

# Acoustic Simulations in Buildings: The Multi-method Approach of COMSOL Multiphysics

Sven Friedel  
COMSOL Zurich

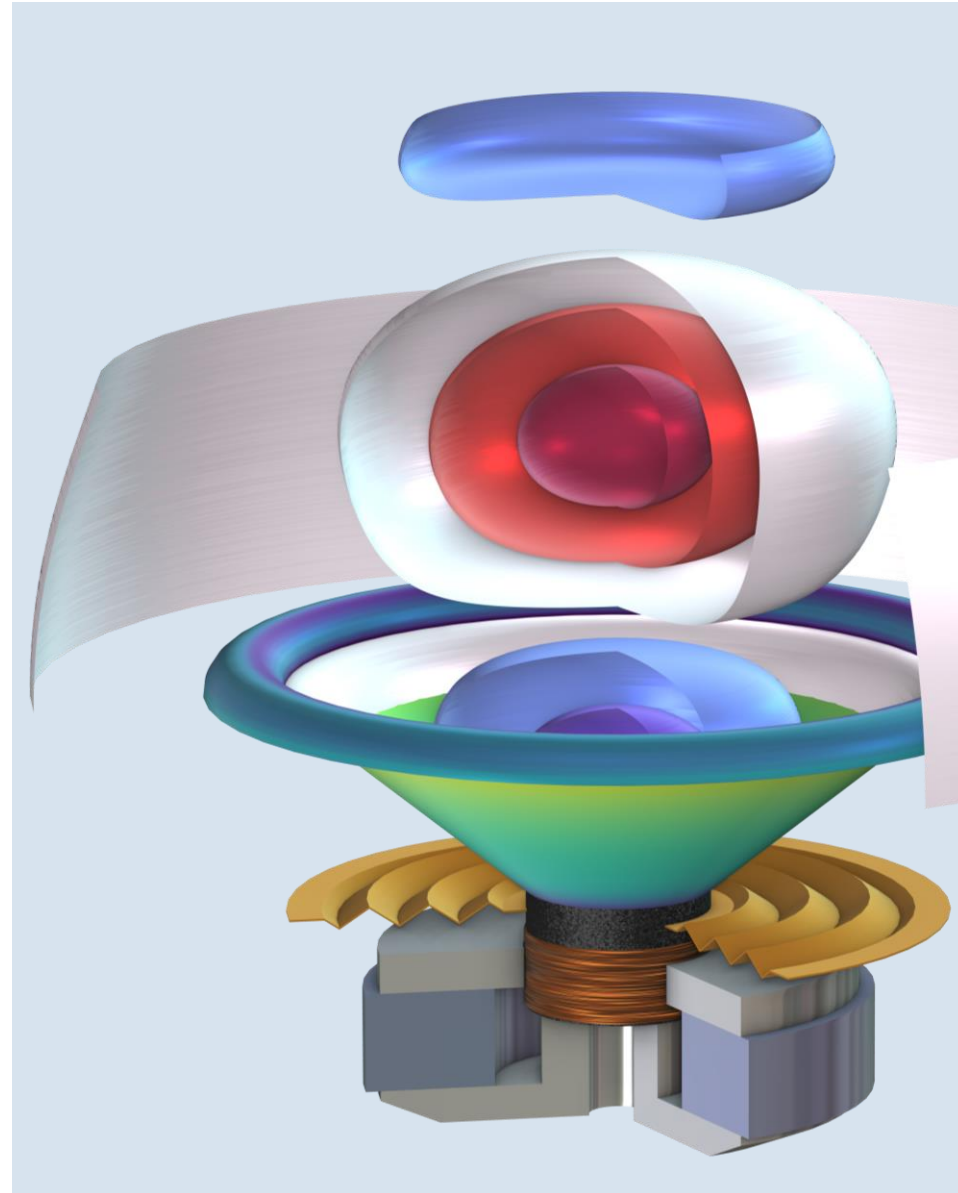
# Agenda

- Introduction – The COMSOL Perspective on Acoustics
- Geometric Acoustics
- Wave Acoustics and Hybrid Modeling
- Acoustic-Structure Interaction

# COMSOL Multiphysics®

*One software environment for  
any engineering field.*

- Provides fully coupled multiphysics and single-physics modeling capabilities.
- Unified User-Interface
- Seamless integration in engineering design workflow
- Allows creation of stand-alone applications



## LOUDSPEAKER MULTIPHYSICS

### *Pressure Acoustics*

Sound wave propagates through air

### *Structural Mechanics*

Membrane vibration excited by EM forces.

### *Electromagnetics*

Voice coil driven by voltage interacts with permanent magnet.

Model tree shows sequences of operations

Definitions

Geometry

Materials

Physics

Electromagnetics

Mesh

Study

Results

loudspeaker\_driver\_3d.mph - COMSOL Multiphysics

File Home Definitions Geometry Materials Physics Mesh Study Results Developer

Application Builder Model Manager Component 1 Add Component Parameters Variables Functions Parameter Case Build All Import LiveLink Part Libraries Add Material Magnetic Fields Add Physics Add Mathematics Build Mesh Mesh 1 Compute Study 2 - Structural Eigenmodes Add Study Combined Plot Add Plot Group Add Predefined Plot Windows Reset Desktop Layout

Workspace Model Definitions Geometry Materials Physics Mesh Study Results Layout

Model Builder

Type filter text

- loudspeaker\_driver\_3d.mph (root)
  - Global Definitions
    - Parameters 1
    - Default Model Inputs
    - Materials
  - Component 1 (comp 1)
    - Definitions
    - Geometry 1
    - Materials
    - Magnetic Fields (mf)
      - Free Space 1
      - Magnetic Insulation 1
      - Initial Values 1
      - Ampère's Law in Solids 1
      - Ampère's Law in Solids 2
      - Ampère's Law in Solids 3
      - Ampère's Law in Solids 4
      - Coil 1
      - Symmetry Plane 1
      - Equation View
    - Pressure Acoustics, Frequency Domain (ac)
    - Solid Mechanics (solid)
    - Multiphysics
    - Mesh 1
  - Study 1 - Frequency Response
  - Study 2 - Structural Eigenmodes
  - Results
    - Datasets
    - Views
    - Derived Values
    - Tables
    - Geometry
    - Combined Plot
      - Streamline 1
      - Volume 1
      - Line 1
      - Surface 1
      - Surface 2
      - Current Density

Settings Properties

Magnetic Fields

Label: Magnetic Fields

Name: mf

Domain Selection

Selection: Manual

1	
4	
5	
6	
7	
8	

Equation

Equation form: Frequency domain

Frequency: From solver

$$\nabla \times \mathbf{H} = \mathbf{J}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{J} = \sigma \mathbf{E} + j\omega \mathbf{D} + \mathbf{J}_e$$

$$\mathbf{E} = -j\omega \mathbf{A}$$

Background Field

Solve for: Full field

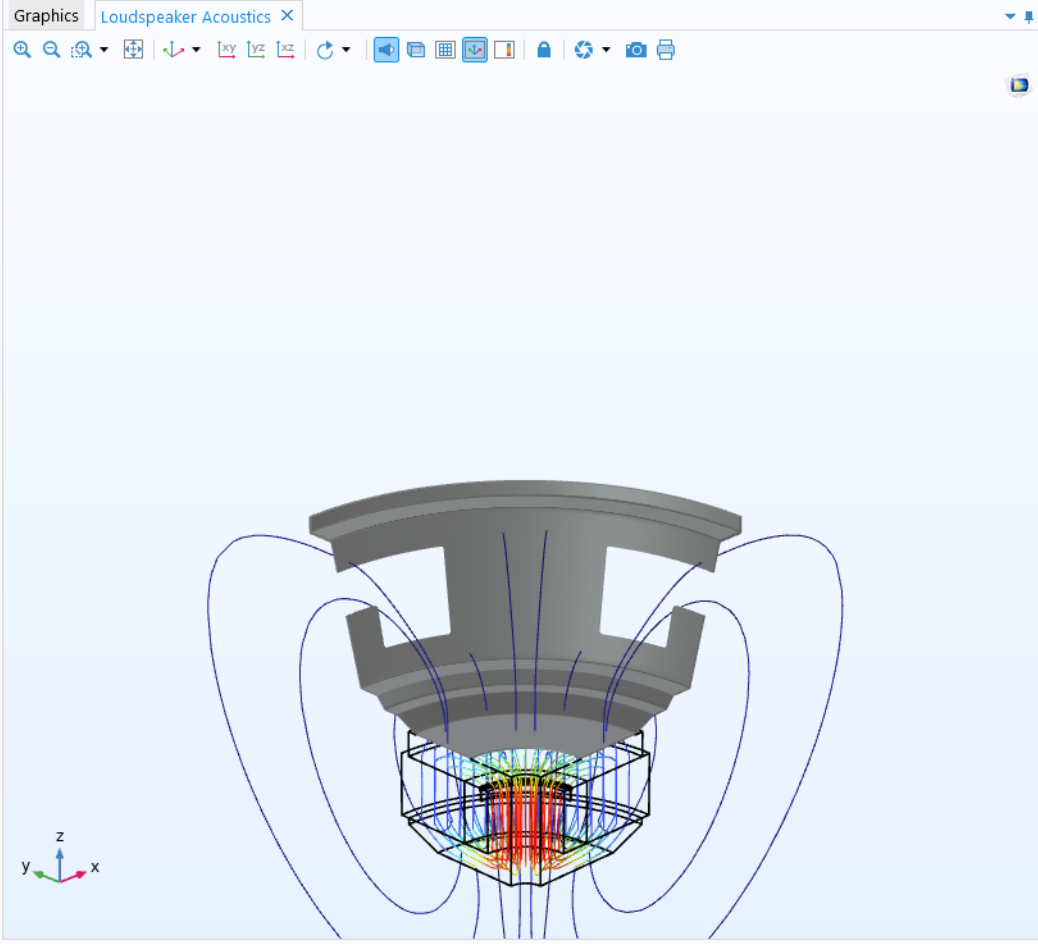
Port Sweep Settings

Use manual port sweep

Error Check

Discretization

Dependent Variables



Messages Progress Log

Model tree shows sequences of operations

Definitions

Geometry

Materials

Physics  
Structural Mech.

Mesh

Study

Results

loudspeaker\_driver\_3d.mph - COMSOL Multiphysics

File Home Definitions Geometry Materials Physics Mesh Study Results Developer

Application Builder Model Manager Component 1 Add Component Parameters Functions Variables Import Build All LiveLink Part Libraries Add Material Solid Mechanics Add Physics Build Mesh Mesh 1 Compute Study 2 - Structural Eigenmodes Combined Plot Add Plot Group Add Predefined Plot Windows Reset Desktop

Workspace Model Definitions Geometry Materials Physics Mesh Study Results Layout

Model Builder

Type filter text

- loudspeaker\_driver\_3d.mph (root)
  - Global Definitions
    - Parameters 1
    - Default Model Inputs
    - Materials
  - Component 1 (comp 1)
    - Definitions
    - Geometry 1
    - Materials
    - Magnetic Fields (mf)
    - Pressure Acoustics, Frequency Domain (ac)
    - Solid Mechanics (solid)
      - Linear Elastic Material 1
        - Free 1
        - Initial Values 1
        - Symmetry 1
        - Fixed Constraint 1
    - Multiphysics
    - Mesh 1
    - Study 1 - Frequency Response
    - Study 2 - Structural Eigenmodes
    - Results
      - Datasets
      - Views
      - Derived Values
      - Tables
      - Geometry
      - Combined Plot
        - Streamline 1
        - Volume 1
        - Line 1
        - Surface 1
        - Surface 2
      - Current Density
      - Acoustic Pressure and SPL
      - Displacement
      - Lorentz-Force (z-Component)
      - Coil Current Density

Settings Properties

Linear Elastic Material

Label: Linear Elastic Material 1

Domain Selection

Selection: All domains

- 1 (not applicable)
- 2
- 3 (not applicable)
- 4
- 5 (not applicable)
- 6 (not applicable)

Equation

Show equation assuming: Study 1 - Frequency Response, Coil Geometry Analysis

$$0 = \nabla \cdot S + Fv$$

$$S = S_{inel} + S_{el}, \epsilon_{el} = \epsilon - \epsilon_{inel}$$

$$\epsilon_{inel} = \epsilon_0 + \epsilon_{ext} + \epsilon_{th} + \epsilon_{hs} + \epsilon_{pl} + \epsilon_{cr} + \epsilon_{vp} + \epsilon_{ve}$$

$$S_{el} = C : \epsilon_{el}$$

$$S_{inel} = S_0 + S_{ext} + S_q$$

$$\epsilon = \frac{1}{2} [(\nabla u)^T + \nabla u]$$

$$C = C(E, \nu)$$

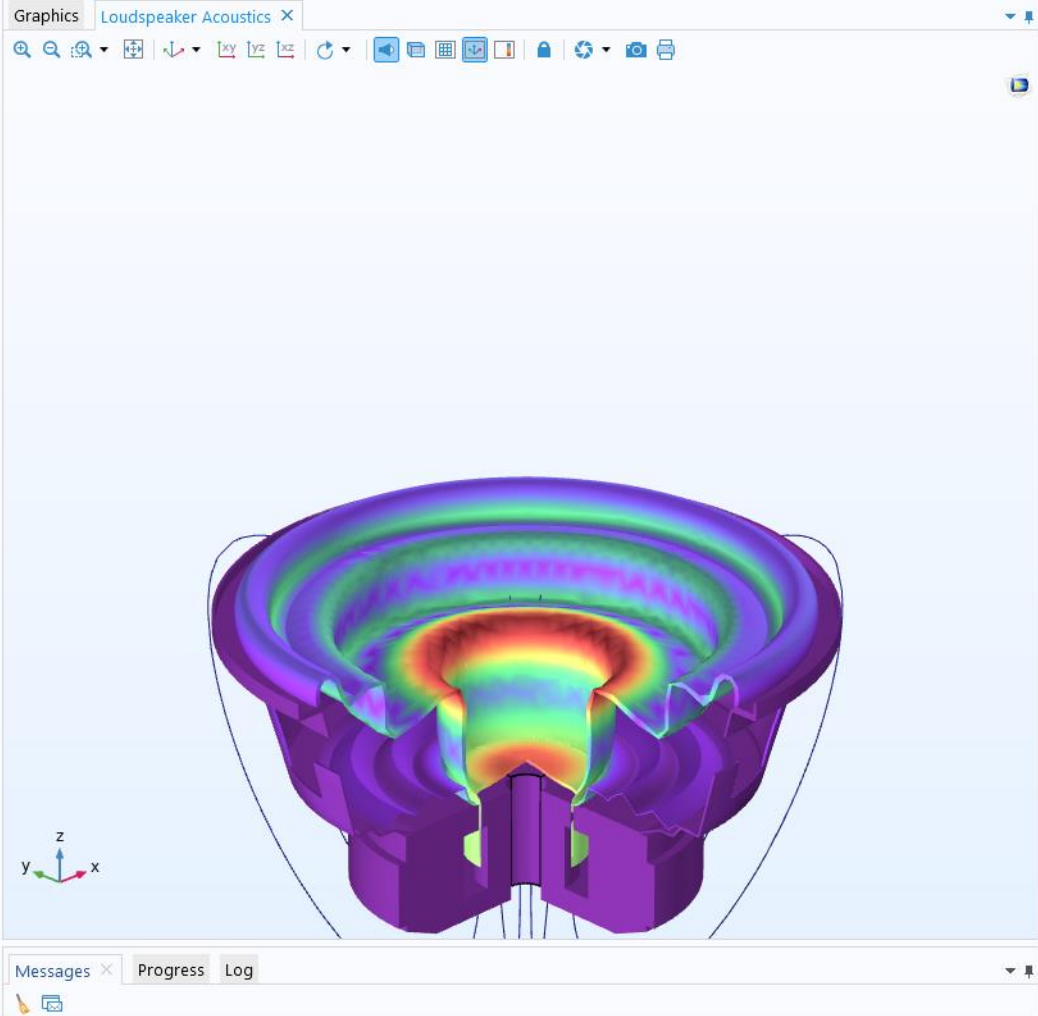
Model Input

Volume reference temperature:  $T_{ref}$  Common model input

Absolute pressure:  $p_A$  User defined 1[atm] Pa

Coordinate System Selection

Coordinate system:



