3D vibro-acoustic simulations of problems with damping layers using the Wave Based Method and its hybrid extensions

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SAPEM 2014, Stockholm, Sweden
December 16–18, 2014

Outline

Outline

Important trends in industry

Increased importance of NVH

- Legislative: Strict limitations on NVH levels
- Commercial: Customer demands on NVH behaviour

Increased use of LW materials

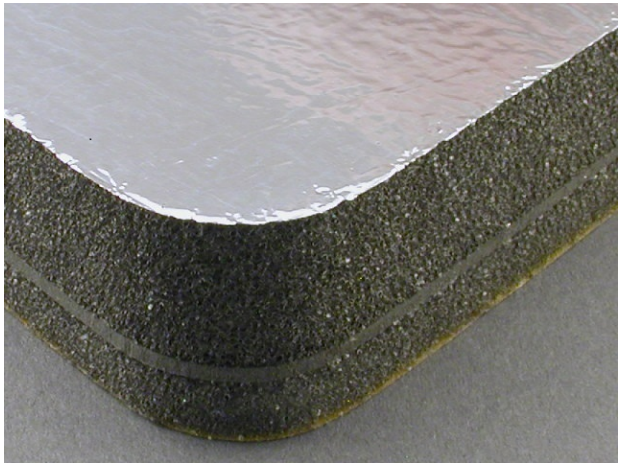
- Direct material cost
- Ecological awareness

Increased use of CAE techniques

- Increase of virtual prototypes
- Shortened product cycle

$\rightarrow$ Robust noise reduction solutions and CAE techniques necessary

Multilayered damping treatments



Layered structure:

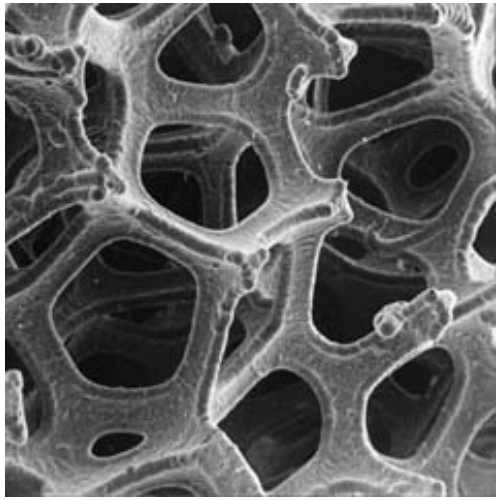
- Elastic layers
- Air layers
- Viscoelastic layers
- Poroelastic layers

Goal:

- Different properties
- Different wavelengths and wave types
- Decoupling
- Hampering sound and vibration propagation

Poroelastic materials

- Open cell structure
- High porosity
- (Deformable) skeleton and interpenetrating fluid
- Energy dissipation
  - Structural
  - Viscous
  - Thermal



$\rightarrow$ Effective reduction of disturbing NVH behaviour

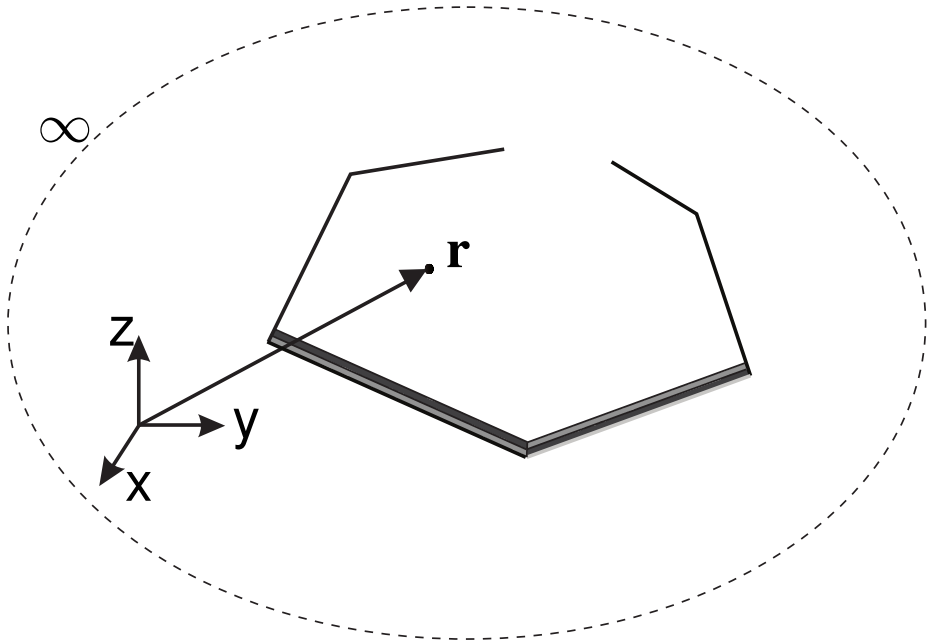
Outline

Mathematical description

Problem definition

Acoustic problem with multilayered damping treatment:

- Acoustic domain
- Damping layer (e.g. poroelastic)
- Mutual interaction surfaces



Mathematical description

Model equations

Acoustics

- Helmholtz equation

$$\mathbf{r} \in \Omega^a : \nabla^2 p^a + k_a^2 p^a = \mathcal{Q}_a$$

Poroelastic materials: Biot equations

$$N\nabla^2 \mathbf{u^s} + \nabla[(\lambda + \frac{\tilde{Q}^2}{\tilde{R}} + N)e^s + \tilde{Q}e^f] = -\omega^2(\tilde{\rho}_{11}\mathbf{u^s} + \tilde{\rho}_{12}\mathbf{u^f}),$$

$$\nabla[\tilde{Q}e^s + \tilde{R}e^f] = -\omega^2(\tilde{\rho}_{12}\mathbf{u^s} + \tilde{\rho}_{22}\mathbf{u^f}),$$

