2.5D FEM in Acoustics

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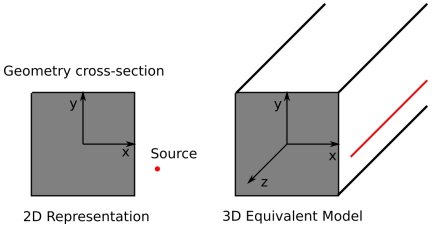
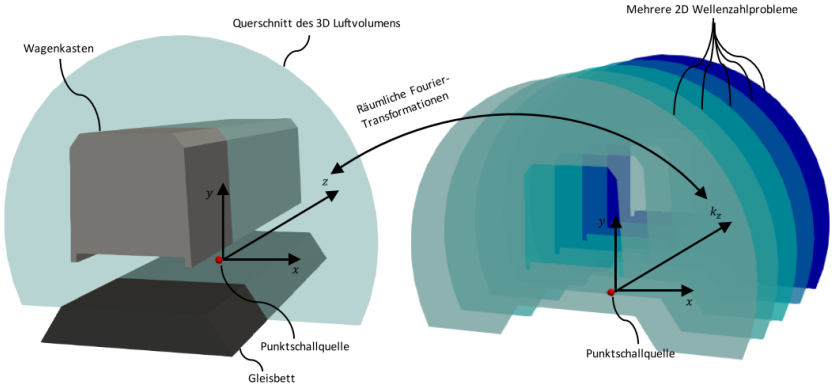
Review 3D and 2D Model

- 3D Model (The Real World)
  - Captures full geometry and physics
  - Allows complex sources (point/line/surface/volume)
  - **Challenge**: High computational cost
- 2D Model (The Simplification)
  - Requires both **geometry** and **loading** to be invariant in one direction
  - Very efficient, but limited applicability
  - Cannot model a 3D point source



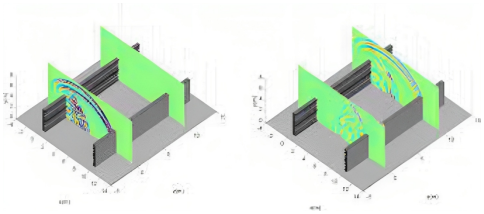
2.5D Model

- Fills the gap between 2D and 3D
- Requires only constant cross-section
- Based on spatial fourier transform, aka. wavenumber domain method
- Transform 3D problem into a series of 2D problems

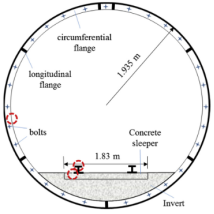


Application of 2.5D Method

- Noise Barrier
  - GAJARDO et al. 2015: Numerical Analysis of Acoustic Barriers with a Diffusive Surface Using a 2.5D Boundary Element Model
  - LI et al. 2019: Analysing the acoustic performance of a nearly-enclosed noise barrier using scale model experiments and a 2.5-D BEM approach
- Vibration Problems in Tunnel
  - JEAN, VILLOT 2015: A comparison of 2D, 2.5D and 3D BEM models for the study of railway induced vibrations
  - JIN et al. 2018: A 2.5D finite element and boundary element model for the ground vibration from trains in tunnels and validation using measurement data
- Railway Acoustics
  - LI et al. 2020: Using a 2.5D boundary element model to predict the sound distribution on train external surfaces due to rolling noise
  - LI et al. 2021: A 2.5D acoustic finite element method applied to railway acoustics

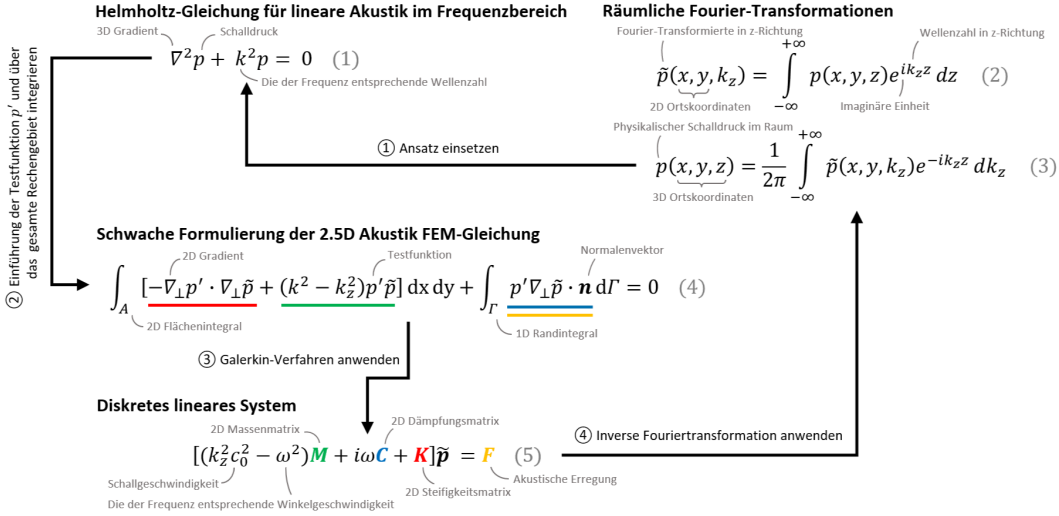


(a) GAJARDO et al. 2015



(b) JIN et al. 2018

Finite Element Formulation[1]



[1] LI et al: A 2.5D acoustic finite element method applied to railway acoustics. Applied Acoustics, Vol. 182. 2021.