Model tree shows sequences of operations

Definitions

Geometry

Materials

Physics

Pressure Acoustics

Mesh

Study

Results

loudspeaker\_driver\_3d.mph - COMSOL Multiphysics

File Home Definitions Geometry Materials Physics Mesh Study Results Developer

Application Builder Model Manager Component Add Component Parameters Functions Parameter Case Build All Materials

Pressure Acoustics, Frequency Domain Build Mesh Compute Combined Plot Windows Add Physics Add Plot Group Add Study Add Mathematics Add Predefined Plot

Workspace Model Definitions Geometry Physics Mesh Study Results Layout

Model Builder

Type filter text

- loudspeaker\_driver\_3d.mph (root)
  - Global Definitions
    - Parameters 1
    - Default Model Inputs
    - Materials
  - Component 1 (comp 1)
    - Definitions
    - Geometry 1
    - Materials
    - Magnetic Fields (mf)
    - Pressure Acoustics, Frequency Domain (ac)
      - Pressure Acoustics 1
        - Sound Hard Boundary (Wall) 1
        - Initial Values 1
        - Symmetry 1
        - Exterior Field Calculation 1
        - Perfectly Matched Boundary 1
        - Narrow Region Acoustics 1
        - Narrow Region Acoustics 2
        - Narrow Region Acoustics 3
      - Equation View
    - Solid Mechanics (solid)
      - Multiphysics
      - Mesh 1
  - Study 1 - Frequency Response
  - Study 2 - Structural Eigenmodes
  - Results
    - Datasets
    - Views
    - Derived Values
    - Tables
    - Geometry
    - Combined Plot
      - Streamline 1
      - Volume 1
      - Line 1
      - Surface 1
      - Surface 2
    - Current Density

Settings Properties

Pressure Acoustics

Label: Pressure Acoustics 1

Domain Selection

Selection: All domains

- 1
- 2 (not applicable)
- 3
- 4 (not applicable)
- 5
- 6 (overridden)

Equation

Show equation assuming: Study 1 - Frequency Response, Coil Geometry Analysis

$$\nabla \cdot \left( -\frac{1}{\rho_c} (\nabla p_t - \mathbf{q}_d) \right) - \frac{k_{eq}^2 p_t}{\rho_c} = Q_m$$

$$p_t = p + p_b$$

$$k_{eq}^2 = \left( \frac{\omega}{c_c} \right)^2$$

$$c_c = c, \quad \rho_c = \rho$$

Model Input

Temperature:

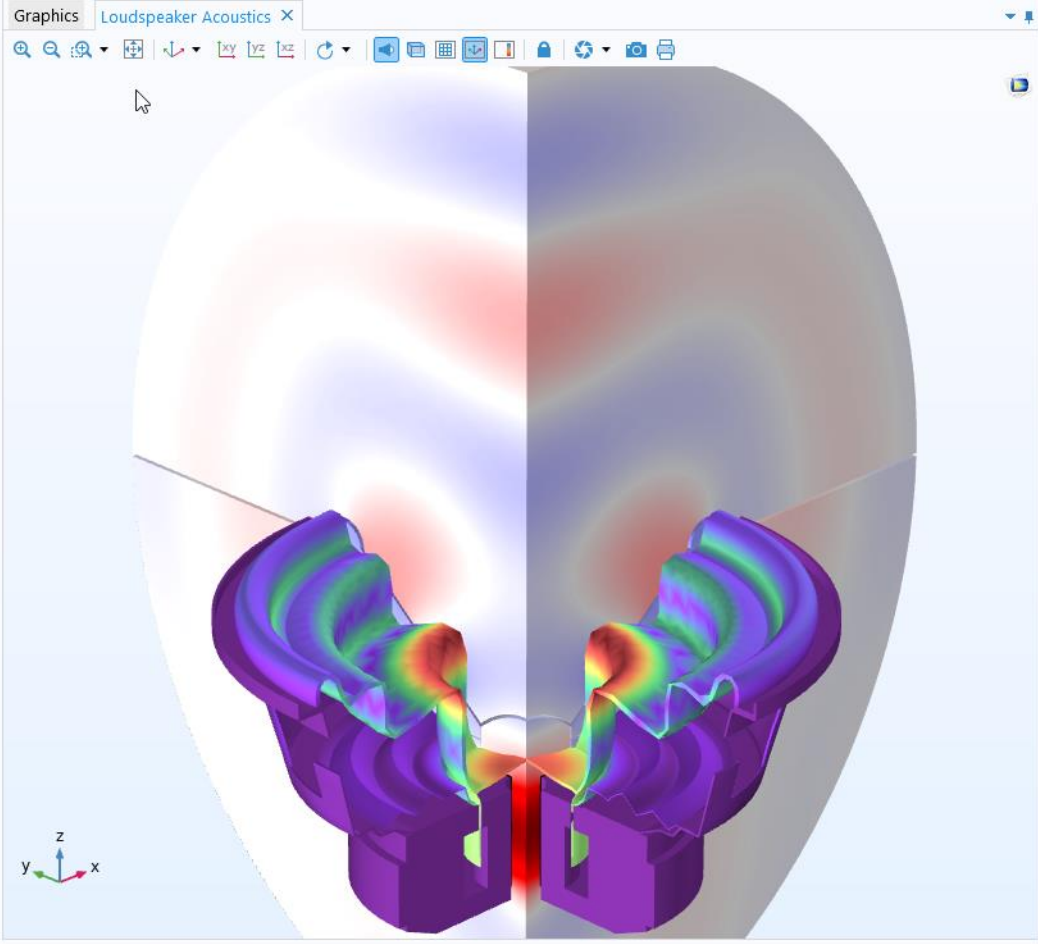
T User defined 293.15[K] K

Absolute pressure:

p<sub>A</sub> User defined 1[atm] Pa

Pressure Acoustics Model

Fluid model: Linear elastic



# Selected Industrial Applications

www.comsol.com

## COMSOL NEWS

THE MULTIPHYSICS SIMULATION MAGAZINE

### Immersive Audio for Virtual Reality

Optimizing a speaker for the gold standard in gaming headsets

COMSOL

PAGE 7

Speakers and Headphones

## MULTIPHYSICS SIMULATION

Sponsored by COMSOL

IEEE SPECTRUM

DECEMBER 2019

### INTERACTIVE PRODUCT DEVELOPMENT

MULTIPHYSICS SIMULATION HELPS BRING AUDIO SYSTEMS INTO A NEW REALITY

PAGE 16

Automotive Acoustics

MULTIPHYSICS COCHLEAR TECHNOLOGY CENTRE BELGIUM, MECHELEN, BELGIUM

### Simulation-Based Design of New Implantable Hearing Device

"A Direct Acoustic Cochlear Implant (DACI) called Codacs™ is a product our company developed from the ground up using COMSOL Multiphysics."

COMSOL NEWS 2012

Hearing aids and Implants

DESIGN OPTIMIZATION

Zeugin Bauberatungen, Switzerland

### HARMONIZING SOUND AND STYLE IN OPEN-PLAN OFFICES

Workplace conversations and calls are generally a distraction in open-plan offices. To improve the acoustical conditions of a workplace, Swiss consultancy Zeugin Bauberatungen models how sound propagates through office building designs and analyzes specific design modifications to find the right fit.

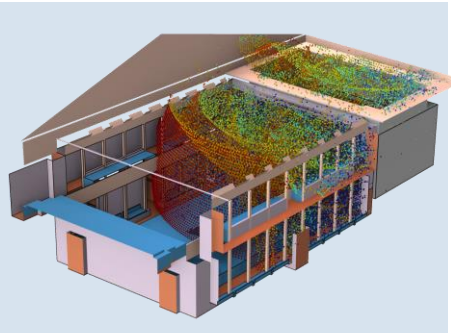
"Our simulations help us propose optimization methods that harmonize with the architects' vision, along with improving employees' acoustical work environment."

— THOMAS ZEUGIN, FOUNDER AND MANAGING DIRECTOR OF ZEUGIN

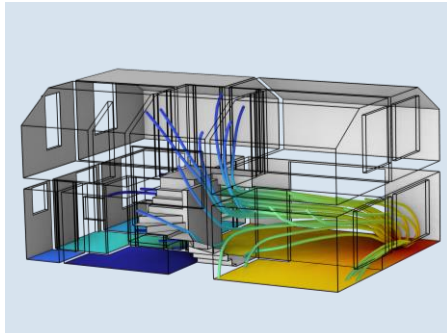
COMSOL NEWS

Building Acoustics

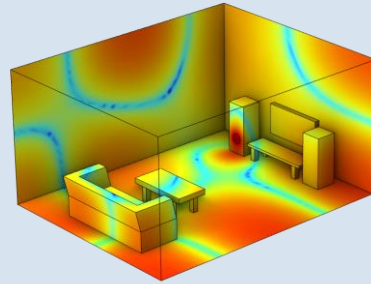
# Physics Interfaces for Acoustics in Buildings



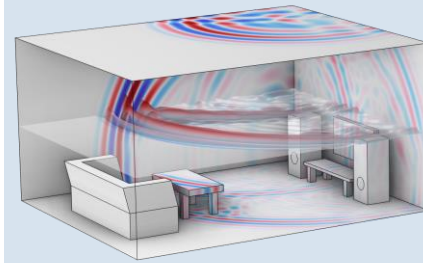
Ray Acoustics



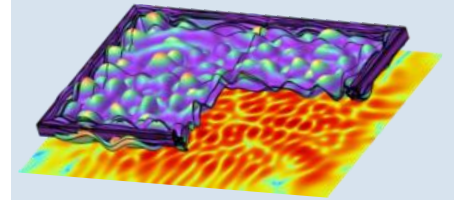
Acoustic Diffusion



Pressure Acoustics,  
Frequency Domain



Pressure Acoustics,  
Time Explicit



Acoustic Structure  
Interaction

# Geometric Acoustics

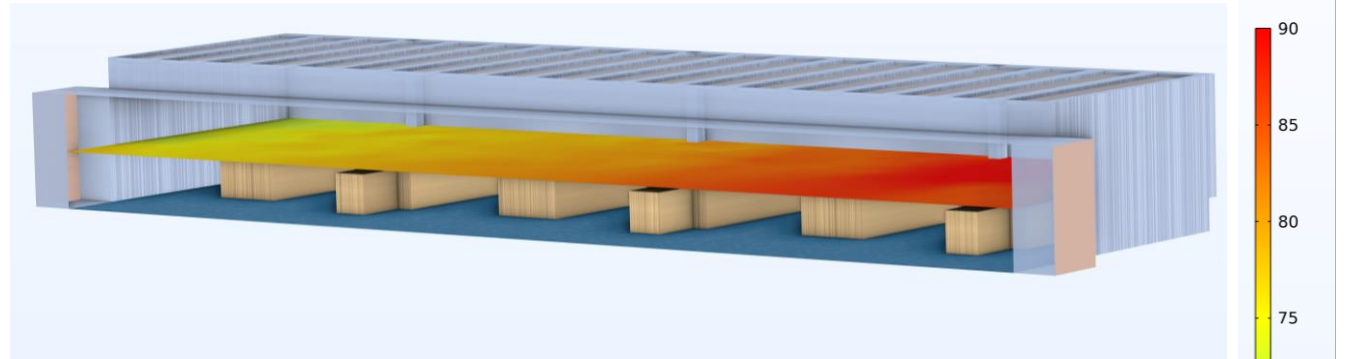
## COSTUMER SUCCESS: ZEUGIN BAUBERATUNGEN

# Harmonizing Sound and Style in Open-Plan Offices

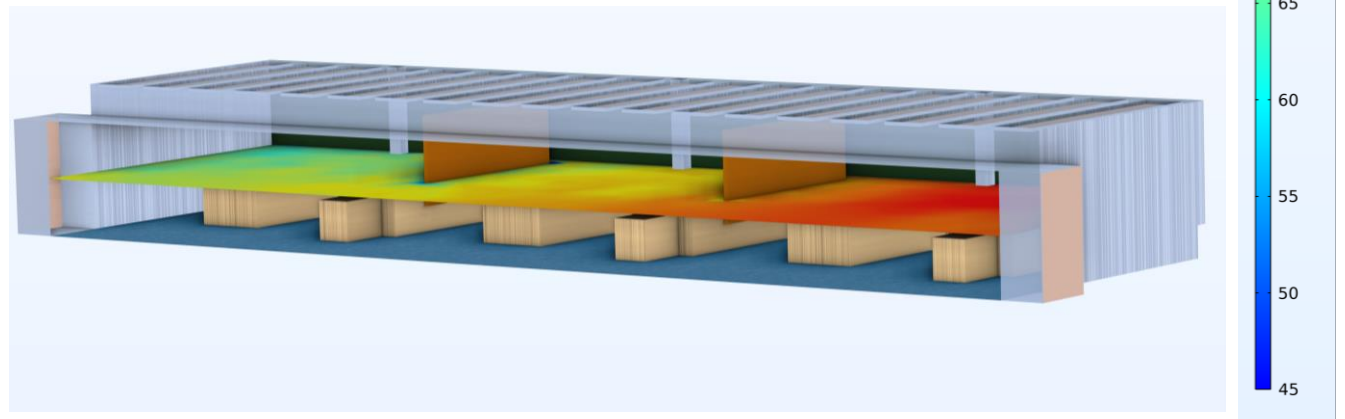
- Project Poststrasse Süd Ostermündingen
- Room acoustic parameters according to EN ISO 3382:2012
- Measures taken:
  1. 80% acoustic floor, hybrid ceiling sail
  2. acoustic curtains
  3. hanging foam plates with 1mm steel inside

	BEFORE	AFTER
Ablenkungsabstand $r_D$	7.8 m	4.5 m
Räumliche Abklingrate $D_{2,S}$	4.9 dB	8.7 dB
A-bewerteter SPL bei 4m $L_{P,A,S,4m}$	52.6 dB(A)	46.3 dB(A)

SPL at 1000 Hz original situation (1)



SPL at 1000 Hz with mitigation measures (2) and (3)



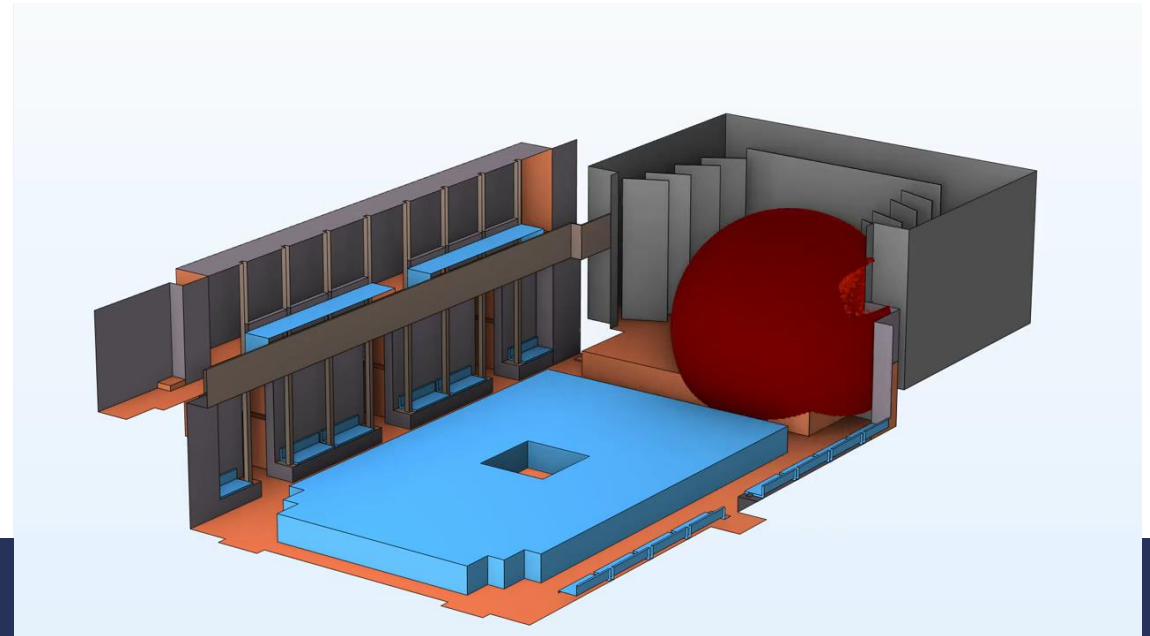
## COMSOL TUTORIAL

# Validation of Ray Tracing Simulations in Konzerthaus Berlin



## Konzerthaus Berlin at Night

- Round robin study: [Brinkmann et al. 2019](#), [Aspöck et al, 2020](#)
- Foto: [Ansgar Koreng](#) – Own work. Licensed under [CC BY 3.0 \(DE\)](#), via [Wikimedia Commons](#).