Mutually coupled

- Elastically deformable continuum
- Johnson-Champoux-Allard equivalent fluid model

Outline

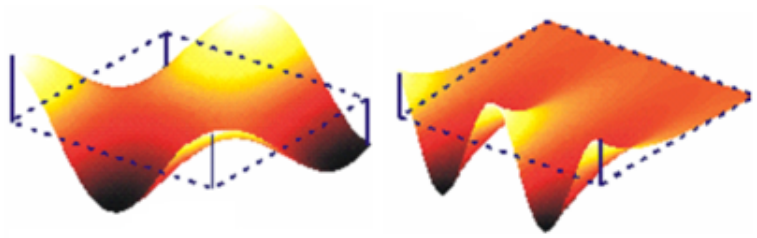
Wave Based Method

Basic concept

Wave Based Method

1. Partitioning of the considered problem domain into convex subdomains
2. Selection of a suitable set of wave functions for each subdomain

$$p^a(\mathbf{r}) \approx \hat{p}^a(\mathbf{r}) = \mathbf{\Phi_a w_a} + \hat{p}^a_q(\mathbf{r}),$$



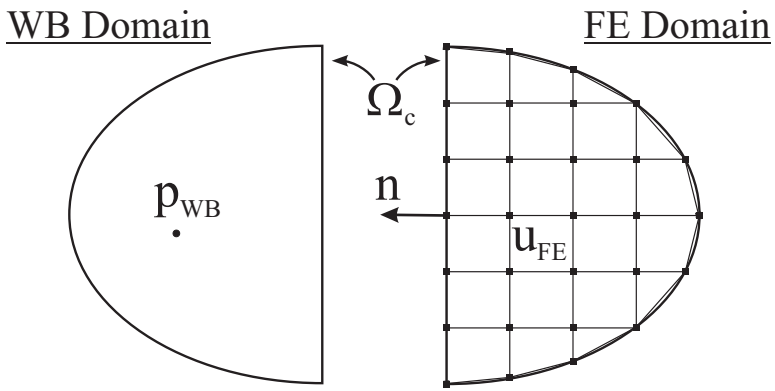
3. Construction of the WB system matrices via a weighted residual formulation of the boundary and interface conditions
4. Solution of the system of equations factors and postprocessing of the dynamic variables

Hybrid FE-WBM

Basic concept

Motivation for a hybrid method

	FEM	WBM
Geometrical flexibility	High	Moderate
Convergence rate	Low	High



Introduction of coupling terms leads to coupled model:

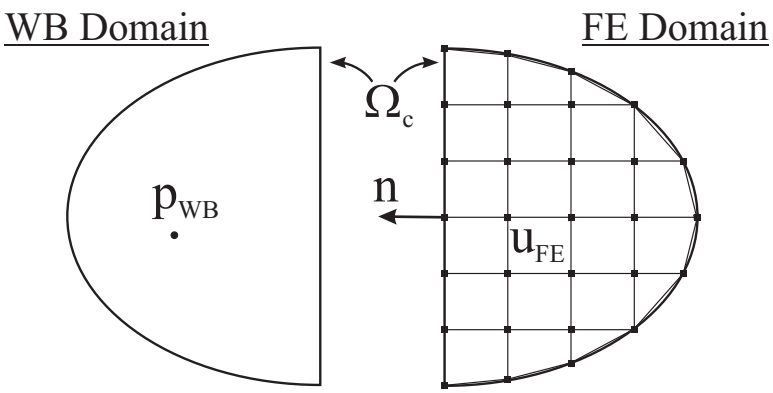
$$\begin{bmatrix} \mathbf{A_{ww}} + \mathbf{C_{ww}} & \mathbf{C_{wf}} \\ \mathbf{C_{fw}} & \mathbf{Z_{ff}} + \mathbf{C_{ff}} \end{bmatrix} \begin{bmatrix} \mathbf{w_w} \\ \mathbf{u_f} \end{bmatrix} = \begin{bmatrix} \mathbf{b_w} + \mathbf{c_{ww}} \\ \mathbf{f_f} + \mathbf{c_{fw}} \end{bmatrix}$$

Hybrid FE-WBM

Acoustic-poroelastic coupling

2 implementations of acoustic-poroelastic hybrid FE-WBM[1]

