconstruction - A few more examples

Reference sound field

Reconstructed sound field



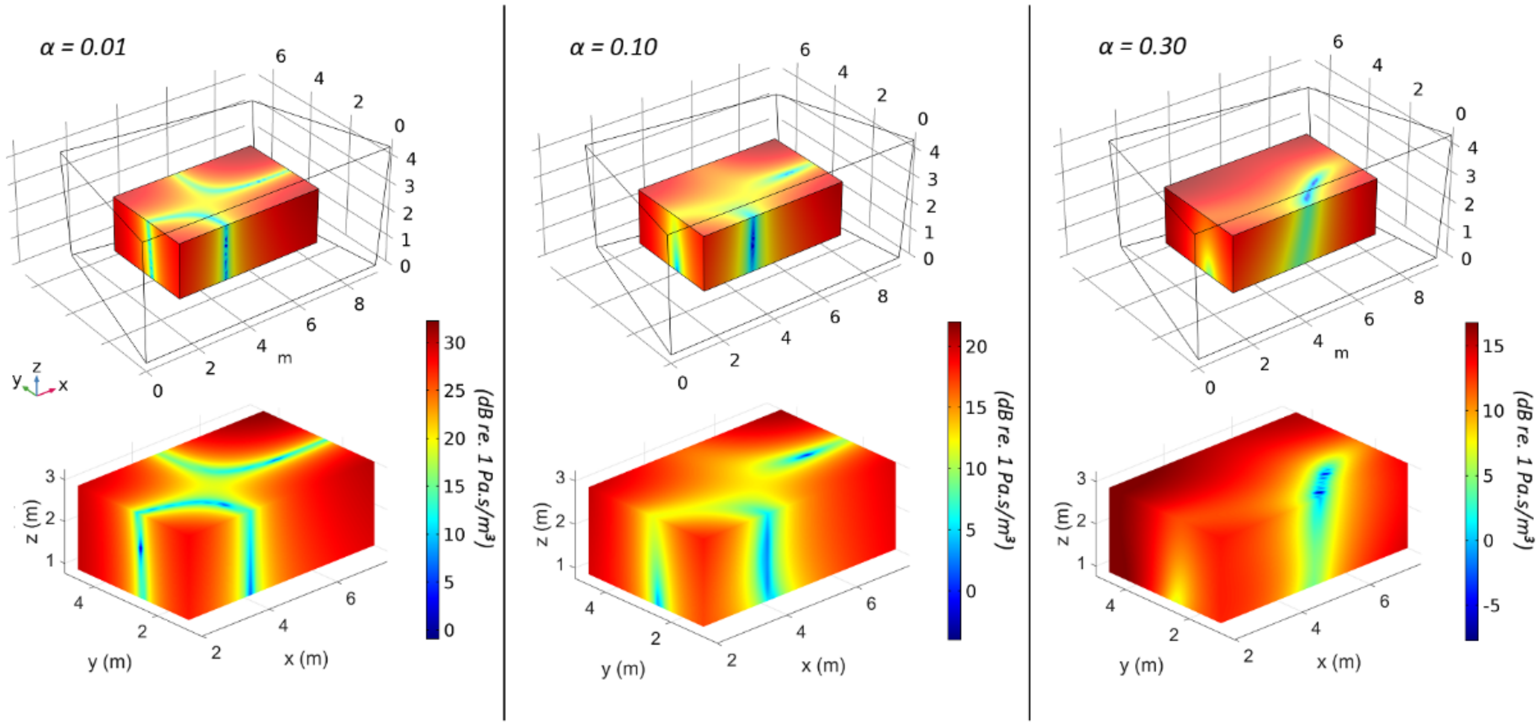
$f = 38.00\ Hz$ $f = 45.25\ Hz$ $f = 55.08\ Hz$