## Ray Acoustics Simulation 100 Hz to 5000 Hz

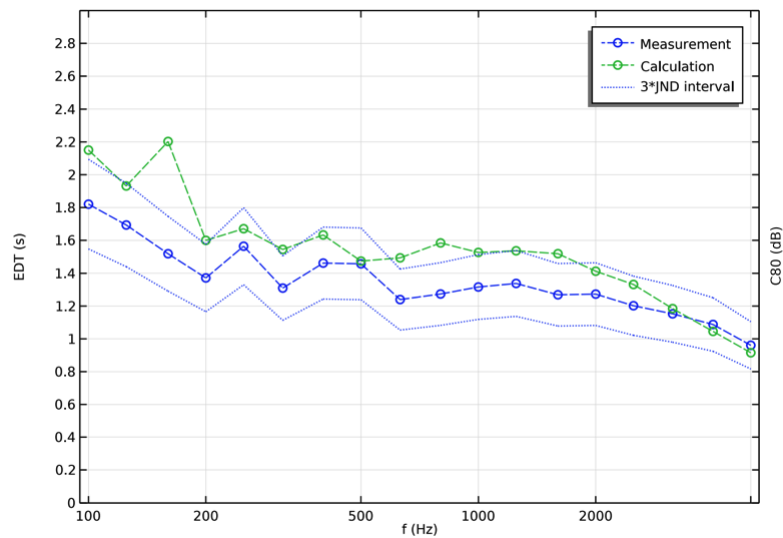
Volume  $2350 \text{ m}^3$ , A-values of all surfaces, 10 source-receiver pairs, power along each ray, mixed specular and diffuse reflection.

## COMSOL TUTORIAL

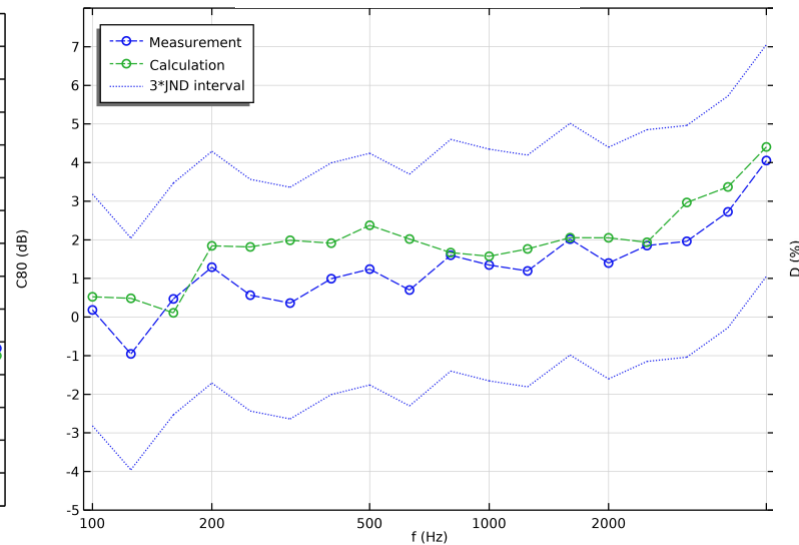
# Validation of Ray Tracing Simulations in Konzerthaus Berlin

- Comparison between measurements (blue) and calculated data (green) and 3\*JND band
- JND = just noticeable difference

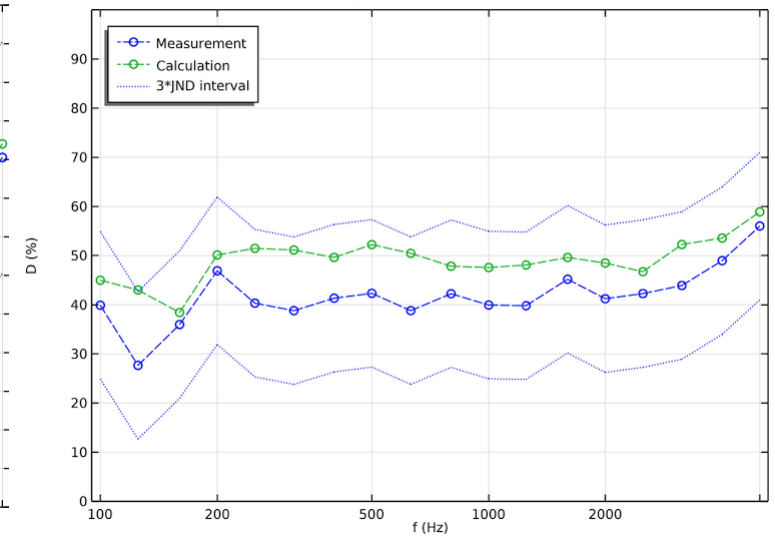
Early decay time (EDT)



Clarity (C80)



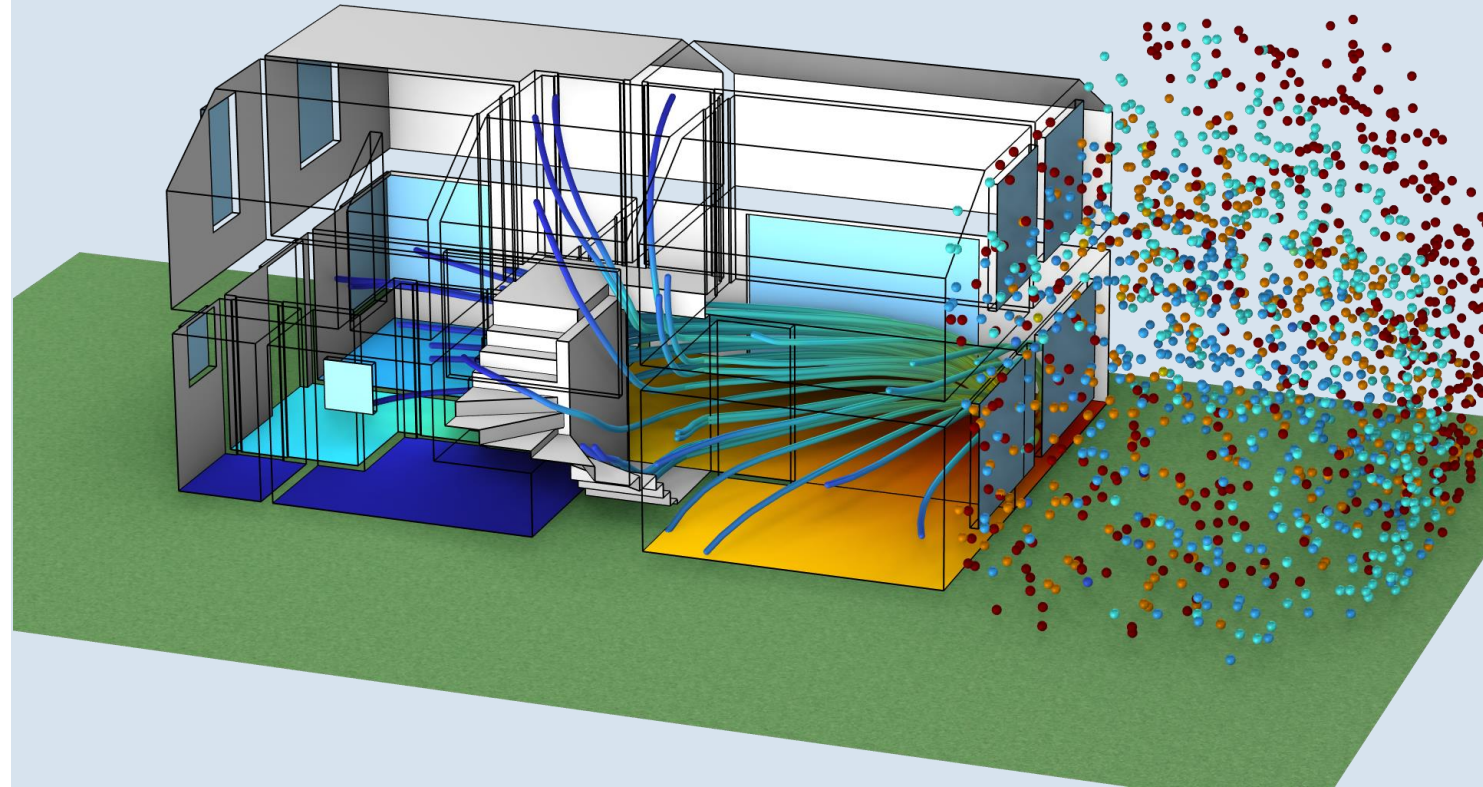
Definition (D)



## GEOMETRICAL ACOUSTICS

# Acoustic Diffusion Equation

- Fast method to analyze energy decay curves and reverberation time in coupled rooms.
- Uses a diffuse field approximation (no direct sound) useful for high frequencies.
- Diffusion constant is geometry dependent (acoustic mean free path)
- Statistical models: Sabine, Eyring, and Modified Eyring
- Band structure for material parameters and source input



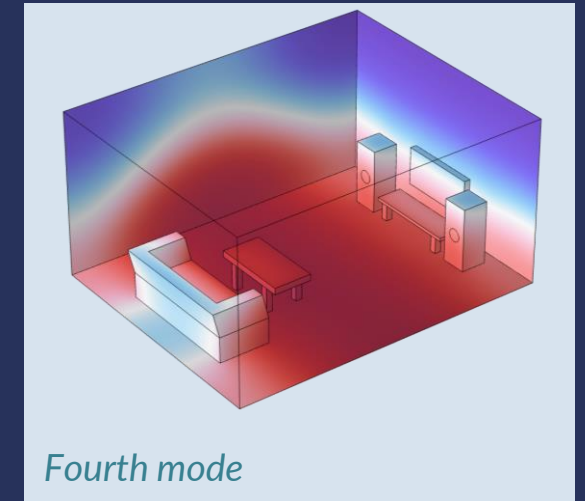
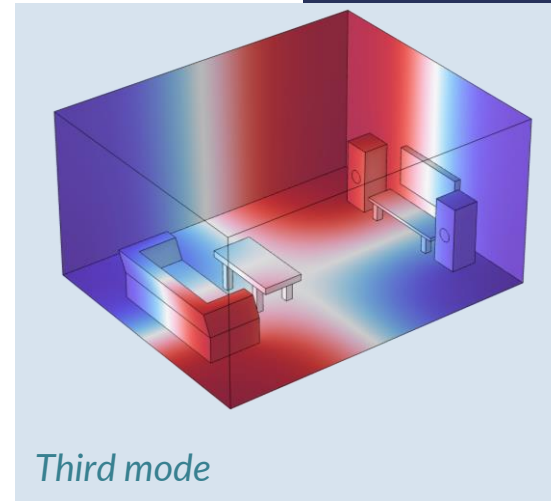
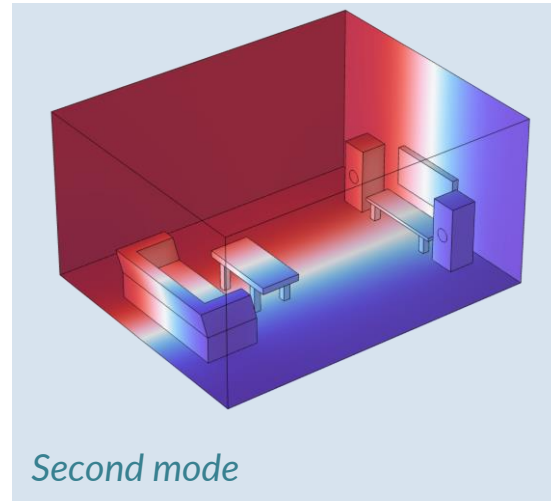
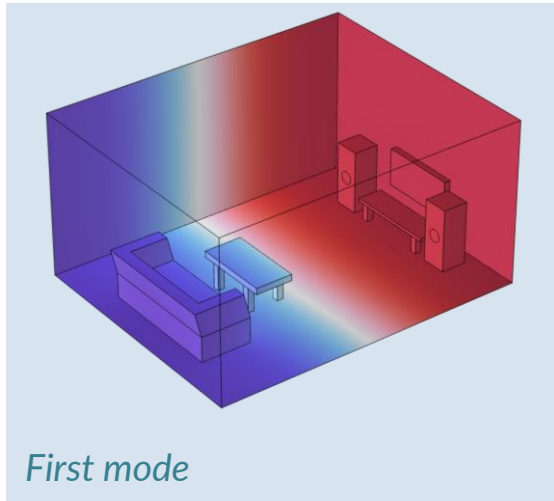
*Sound pressure level distribution and energy flux inside a [single-family house](#).*

# Limitations of Geometrical Acoustics

- Low frequency limit: Bad resolution of resonance dominated modal region
- High frequency limit: Wavelength smaller than objects (diffraction)
- No solids: No acoustic Structure interaction
- Simplified Sources: Often modeled as points or simple vibrating surfaces
  
- Acoustic diffusion: No direct sound, no phase information, no early reflections

# Wave Acoustics

# Modal Analysis



The mode shapes give the locations of pressure nodes and can help identify poor listening positions.