- $(\mathbf{u}^s, \mathbf{u}^f)$ formulation
- $(\mathbf{u}^s, p^f)$ formulation



Software and solving

WBM

- In house Matlab code
- Matrix solving via \

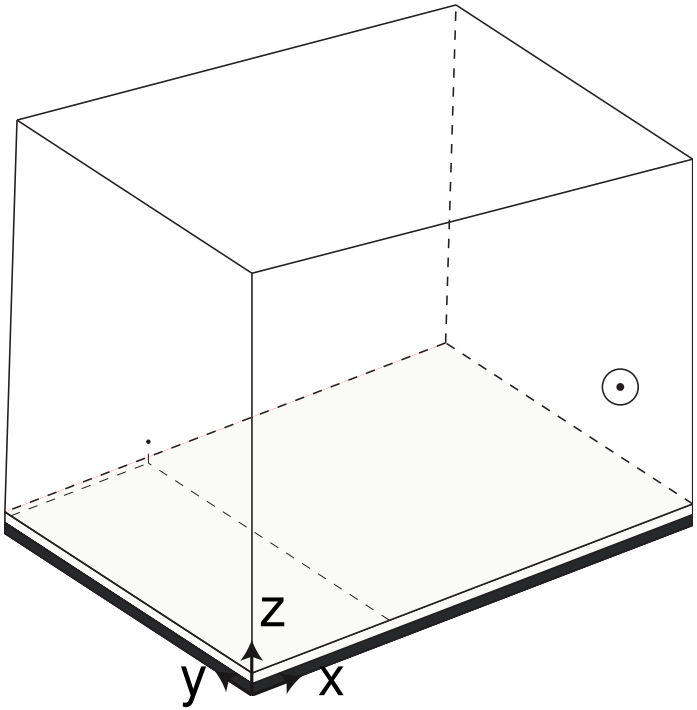
FEM

- Comsol 4.1
- Matrix solving via Nastran

[1] S. Jonckheere et al. A direct hybrid Finite Element Ű Wave Based Method for the steady-state analysis of acoustic cavities with poro-elastic damping layers using the coupled Helmholtz-Biot equations. CMAME 263, 144–157, 2013.

Numerical example

- Acoustic cavity
  (1.122m x 0.82m x 0.982m)
- Point source
  (1.03 ; 0.12 ; 0.3)
- Poro-elastic multi-layer
  (2 x 2.5cm, sliding BC, Carpet[1] + Melamine[2])



Model	#	Acoustic DOFs	Poro-elastic DOFs
Hybrid $(\mathbf{u}^s, \mathbf{u}^f)$	Q	150-382 WF	38148 DOFs
Hybrid $(\mathbf{u}^s, p^f)$	Q	150-382 WF	25432 DOFs
FEM $(\mathbf{u}^s, p^f)$	C	10648 DOFs	50336 DOFs

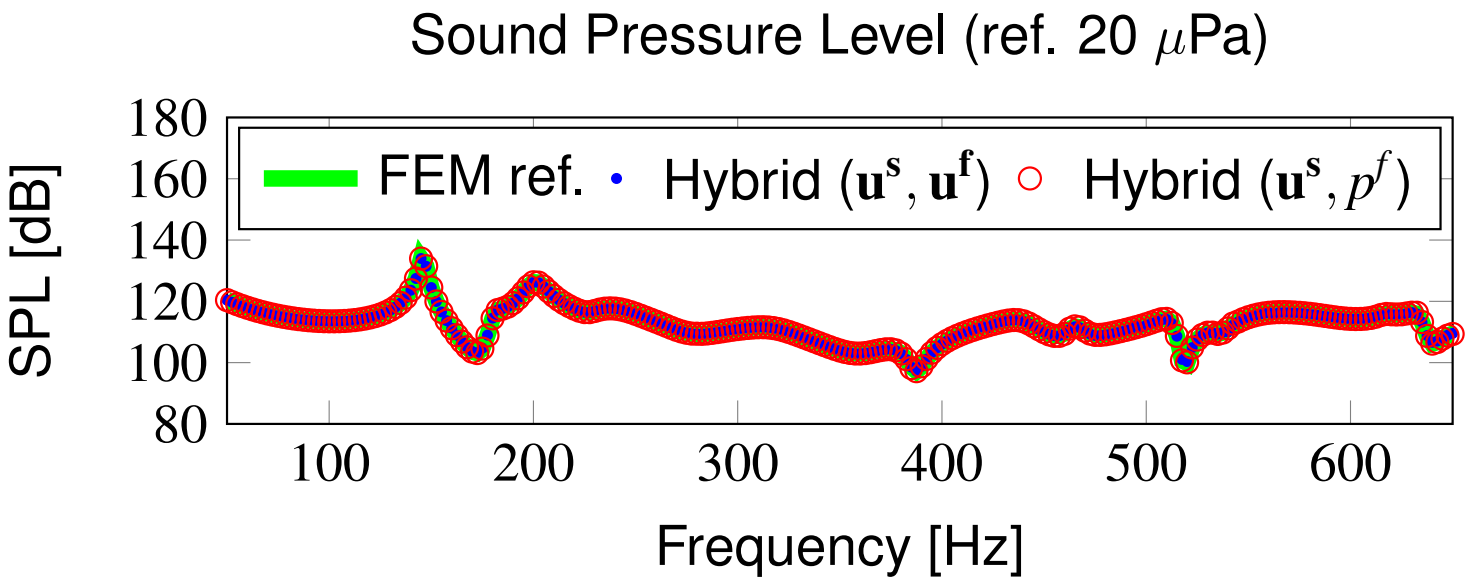
[1] Debergue et al. Boundary conditions for the weak formulation of the mixed (u,p) poroelasticity problem. JASA 106(5), 2383–2390, 1999.