Numerical Validation:
2. Spatial Sound Field Reconstruction
3D demo

Numerical Validation:
3. Higher Wall Damping

Reference sound field

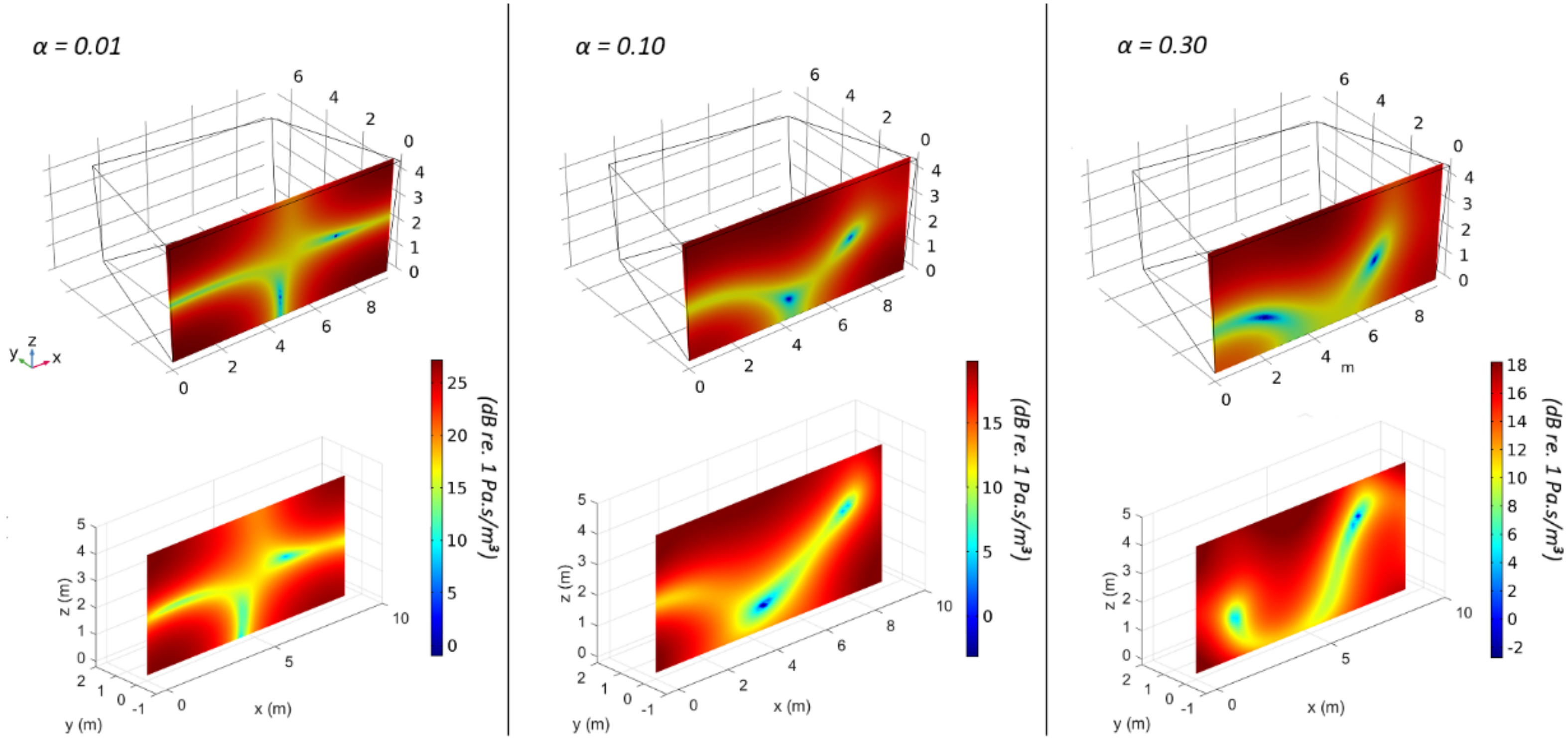
Reconstructed sound field



Numerical Validation:
3. Higher Wall Damping

Reference sound field

Reconstructed sound field



Numerical Validation:
3. Higher Wall Damping

- Reconstruction maintains accuracy for regions not close to the wall

- Near-wall performance is not as good
  - Reasons:
    - Boundary is always harder for interpolation
    - Orthogonality of modeshapes functions is less valid

- Meaningful for assessing sound field control/manipulation

Conclusion

- Compressive Sensing Algorithm is valid for sound field reconstruction even in case of a non-rectangular room
- Reconstruction validated with different damping conditions
- Useful for assessing room acoustic and evaluating active/passive modal equalization methods
- Future work: boundary reconstruction improvement, reduce number of microphones

Thank you