# Statistics: Number of Modes

- Compare modal statistics with the theoretical predictions

$L$  = room volume

$S$  = total surface area

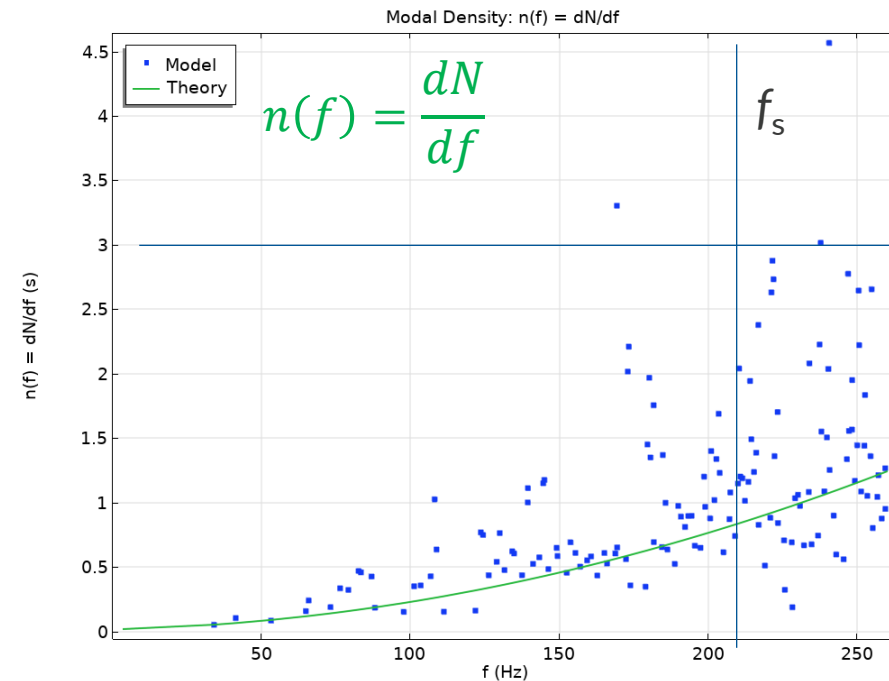
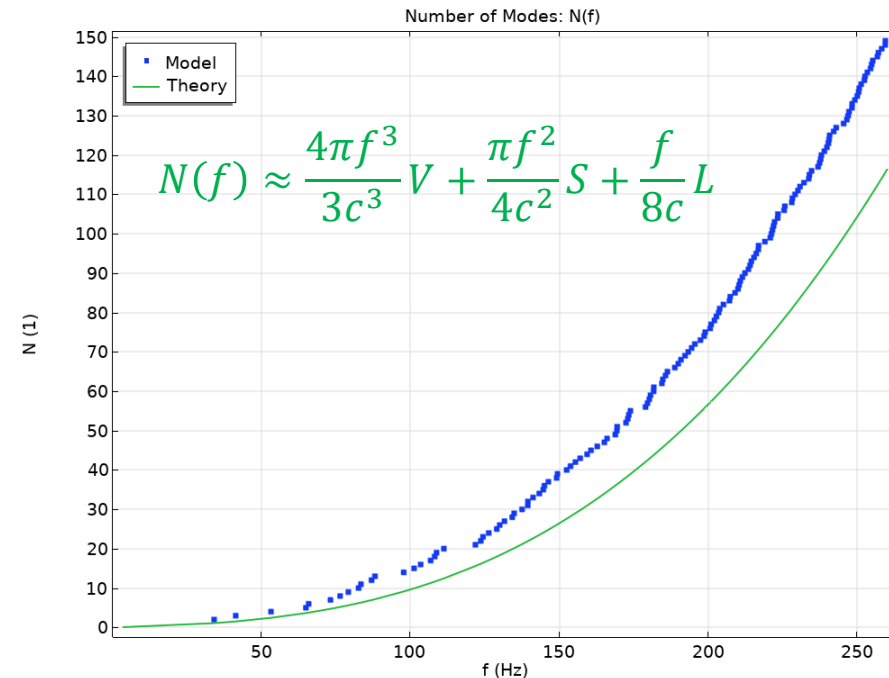
$L$  = total edge lengths

$N(f)$  = number of modes

$n(f)$  = modal density

$$f_s \approx 2000 \sqrt{\frac{T_{60}}{V}} = \text{Schroeder Frequency}$$

- The frequency domain analysis contains already much more information than simple theoretical predictions.



# Single Mode Reverberation Time: Transient

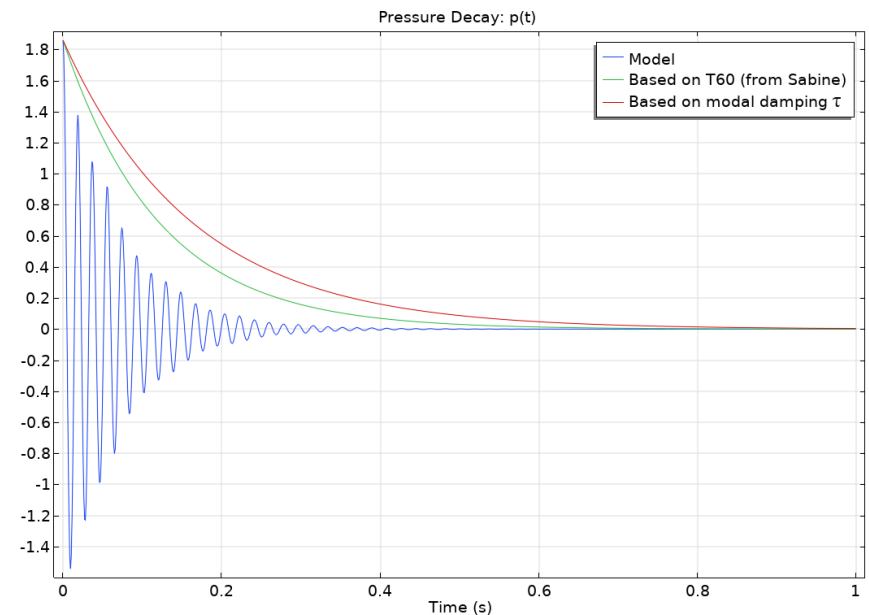
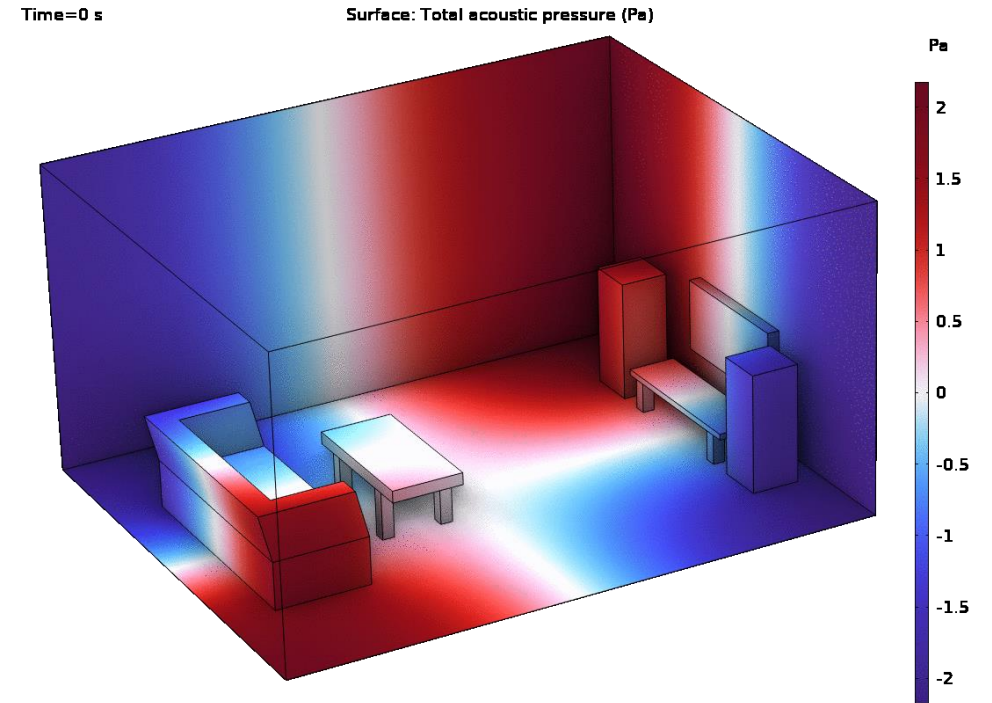
- Modal analysis also yields information about decay of modes, when *impedance boundary conditions* are used (floor, sofa, ceiling) → complex eigenfrequency:
- $f = (53.3 + 0.013i)$  Hz

$$p(t) = p_0 \exp\left(-\frac{t}{\tau}\right) \cos(\omega t)$$

$$\approx p_0 \exp\left(-\frac{3 \log(10)}{T_{60}} t\right) \cos(\omega t)$$

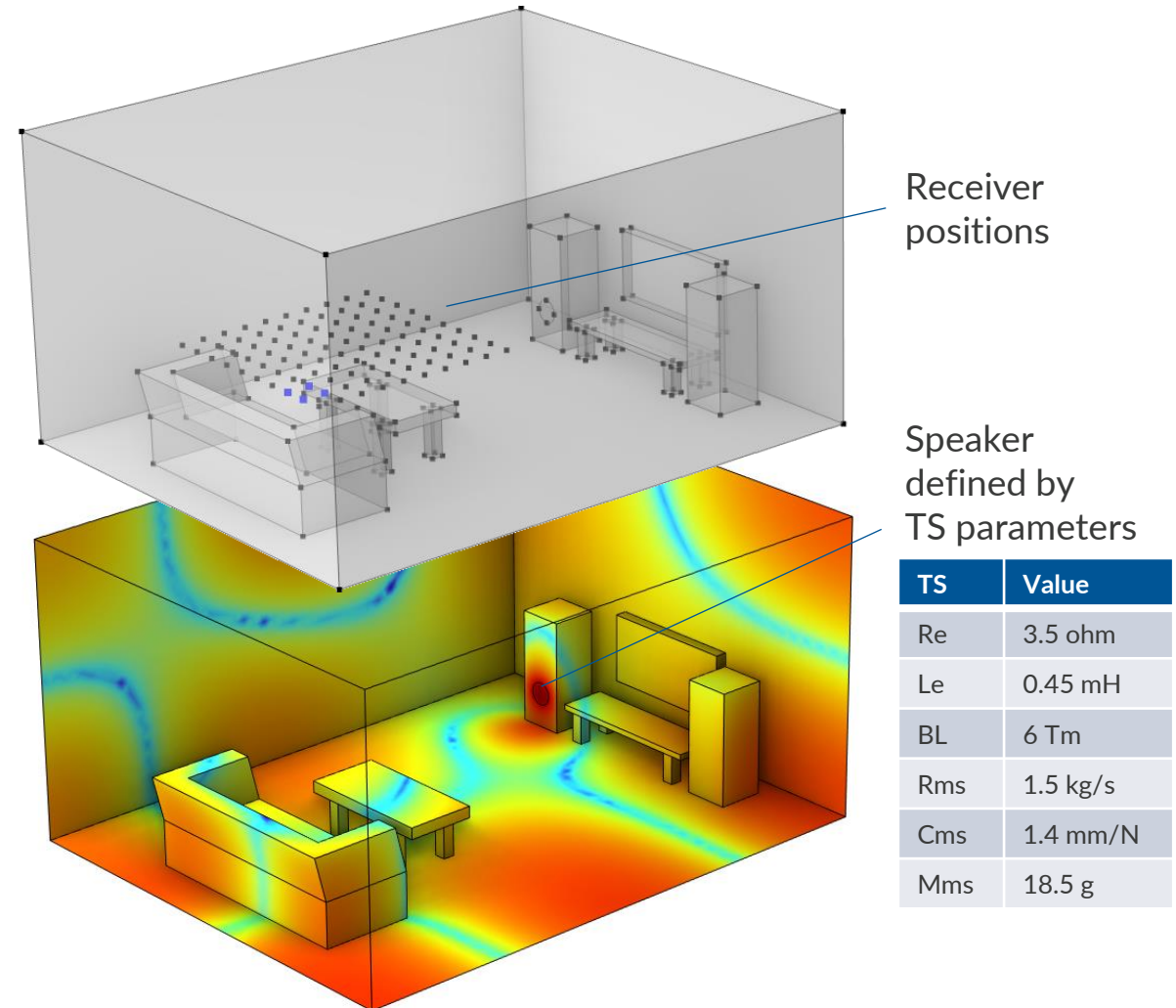
$$\tau = 2\alpha = 4\pi \operatorname{Re}(f)$$

$$\omega = 2\pi \operatorname{Imag}(f) f$$



# Time-Harmonic Analysis

- Compute response of room in the frequency domain
- Full-wave analysis
- Analyze transfer functions
- Room impulse response from IFFT
- **Detailed boundary conditions**



# Impedance Boundary Condition and Porous Materials

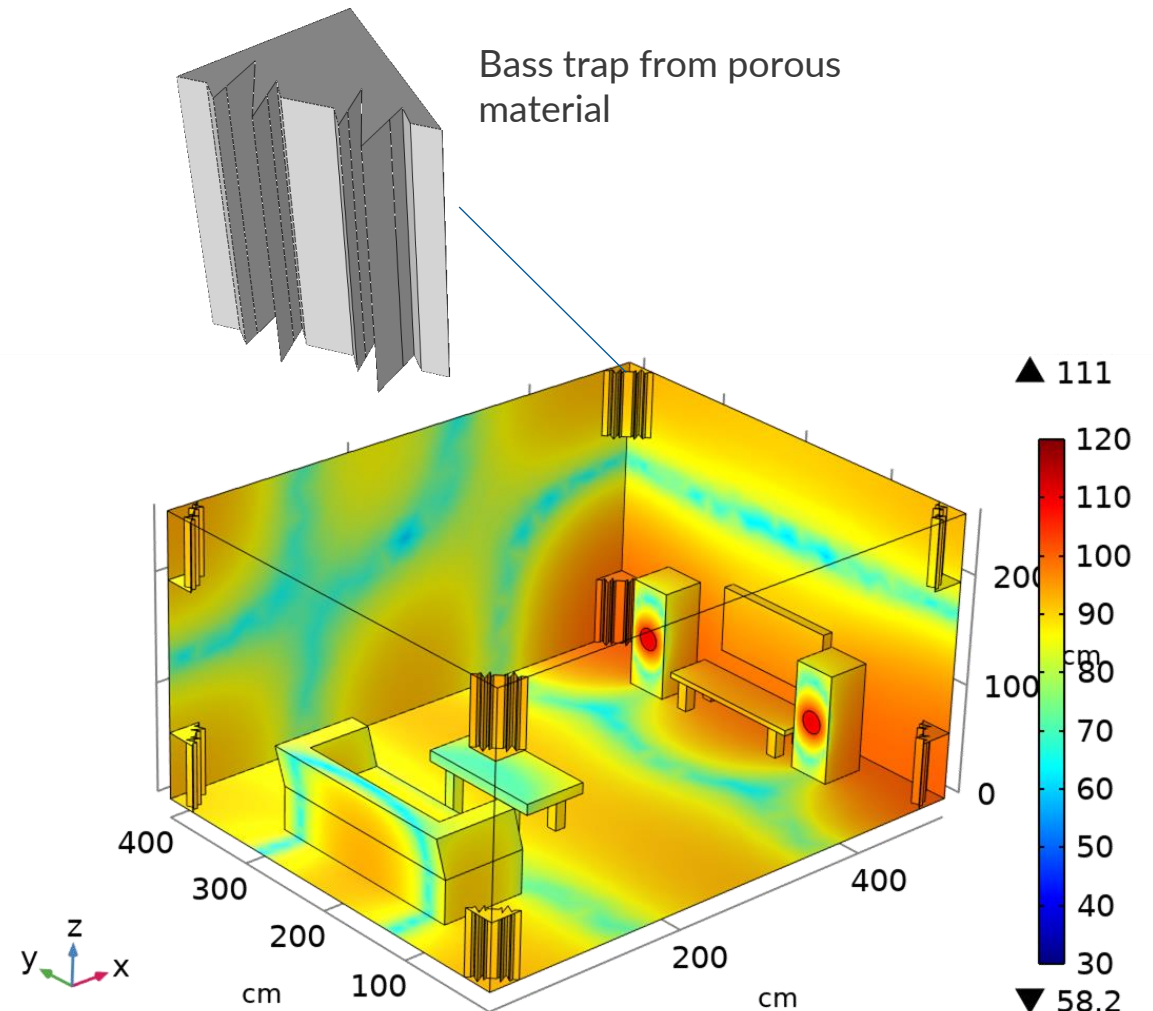
- In *Pressure Acoustics* impedance boundary conditions (IBC) describe the damping at surfaces.