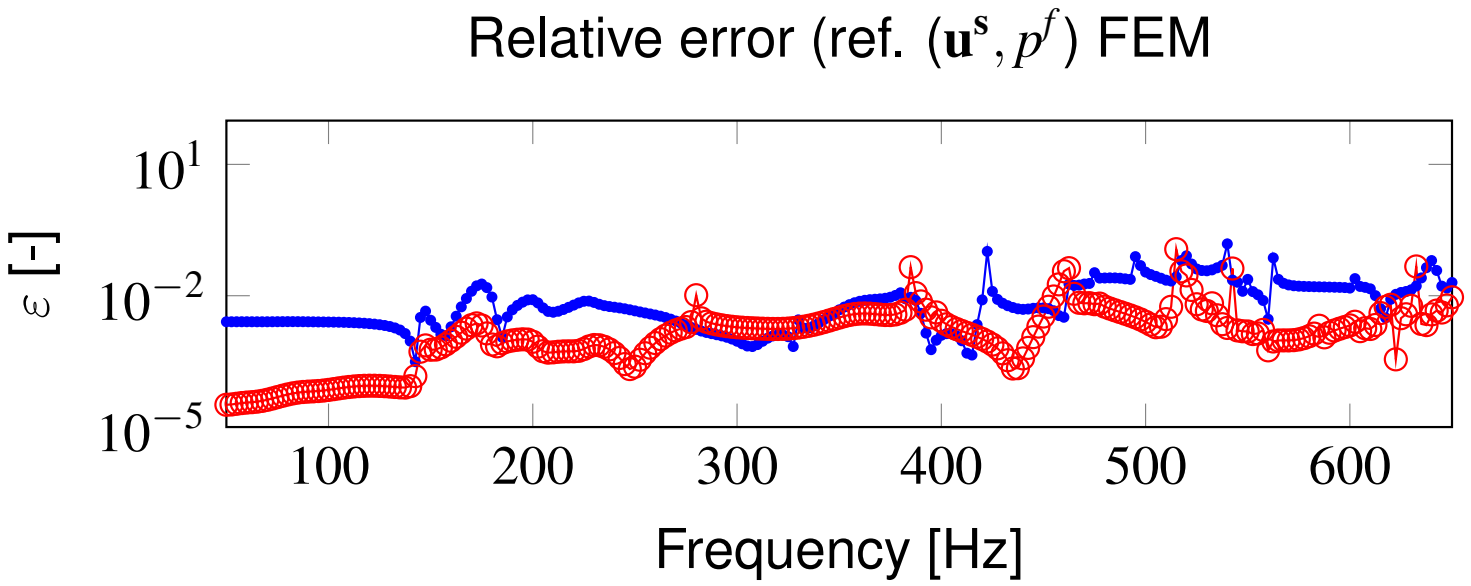
[2] Vigran, et al. Prediction and measurements of the influence of boundary conditions in a standing wave tube. Acta Acustica United with Acustica 83(3), 419–423, 1997.

Hybrid FE-WBM

Numerical example

(0.35,0.80,0.10)

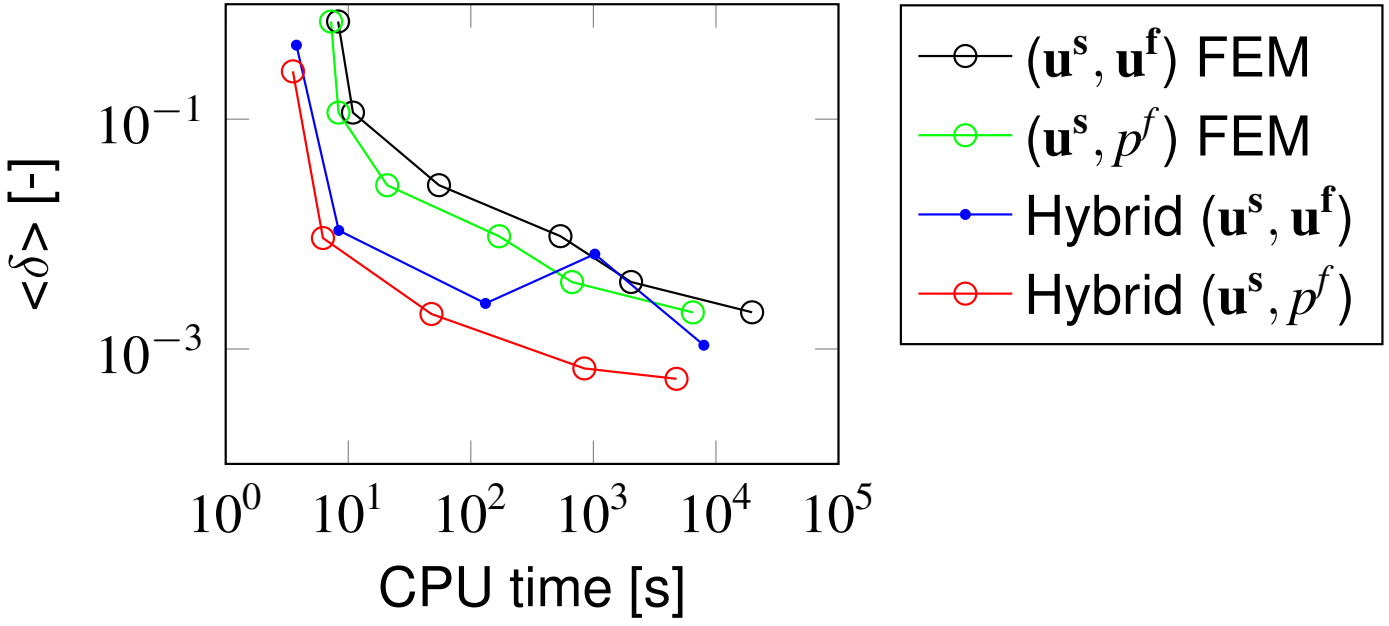




Hybrid FE-WBM

Numerical example

Convergence at 450 Hz (avg. 512 pts.)