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Calculation of Wavenumber Spectrum

- New analysis type `harmonic25d` in openCFS
- Input parameters:
  - `analysisFreq` - Excitation frequency in Hz
  - `cutoffFreq` - Cutoff frequency (integration bounds) in Hz
  - `freqRes` - Resolution of wavenumber spectrum (step size) in Hz
- Wavenumber domain solution $\tilde{p}(x, y, k_z)$ stored to solution file
- Discretized wavenumber $k_{z,i}$ as step value

```
<analysis>
  <harmonic25d>
    <excitationFreq>200</excitationFreq>
    <cutoffFreq>240</cutoffFreq>
    <freqResolution>0.25</freqResolution>
  </harmonic25d>
</analysis>
```

XML scheme of 2.5D analysis in openCFS

$$[\underbrace{(k_z^2 c_0^2}_{\omega_{k_z}^2} - \omega^2)\mathbf{M} + i\omega\mathbf{C} + \mathbf{K}]\tilde{p} = \mathbf{F} \tag{1}$$

$$p(x, y, z) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{p}(x, y, k_z)\, e^{-ik_z z}\, \mathrm{d}k_z \tag{2}$$

$$\approx \frac{1}{2\pi}\int_{-k_{z,\mathrm{cutoff}}}^{+k_{z,\mathrm{cutoff}}} \tilde{p}(x, y, k_z)\, e^{-ik_z z}\, \mathrm{d}k_z \tag{3}$$

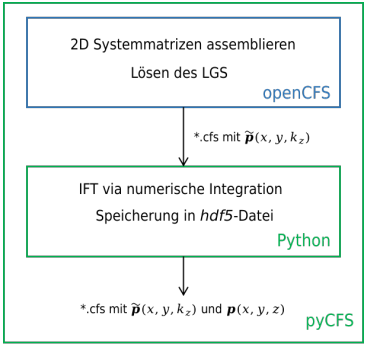
$$\approx \underbrace{\frac{\Delta k_z}{2}\sum_i \left(f(k_{z,i}) + f(k_{z,i+1})\right)}_{\text{trapezoidal rule}} \tag{4}$$

Inverse Fourier Transform

- External python script /share/python/postprocess_25d.py
- Key parameters:
  - `file_name` - solution file with wavenumber spectrum
  - `pos_list` - list of z values in m
- The modified hdf5(.cfs) file contains two `MultiSteps`:
  - `MultiStep_1` - Solution in wavenumber domain $\tilde{p}(x, y, k_z)$ for different k_z
  - `MultiStep_2` - Sound pressure $p(x, y, z)$ at different z positions
- 2.5D workflow can be automated with pyCFS

```
def PostProcessHarmonic25d(file_name,
↪  copy_file_name, pos_list =
↪  np.array([0.0]), create_copy = True):
```

Python function for postprocessing



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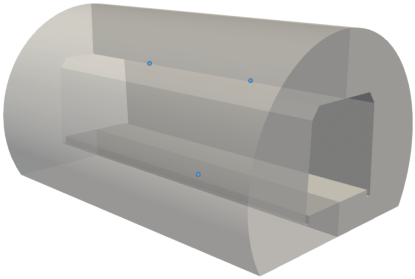
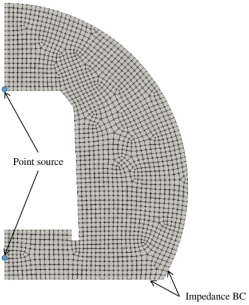
Train in Tunnel

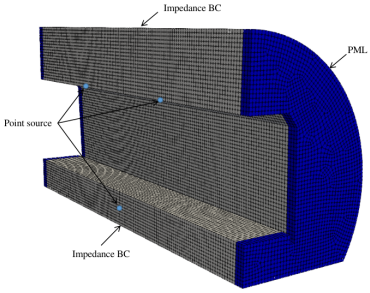
- Sound propagation in tunnel (Ø 7 m)
- Sound sources at underfloor region or on the roof
- Standing car body without components
- Tunnel wall and floor with constant sound absorbing properties
- Small amount of sound absorption



FE Model

- Half model
- Second order hexahedral element, $h = 0.086\,\mathrm{m}$
- Air with $\rho = 1.204\,\mathrm{kg\,m^{-3}}$, $c_0 = 343\,\mathrm{m\,s^{-1}}$
- Sound hard BC
  - Car body surface
  - Symmetric plane
- Impedance BC with $\hat{Z} = 78$
  - Tunnel wall and floor
- 3D Model $l = 10\,\mathrm{m}$, PML at both ends
- Point sources on roof and in underfloor area