$$\mathbf{u} \cdot \mathbf{n} = \frac{p}{Z_n}$$

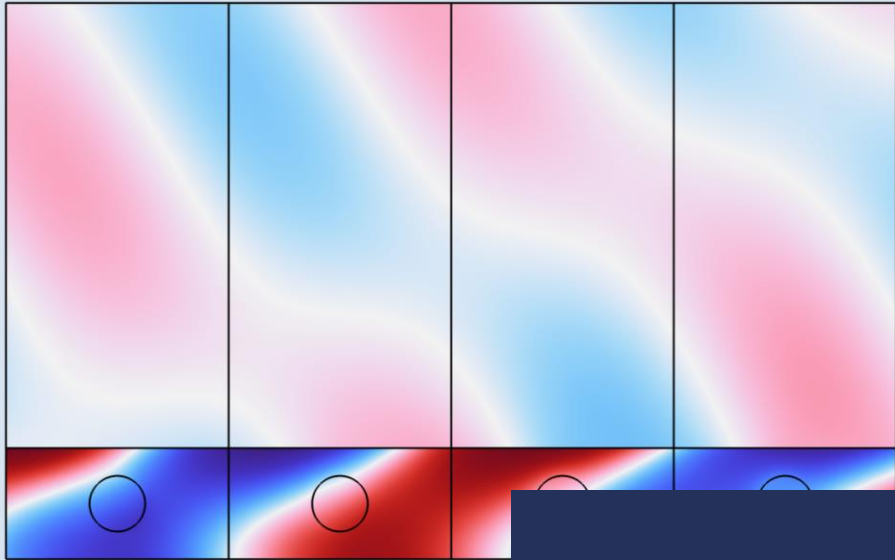
- Unlike in Ray Tracing only the normal component of the impedance is accounted for, whereas in reality it depends on the angle of incidence.

$$Z_n = Z_n(f, \theta)$$

- If in doubt: model the porous layers or parts explicitly

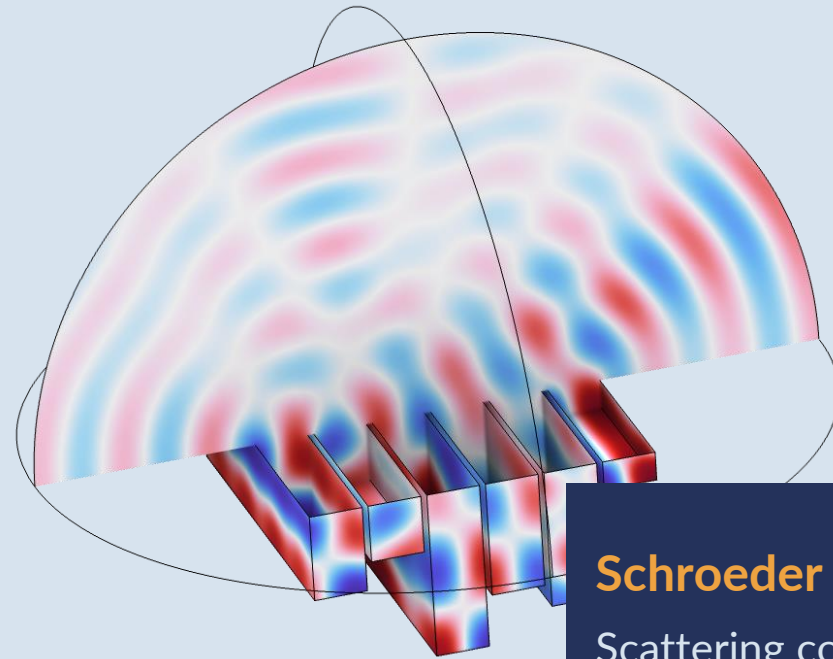


# Sub-Modeling of Building Elements



## Porous Absorber

Absorption and reflection coefficients, surface impedance

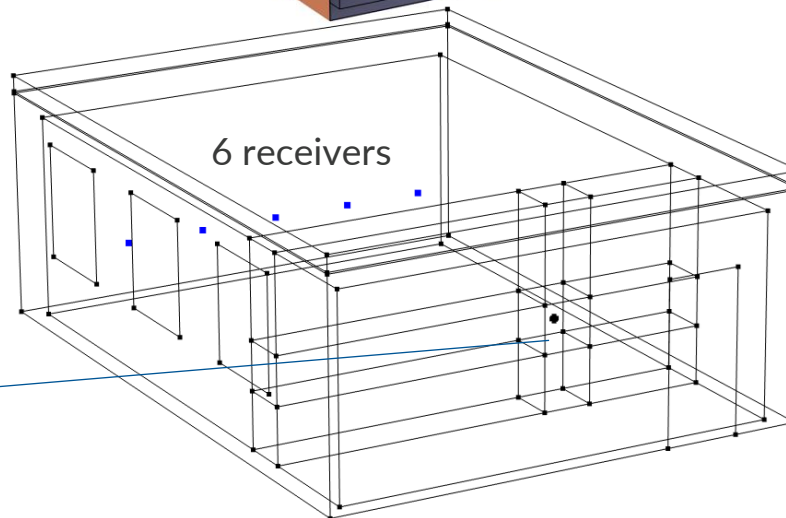
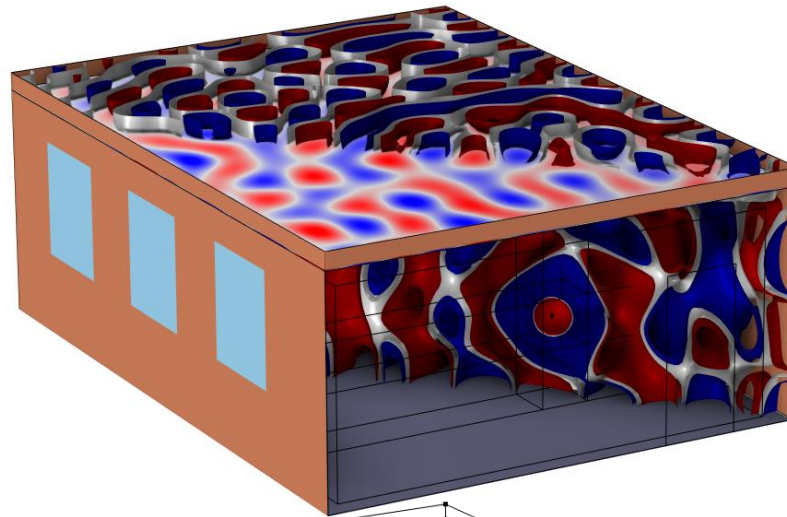


## Schroeder Diffuser

Scattering coefficient for single, multiple, or infinite arrangement(s)

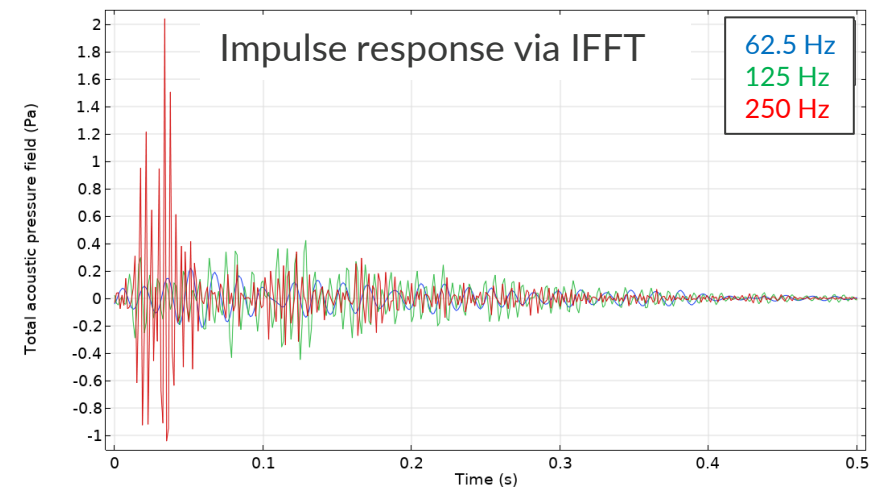
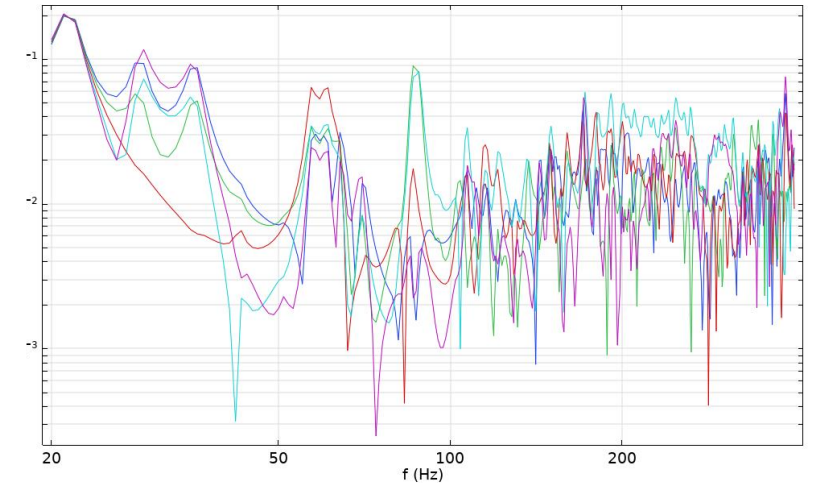
# Classroom with Low Ceiling: Transfer Function

- Vol = 144 m<sup>3</sup>,
- 20 Hz to 400 Hz,
- 1Hz resolution
- 55 min,
- 7 GB RAM
  
- Inverse Fourier Transformation with window



Point source

Transfer function 20 Hz - 400 Hz



# FEM at Higher Frequencies and in Large Rooms?

## The Problem

- The *computational expense* raises linearly with volume  $V$  but exponentially with the frequency:

$$N_{DOF} = \frac{V(f N_\lambda)^3}{c^3}$$

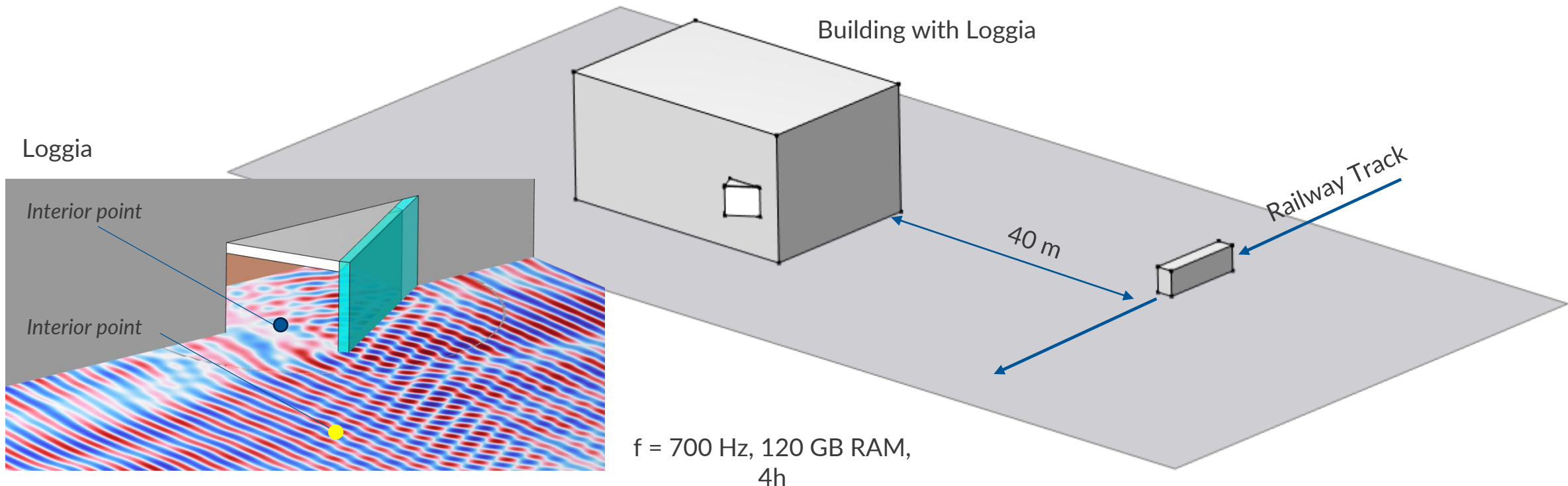
$N_\lambda$  = number of mesh cells per  $\lambda$   
 $N_{DOF}$  = number degrees of freedom

## The Solutions

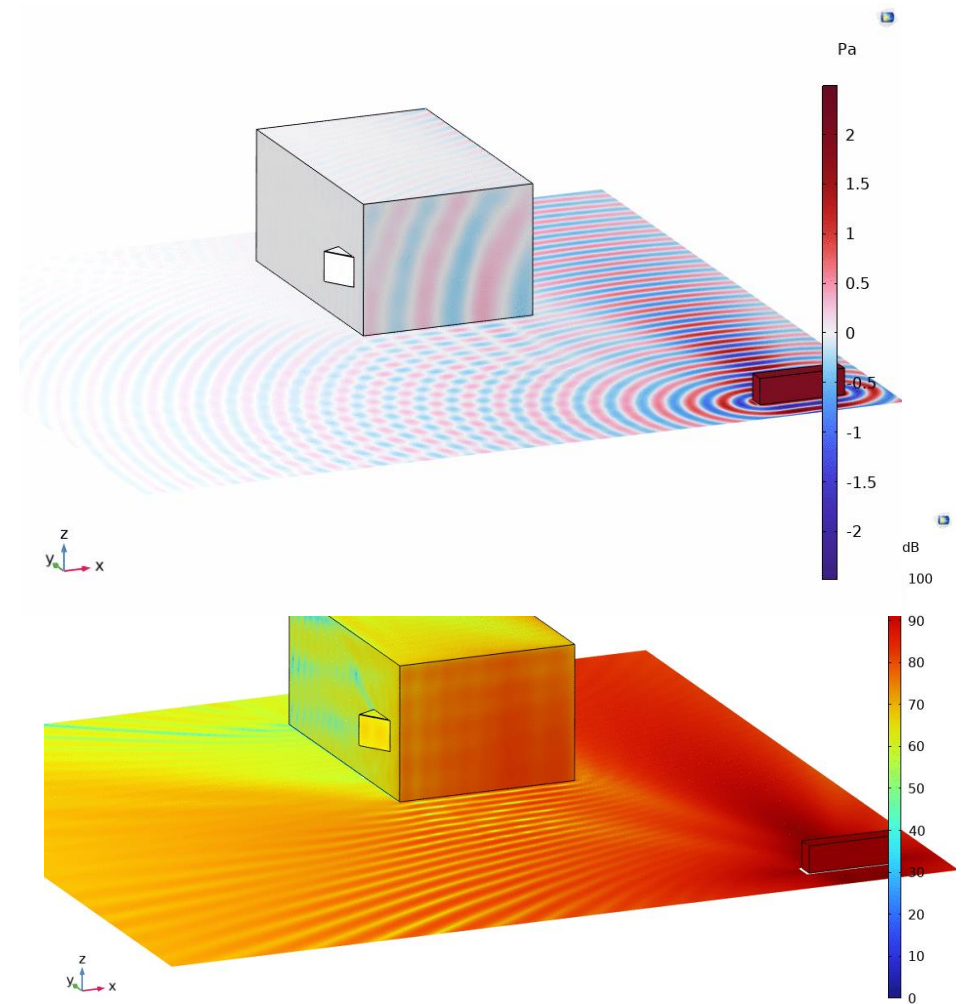
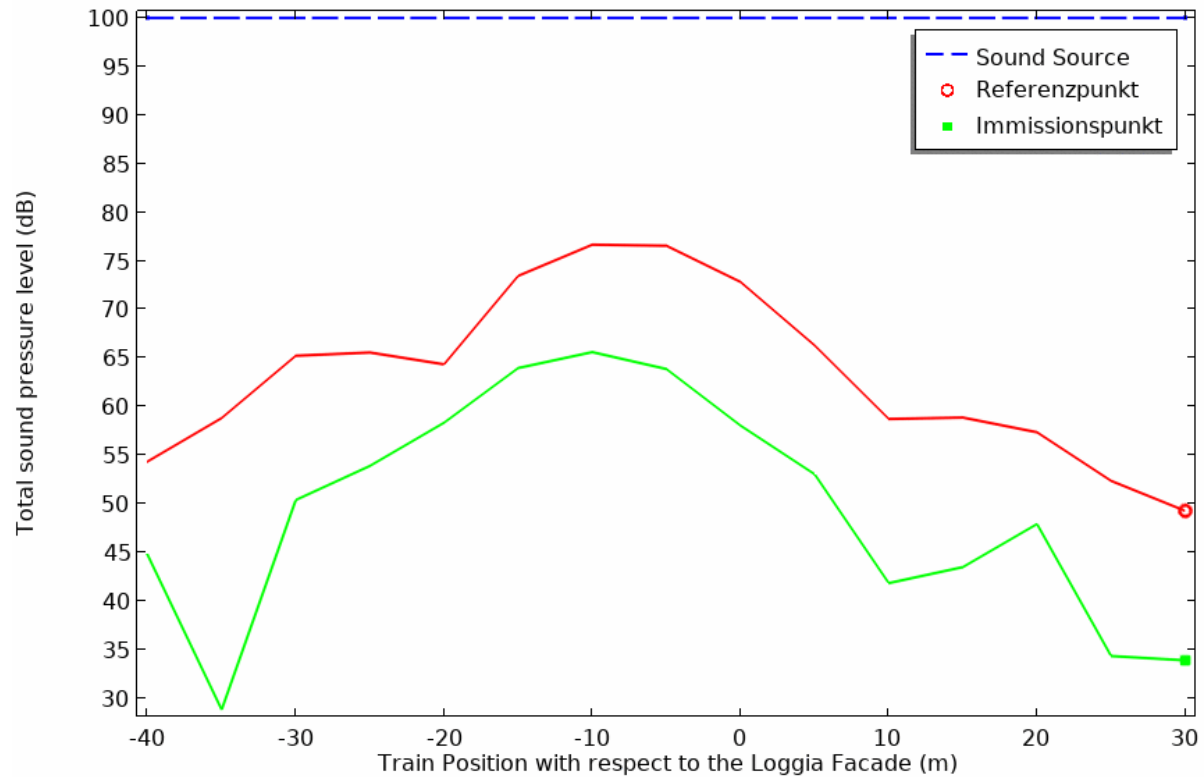
- **Hybrid Methods:** use full-wave FEM only where it is needed and combine with ray tracing where it is possible:
  - FEM – BEM coupling
  - FEM – Ray coupling
  - FEM – Ray hybrids in frequency ranges
- **Lean FEM methods:** higher order discretization and time-explicit.
  - Discontinuous Galerkin