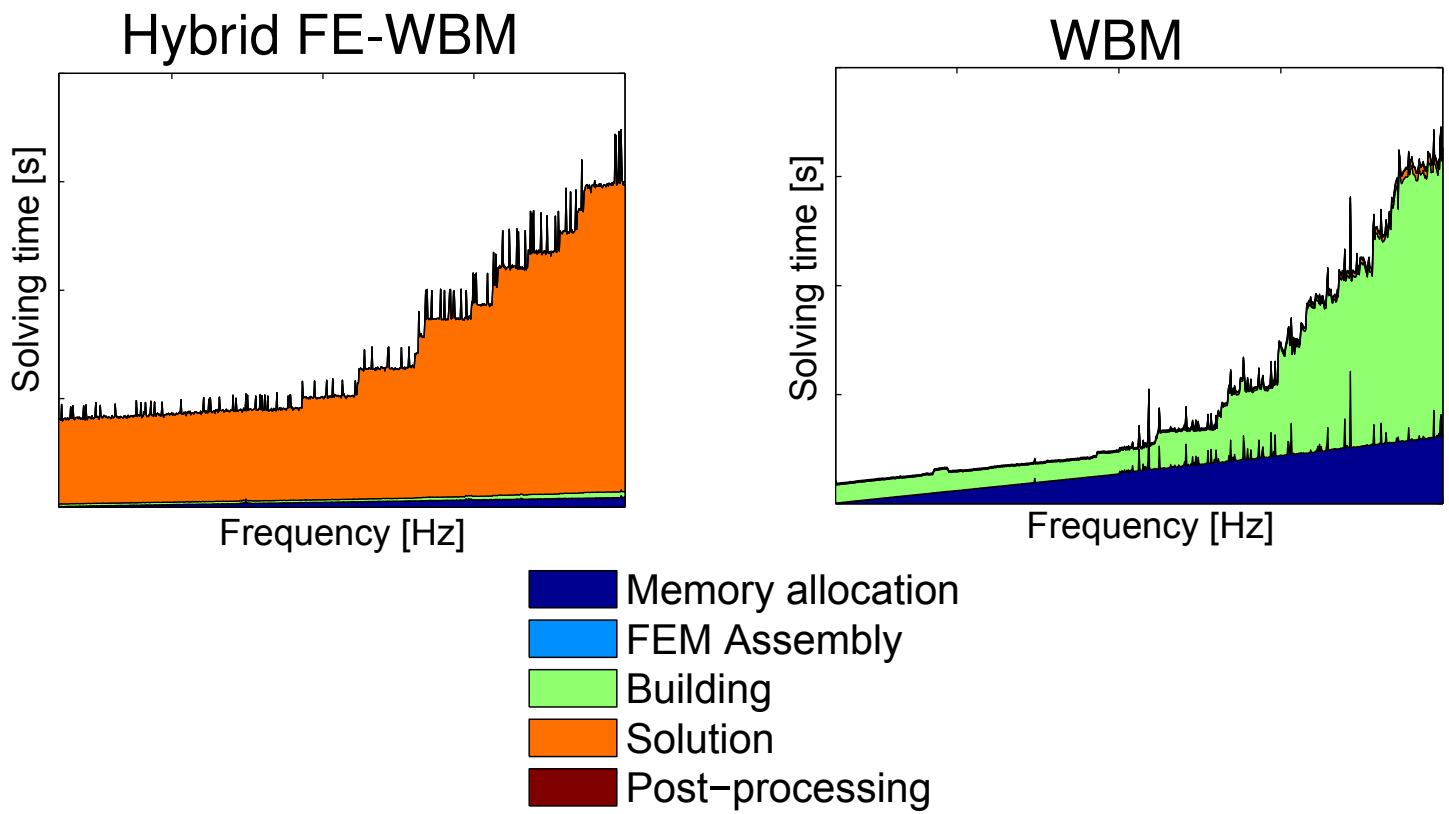


- Both hybrids faster/more accurate than FEM
- $(\mathbf{u}^s, p^f)$ most accurate/stable

Hybrid FE-WBM

Numerical example

Typical timing distribution



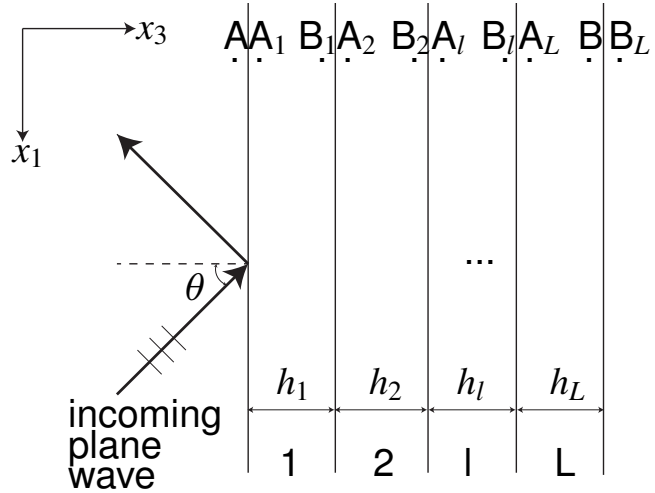
- Main computational cost in solving FE submodel
- Further reduction?
  - Modal reduction of FE model
    $\Rightarrow$ Still difficult, especially for multilayers
  - Transfer Matrix Method

Outline

Transfer Matrix Method

Basic concepts

1. Partitioning of the multilayer in L layers

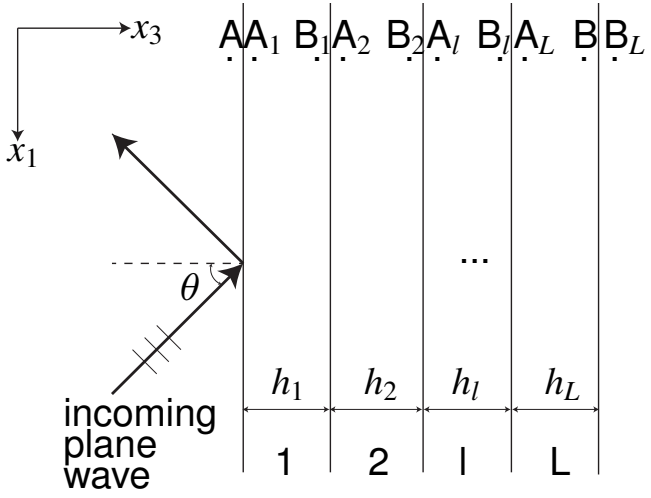


2. Expression of the wave propagation in layer l
3. Calculation of the transfer matrix through each layer l
4. Assembly of the global transfer matrix
5. Condensation of internal DOFs

$$\begin{Bmatrix} p_B \\ v_A \end{Bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{Bmatrix} p_A \\ v_B \end{Bmatrix}$$