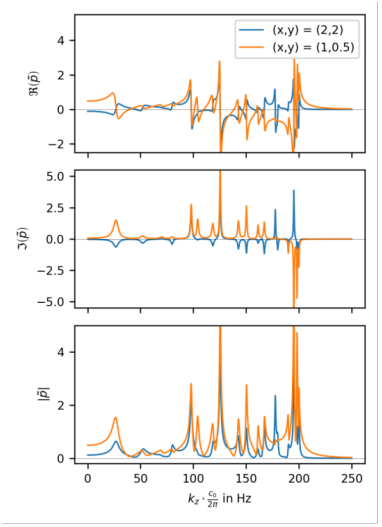


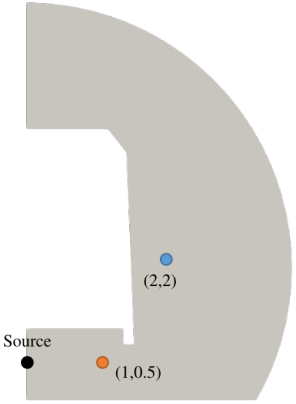


Results

Wavenumber Spectrum, Sound Source in Underfloor Area

- $f_{\text{excitation}} = 200\,\text{Hz}$, $f_{\text{cutoff}} = 250\,\text{Hz}$, $\Delta f = 0.25\,\text{Hz}$
- Complex-valued wavenumber spectrum $\tilde{p}(k_z)$ at each (x,y)
- Peaks correspond to tunnel eigenmodes

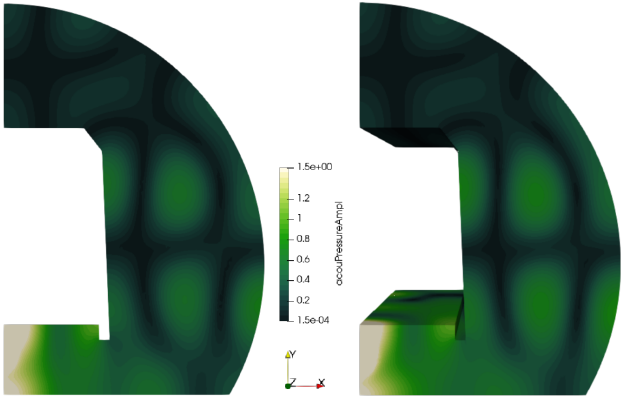




Results

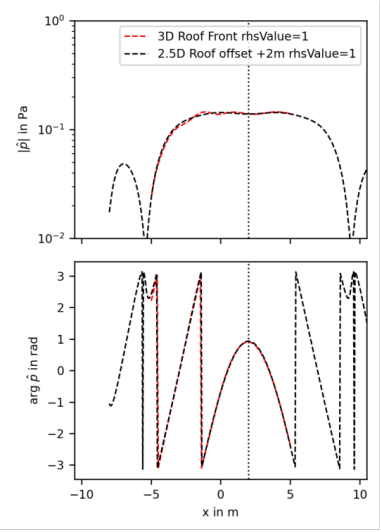
Pressure Field, Sound Source in Underfloor Area

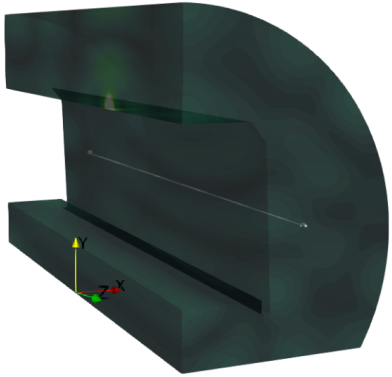
- Sound pressure in spatial domain $p(x, y, z)$ at $z = 0\,\mathrm{m}$
- Integration of wavenumber spectrum $\tilde{p}(x, y, k_z)$



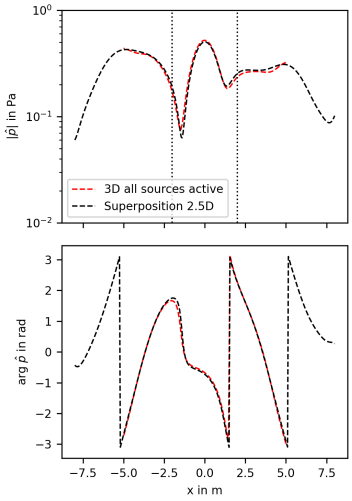
Results

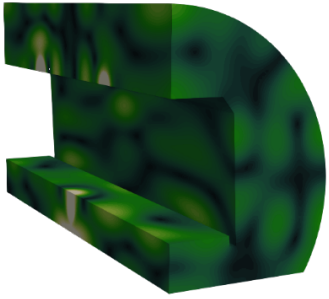
Pressure Field, Sound Source on Roof





Superposition of Sound Sources





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Summary

- Introduction to 2.5D Modeling
- 2.5D finite element formulation for linear acoustic problem in frequency domain
- Implementation of harmonic25d driver in openCFS
- Application example as validation

Q & A

Questions?