# The Loggia Example – FEM-BEM Coupling

- Client wants to know the insertion loss between points inside and outside the loggia. The desired frequency 4 kHz across a distance of >40 m would require a classical FEM to solve for 125 Mio DOFs: solution model incident field with BEM



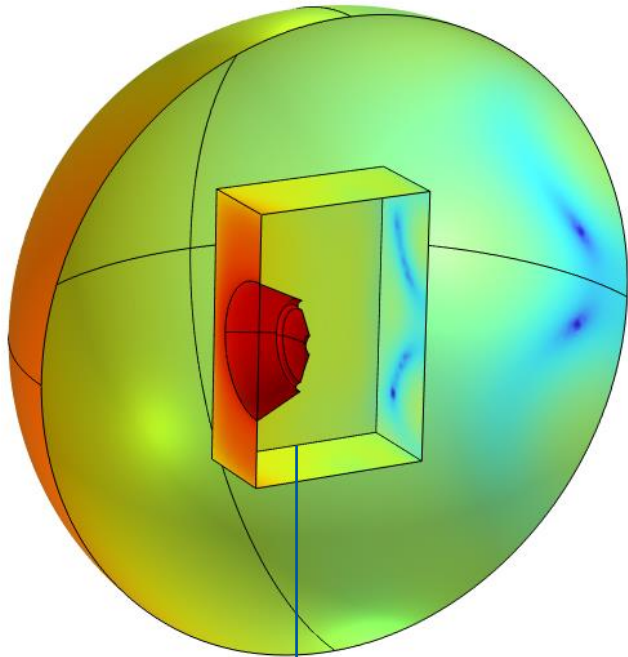
# Insertion Loss vs. Sound Source Position (100 Hz, FEM-BEM)



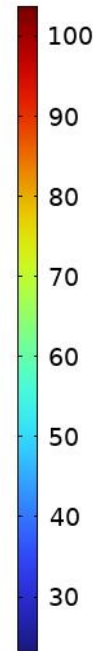
# FEM-Ray Coupling: Near-field and far-field

freq(4)=1000 Hz

Surface: Total sound pressure level (dB)

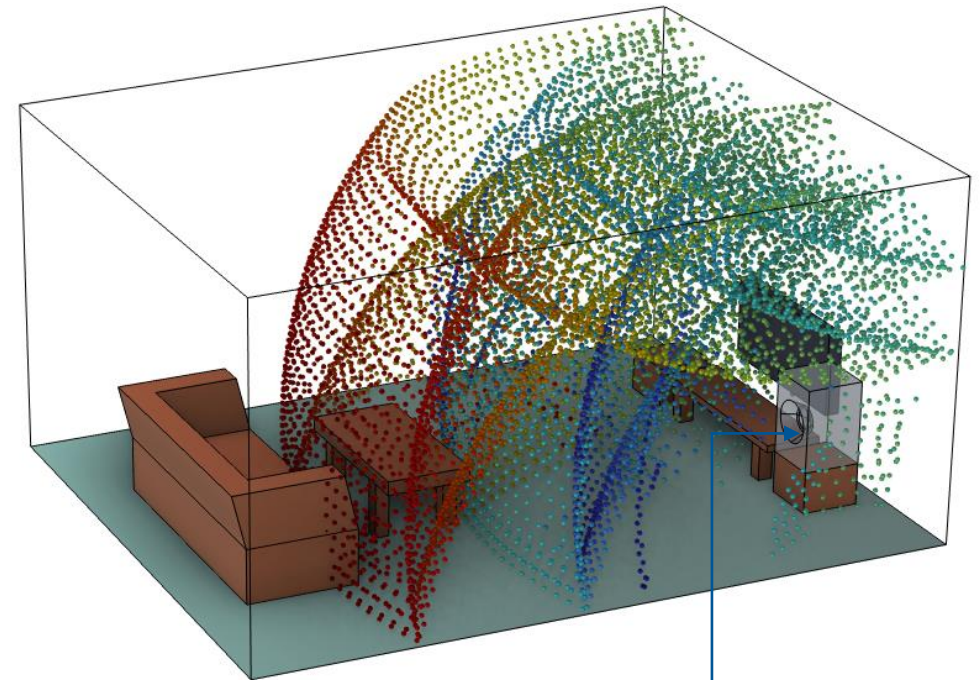


dB

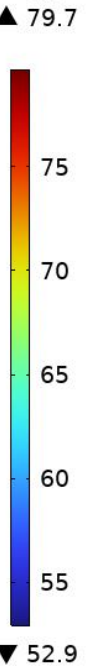


f0(3)=500 Hz Time=10 ms

Ray Trajectories (rac) - Source with Directivity



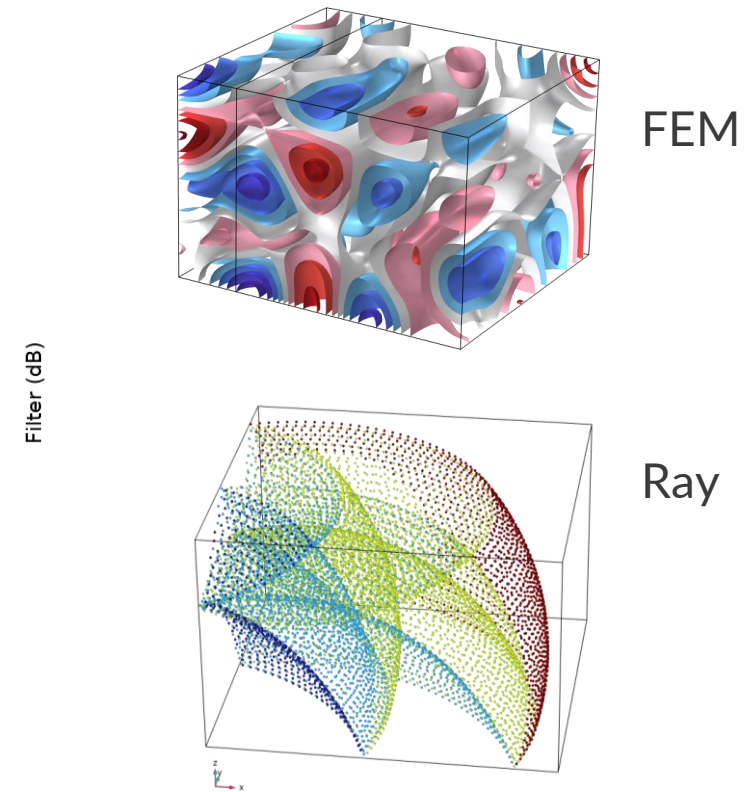
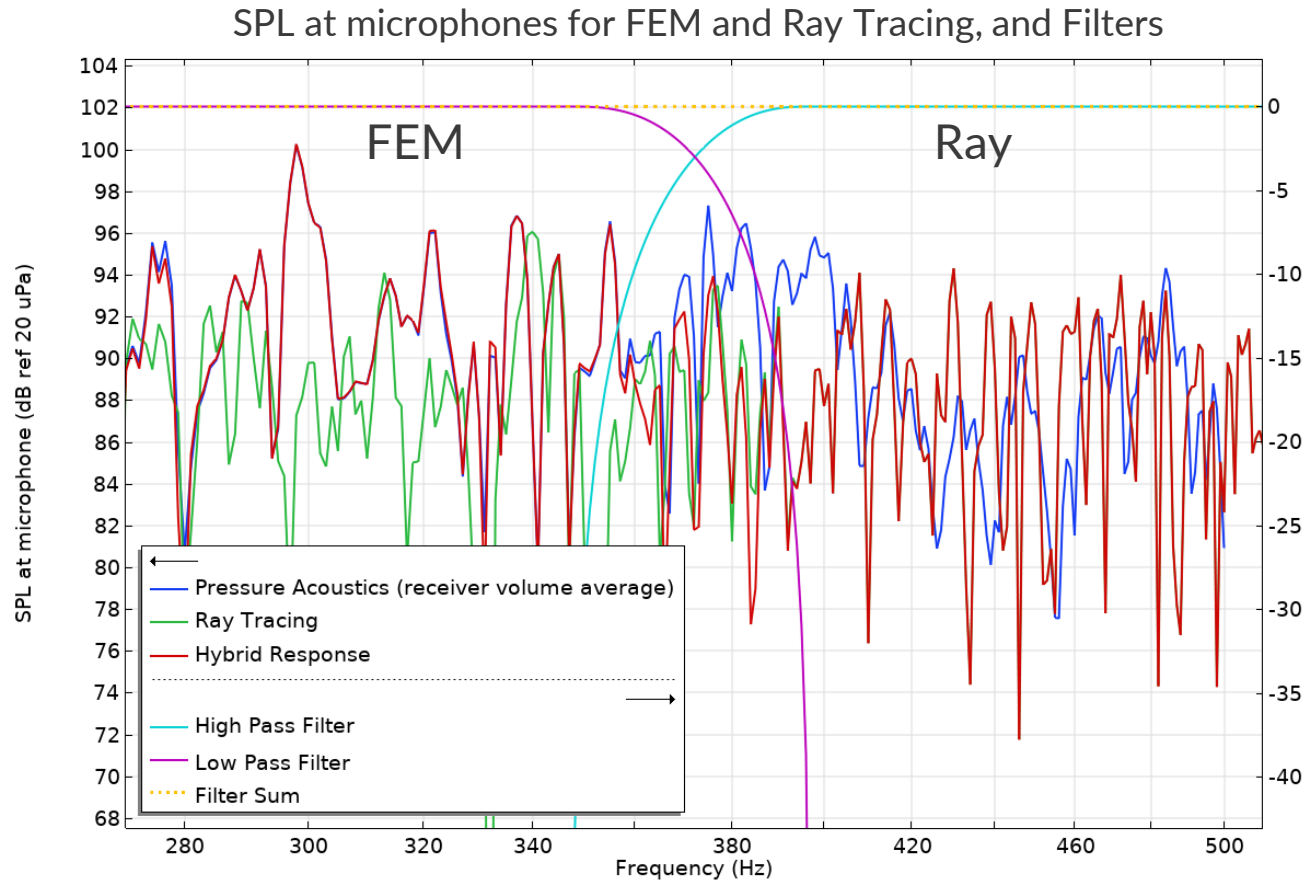
dB



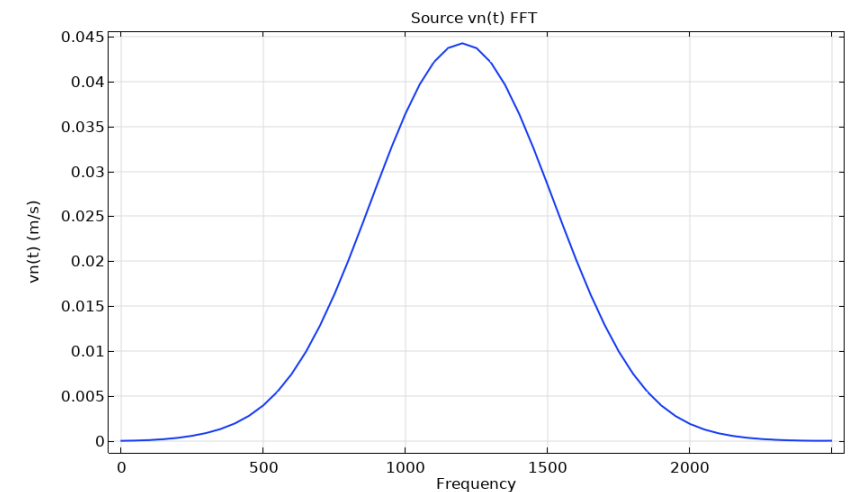
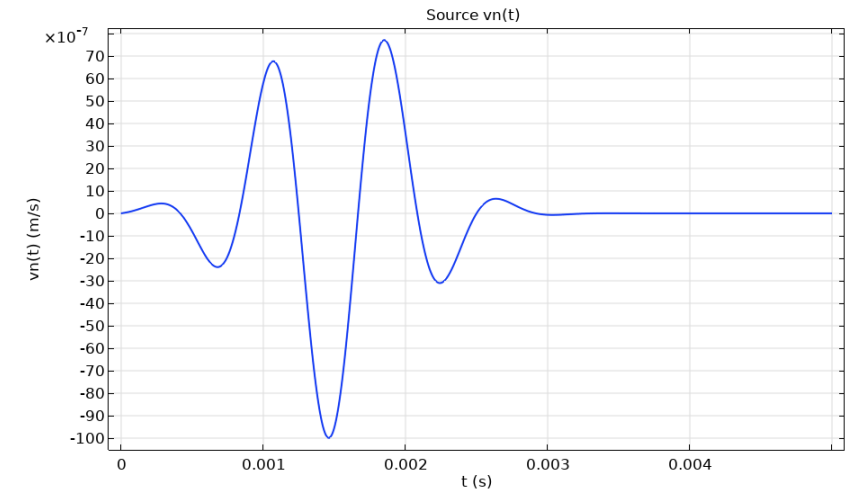
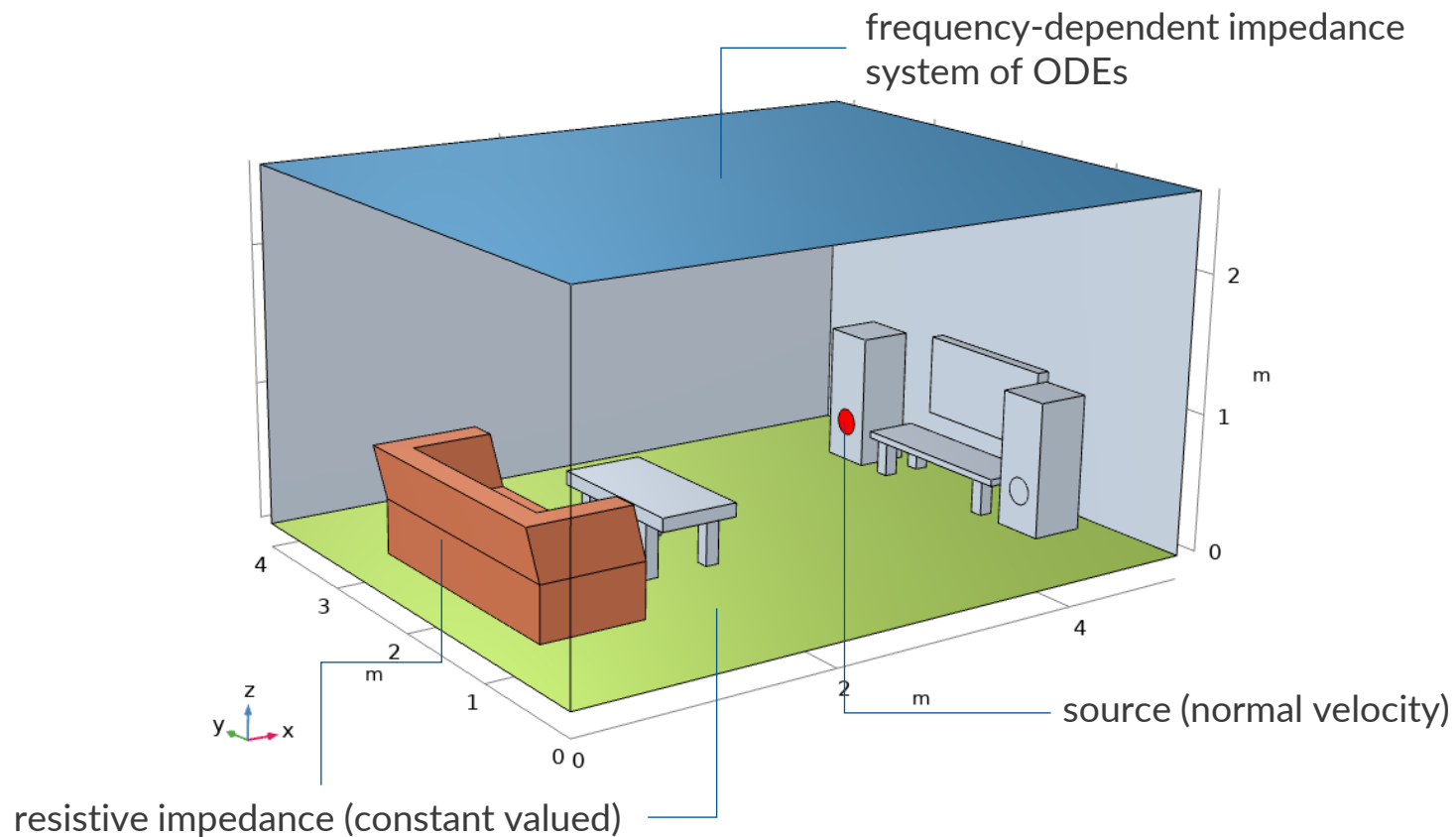
FEM to Ray Coupling for Source