Transfer Matrix Method

Basic concepts

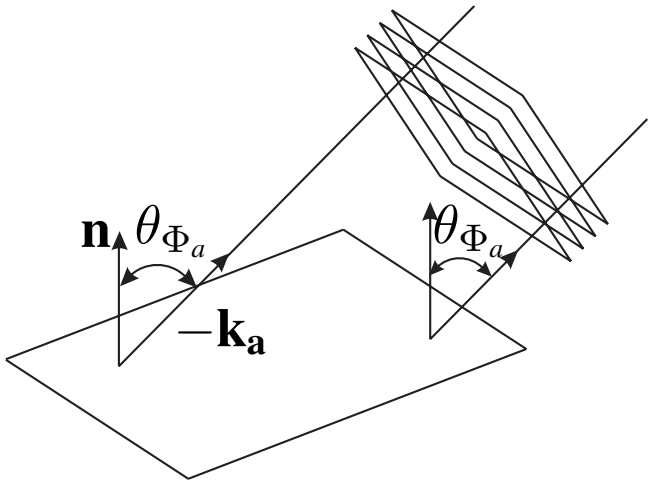


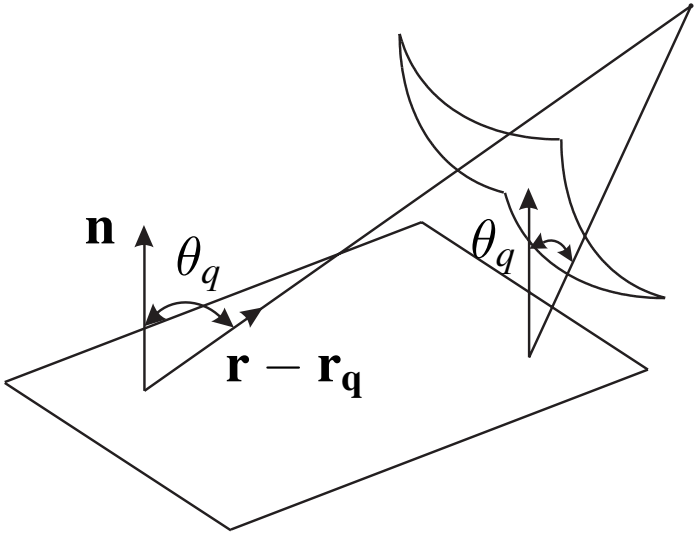
Choice of θ:

- Normal incidence
  ($\theta = 0^\circ \sim$ Kundt tube)
- Omnidirectional
  (averaged over $0 \leq \theta \leq \pi/2 \sim$ Reverberant room)
- WBTMM

Transfer Matrix Method

Choice of θ – WBTMM





Wave function dependent angle of incidence

$$\cos\left(\theta_{\Phi_a}\right) = -\frac{\mathbf{k_a} \cdot \mathbf{n}}{\|\mathbf{k_a}\|}$$

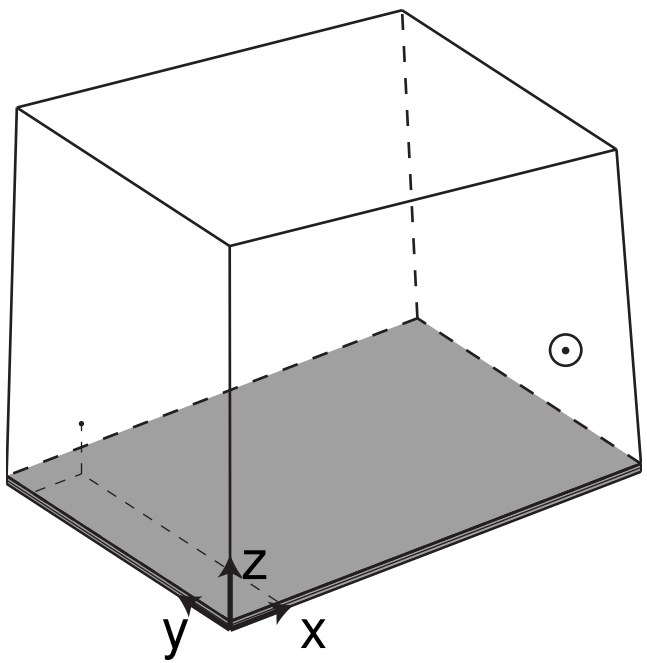
Source/location dependent angle of incidence:

$$\cos\left(\theta_q(\mathbf{r})\right) = -\frac{(\mathbf{r} - \mathbf{r_q}) \cdot \mathbf{n}}{\|\mathbf{r} - \mathbf{r_q}\|}$$

Transfer Matrix Method

Numerical example

- Acoustic cavity
  (1.15m x 0.815m x 0.982m)
- Point source
  (1.03 ; 0.12 ; 0.3)
- Poro-elastic multilayer
  (2 x 1cm, sliding BC, Eurocell[1] + Fireflex[1])