Read More in the [blog](#).

# FEM-Ray Hybrid: Low frequency and High frequency

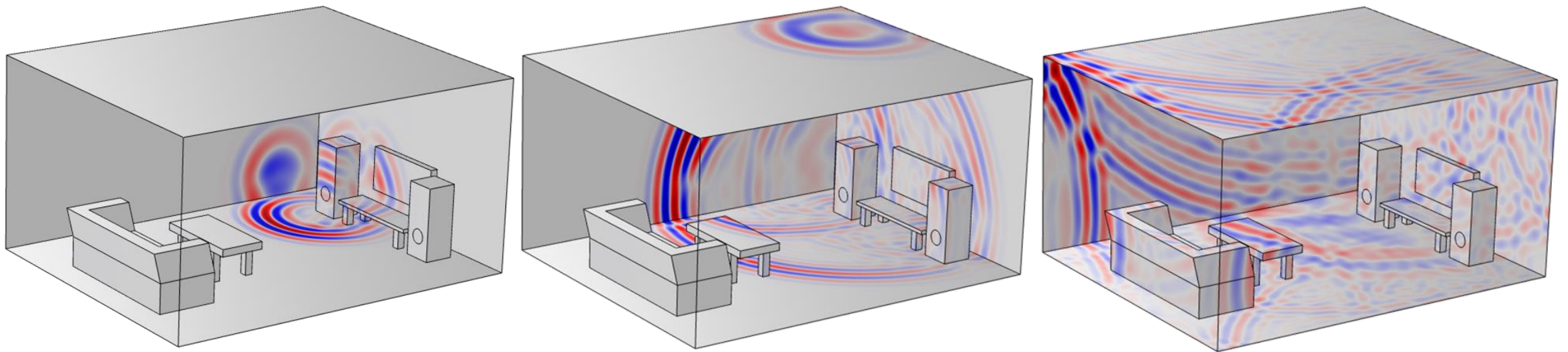


# Full Wave Room Acoustics with DG-Time Explicit Method



# Full Wave Room Acoustics with DG-Time Explicit Method

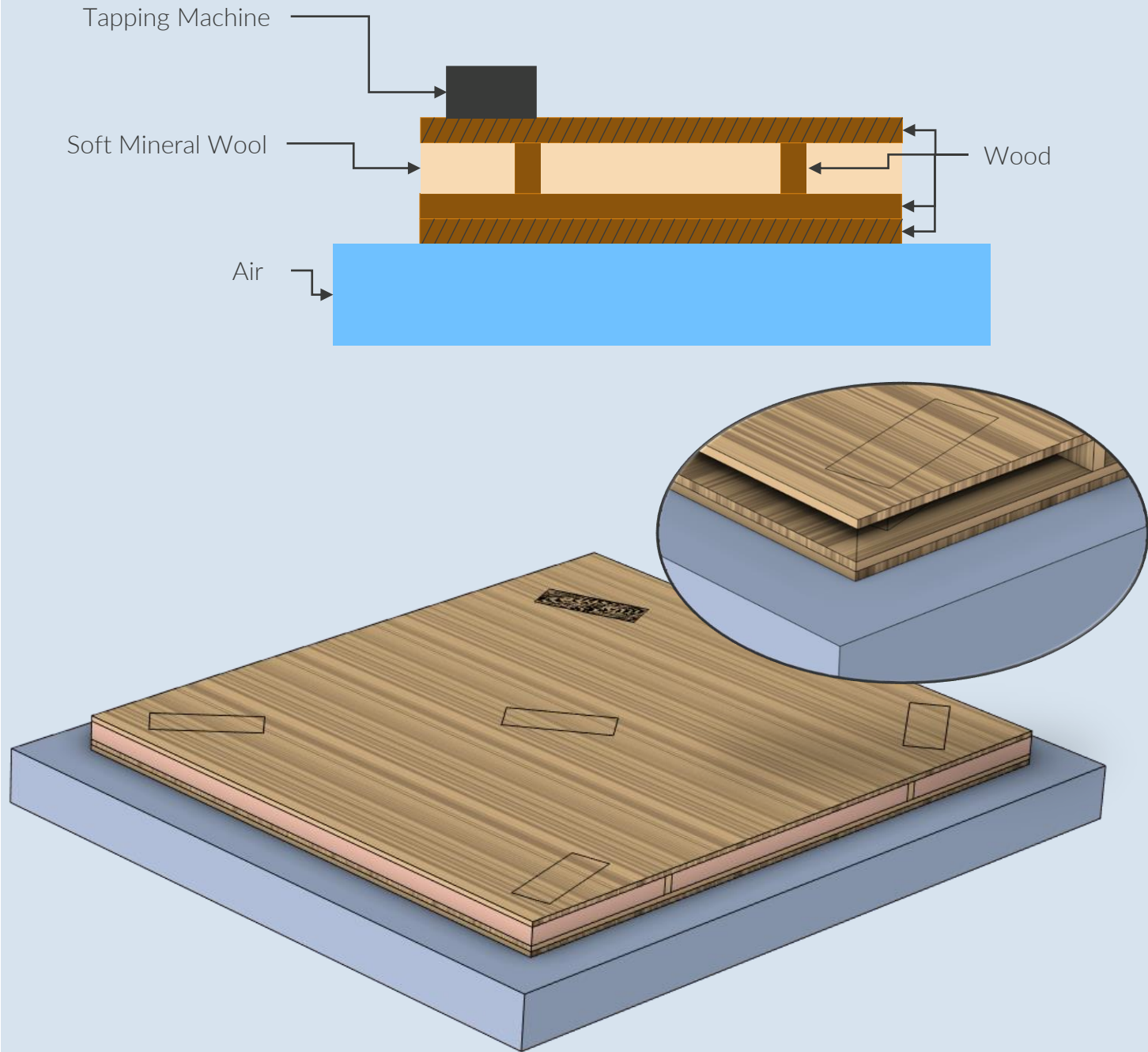
- Model volume  $51 \text{ m}^3$ ,  $700 \text{ Hz}$ ,  $0.04\text{s} = 30 \cdot T_0$ : computation time on single workstation 25h
- Discontinuous Galerkin (dG) method well suited for distributed computing on a cluster architecture / cloud.



# Acoustic Structure Interaction

# Tapping Machine on Wooden Floor

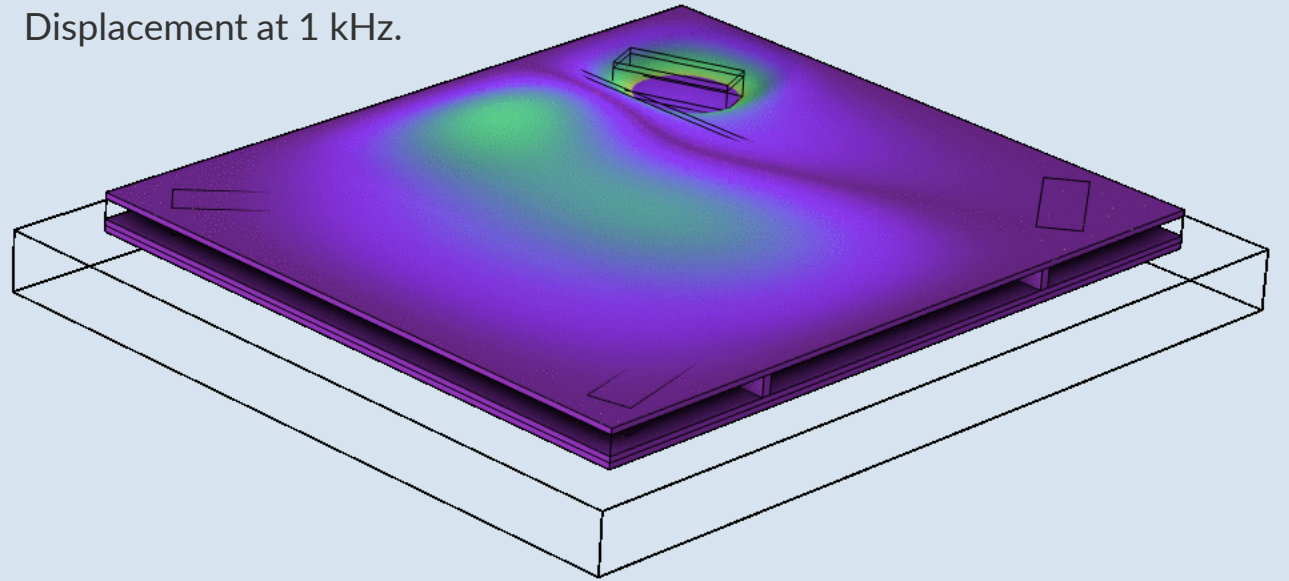
- Impact of an ISO tapping machine B&K 3402 Tapping machine
- Floor made of three layers and two beams of anisotropic wood separated with a soft mineral wool.
- Wood fixed at sides.
- Air domain underneath surrounded by PML (not shown)
- *Model courtesy of Chloé Balmes (DTU, COMSOL DK) made in Nov 2023*



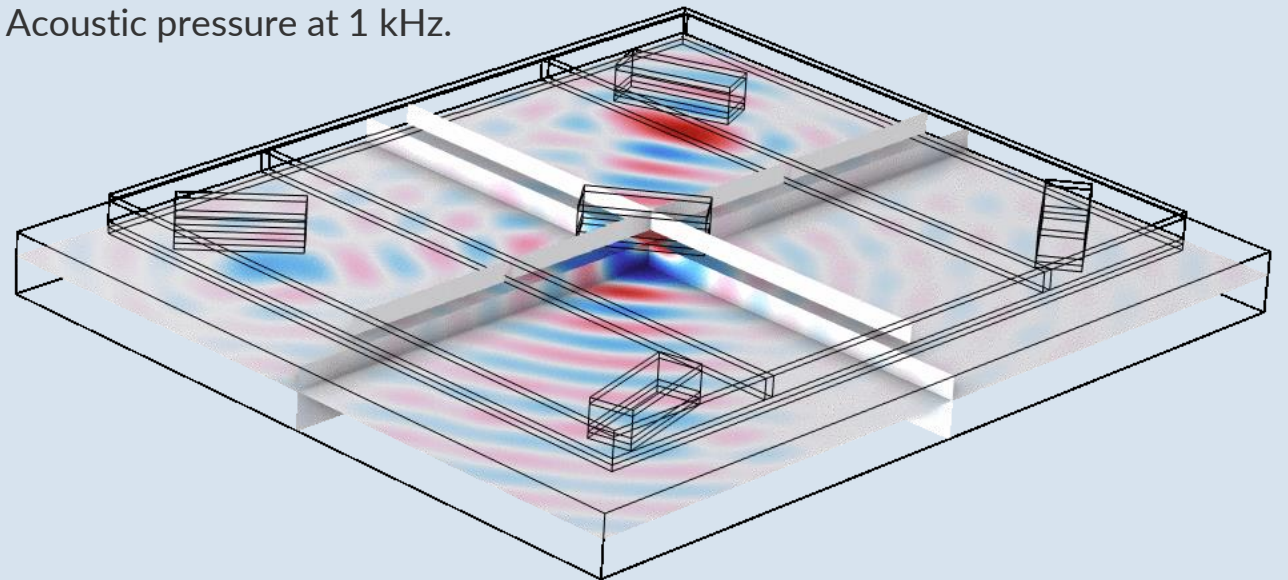
# Tapping Machine on Wooden Floor

- Frequency domain response calculated for 14 Frequencies between 50 Hz and 1 kHz.
- Computational Expense:
  - 15 GB RAM
  - 15 min compute time per source

Displacement at 1 kHz.