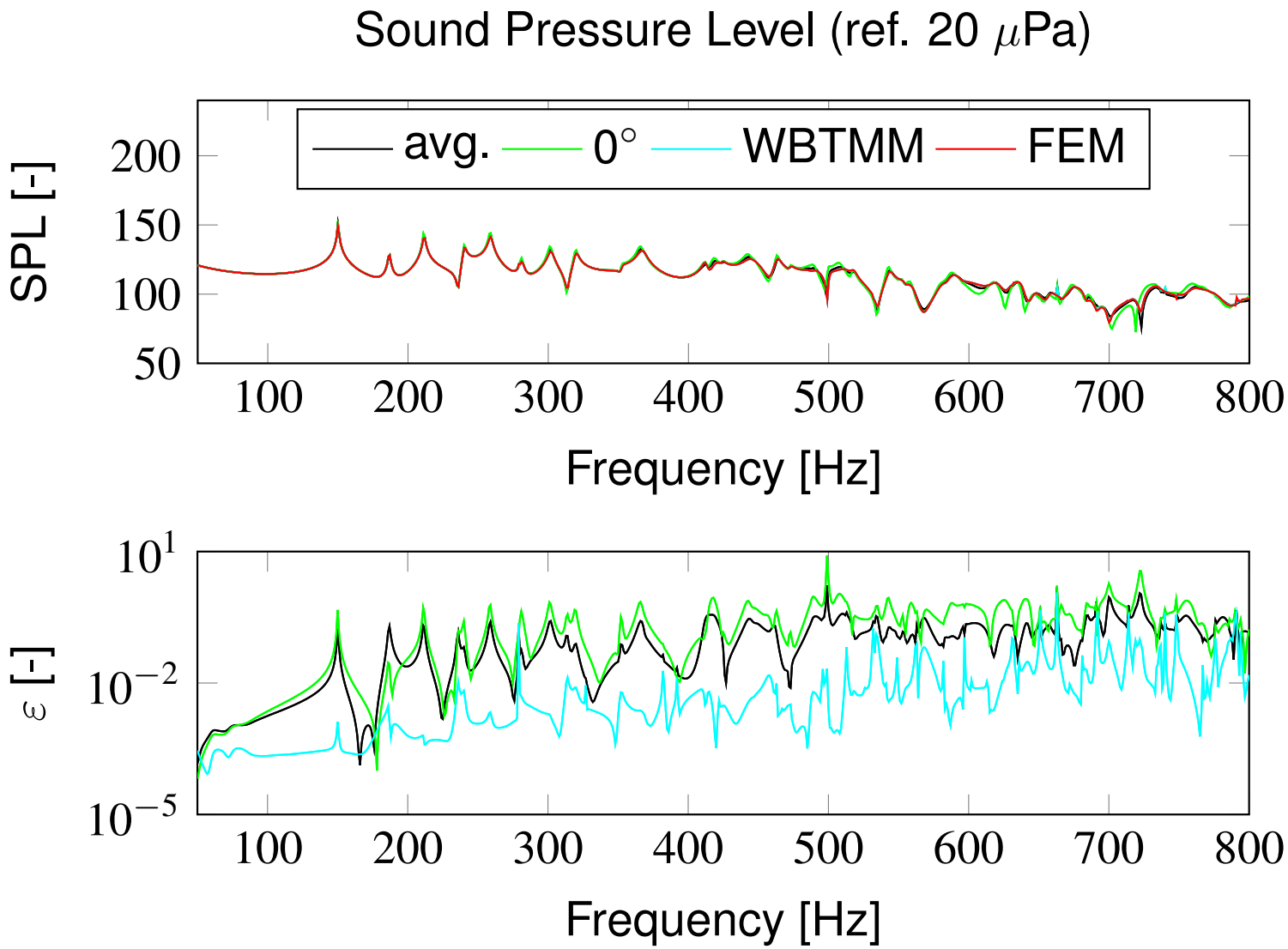
Model	#	Acoustic DOFs	Poro-elastic DOFs
WBM-TMM	–	24-518 WF	0°/avg./WBTMM
Hybrid $(\mathbf{u}^s, p^f)$	Q	24-518 WF	12296 DOFs

[1] J. Descheemaeker. Elastic characterization of porous materials by surface and guided acoustic wave propagation analysis. KU Leuven, Dept. of Physics, PhD. thesis, Leuven, 2011.

Transfer Matrix Method

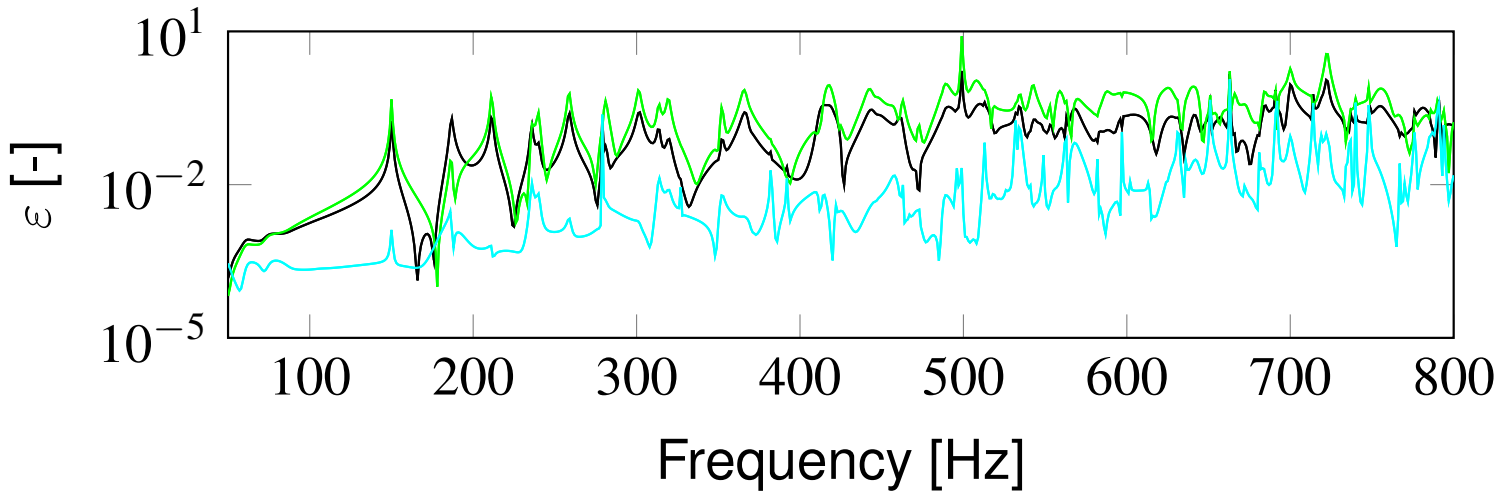
Numerical example

(0.13,0.72,0.15)