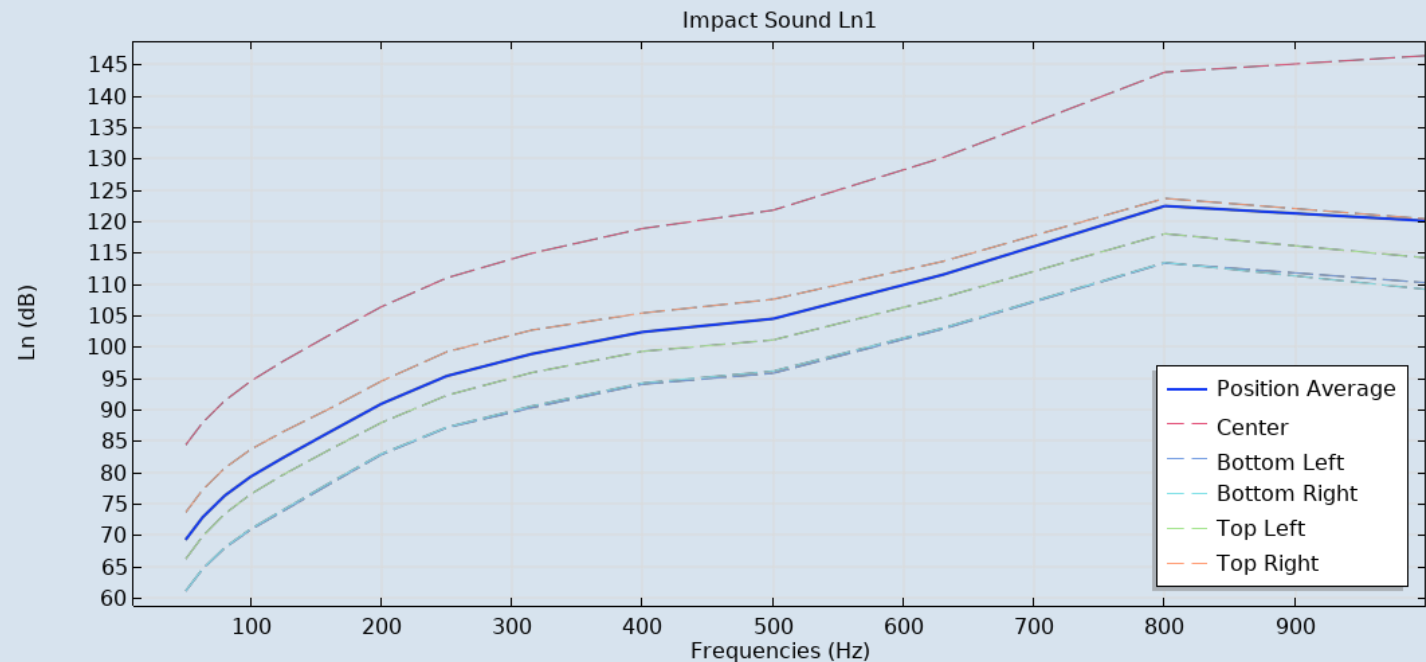
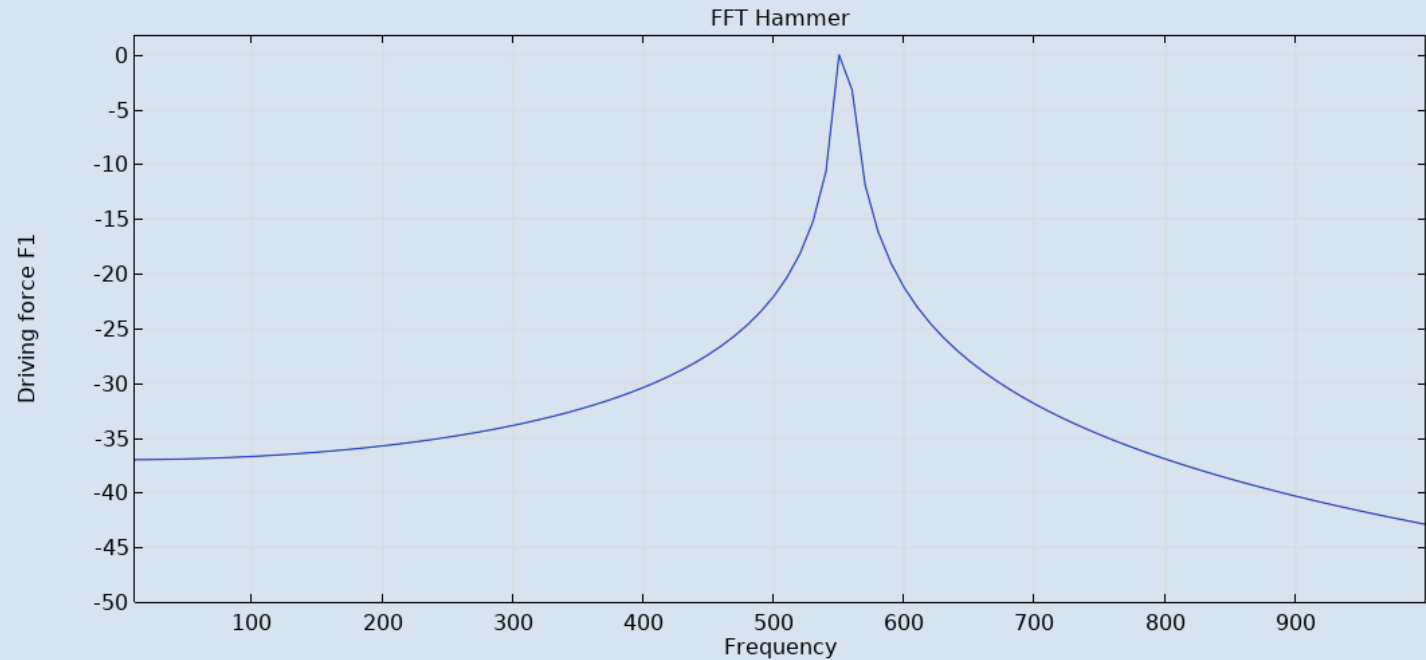


Acoustic pressure at 1 kHz.



# Tapping Machine on Wooden Floor

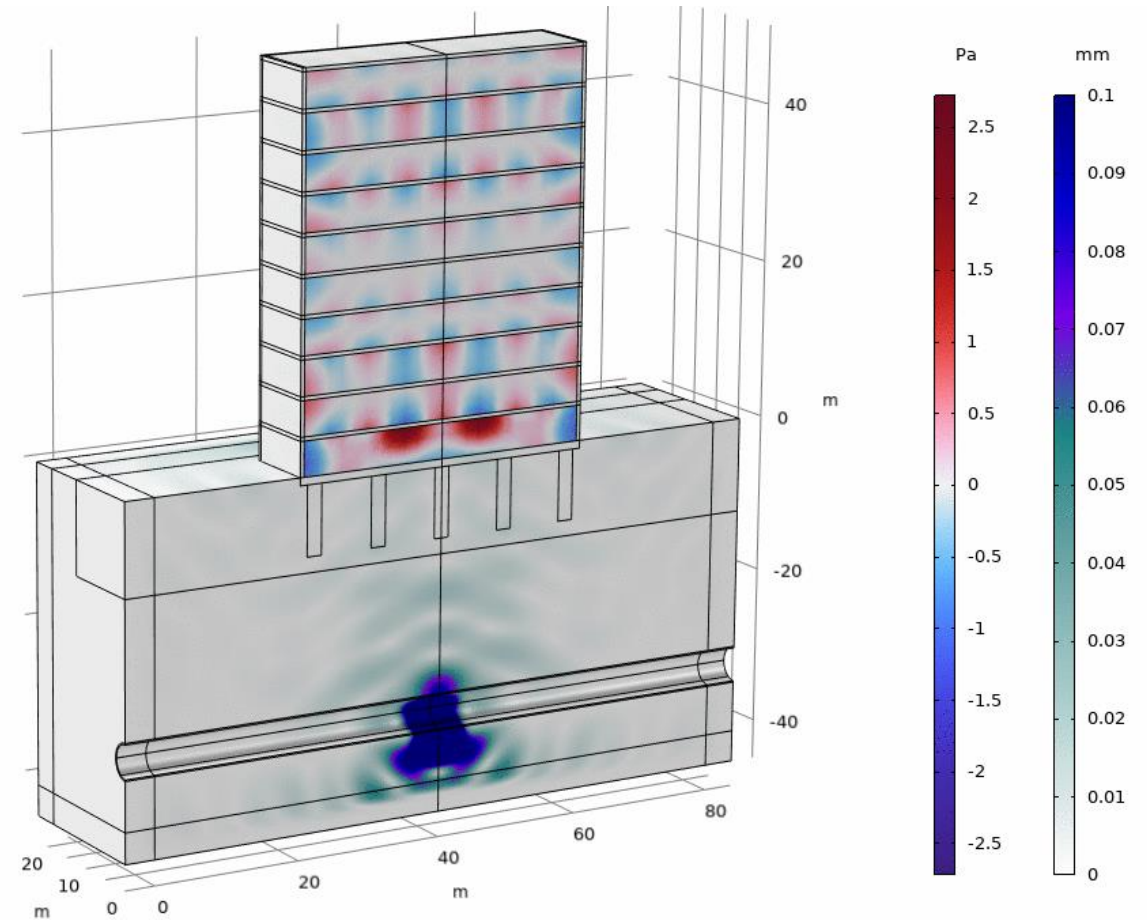
- Tapping source modeled in response to floor stiffness (Brunskog & Hammer, 2003).
- Simulation *validated* on a 5-layer wooden floor measured in the anechoic room of DTU (Technical university of Denmark), data available after publication.



## COMSOL TUTORIAL

# Underground Train-Induced Noise in Urban Buildings

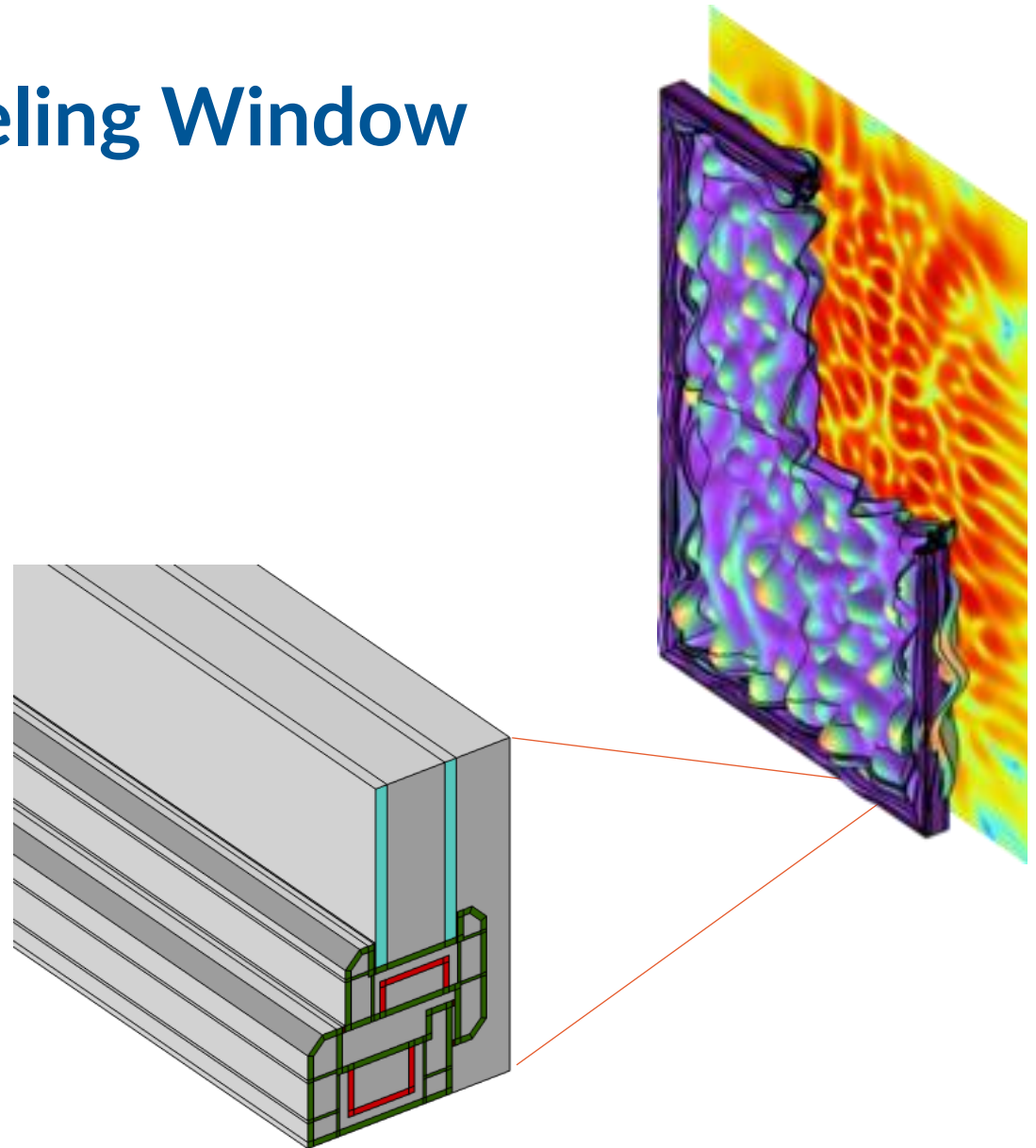
- Fully-coupled Acoustics-Structure
- Damping in soil and concrete materials
- Elastic waves in the soil can leave the computational domain without any reflection, using the *Perfectly Matched Layers*
- [Underground Train-Induced Noise in Urban Buildings](#)



## COMSOL TUTORIAL

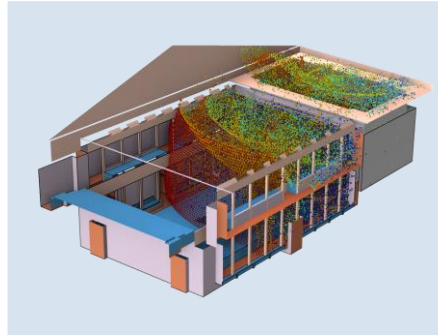
# Sound Transmission Loss Modeling Window

- The loggia glazing can be modeled by the *Elastic Waves* physics interface
  - A fully coupled acoustics-structure interaction
- Resources:
  - [Sound Transmission Loss Through a Window](#)
  - [Sound Transmission Loss Through a Concrete Wall](#)
  - [Technical Papers and User's Presentations](#)

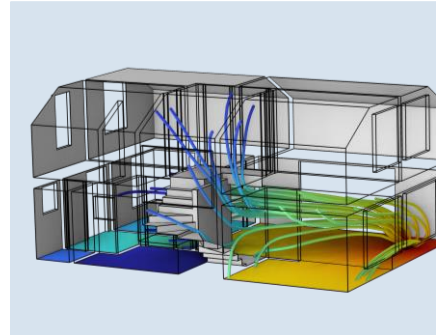


# Summary: Multimethod Building Acoustics in COMSOL

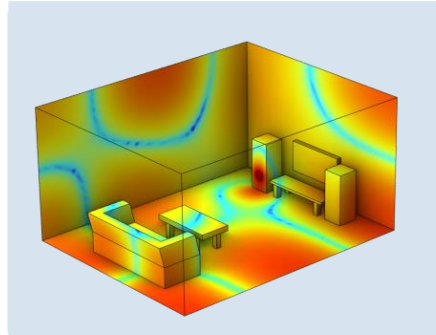
- COMSOL offers a wide spectrum of modeling tools for acoustics in rooms and buildings.
- **Traditional ray-acoustics** has limitations in modal and diffraction regions.
- **Full-wave modeling** offers more information but becomes computationally expensive at high frequencies and in large rooms.
- **Hybrid approaches** available in a homogenized GUI can compensate the shortcomings and combine the virtues of each method.



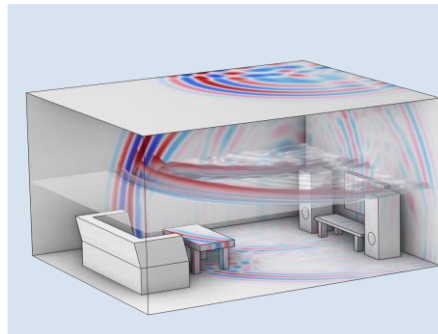
Ray Acoustics



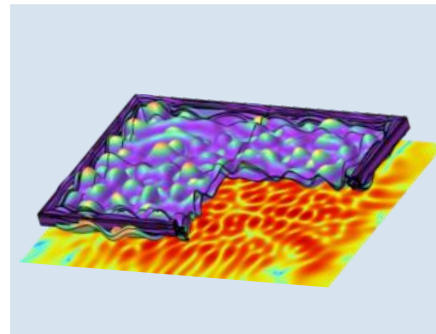
Acoustic Diffusion



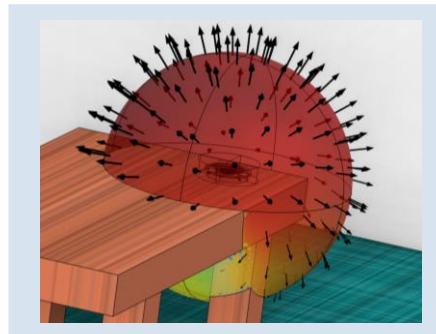
Pressure Acoustics,  
Harmonic



Pressure Acoustics,  
Transient



Acoustic Structure  
Interaction



Hybrid Methods