Transfer Matrix Method

Numerical example



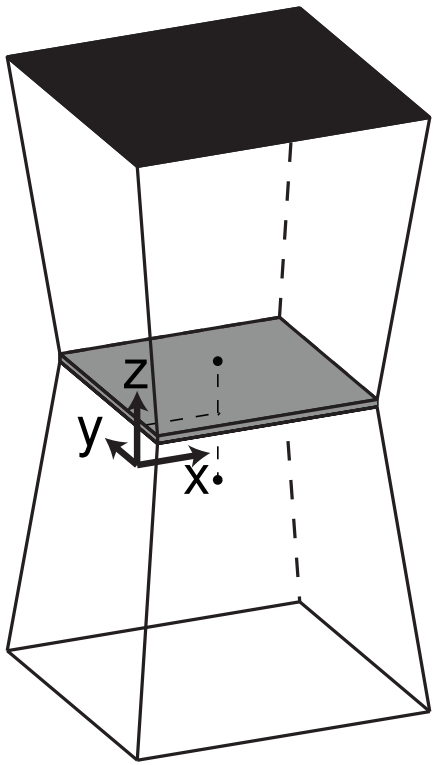
WBTMM

- 0° (∼ Kundt tube) reasonable
- avg. (∼ reverberant room) slightly better
- WBTMM outperforms 0°/avg.

Transfer Matrix Method

Numerical example

- Acoustic cavity
  2x (0.4m x 0.4m x 0.4m)
- Normal velocity
- Poro-elastic multilayer
  (1cm Eurocell[1], sliding BC, glued to plate)
- Aluminium plate
  3 mm, simply supported



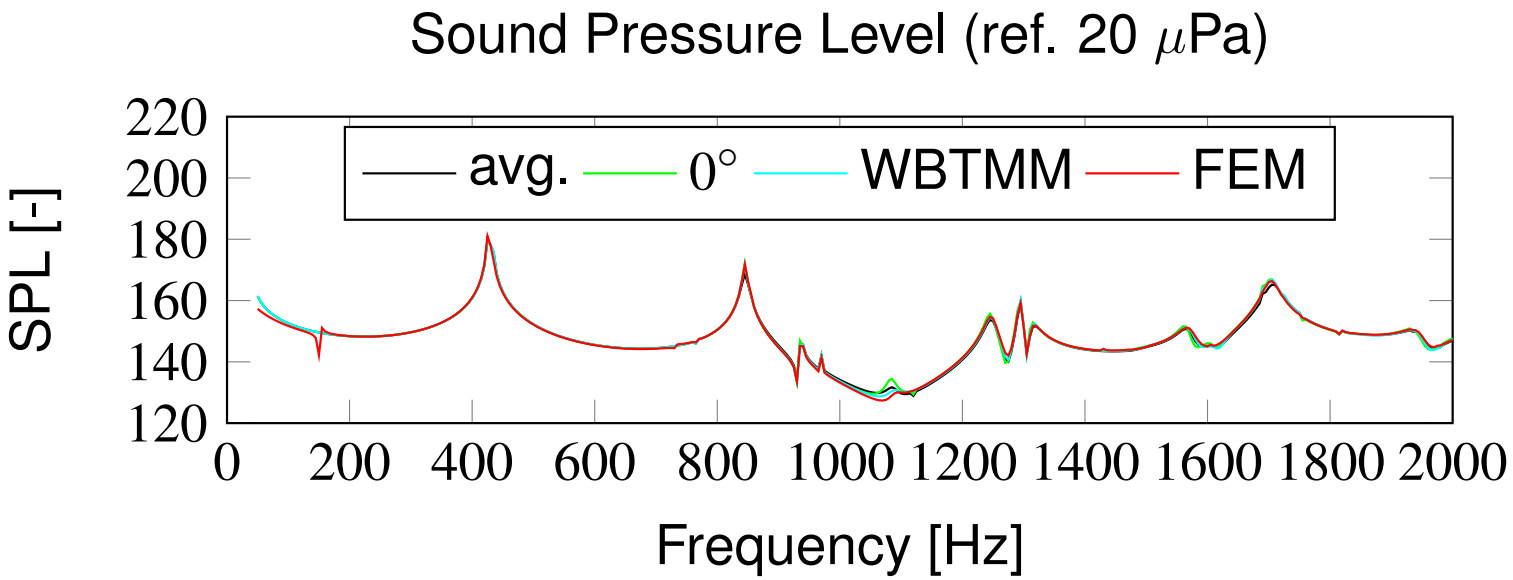
Model	#	Acoustic DOFs	Poro-elastic DOFs	Plate DOFs
WBM-TMpackage	–	300-1200 WF	0°/avg./WBTMM	
WBM-TMM-WBM	–	300-1200 WF	0°/avg./WBTMM	40-80 WF
Hybrid $(\mathbf{u}^s, p^f)$	Q	300-1200 WF	8092 DOFs	1734 DOFs

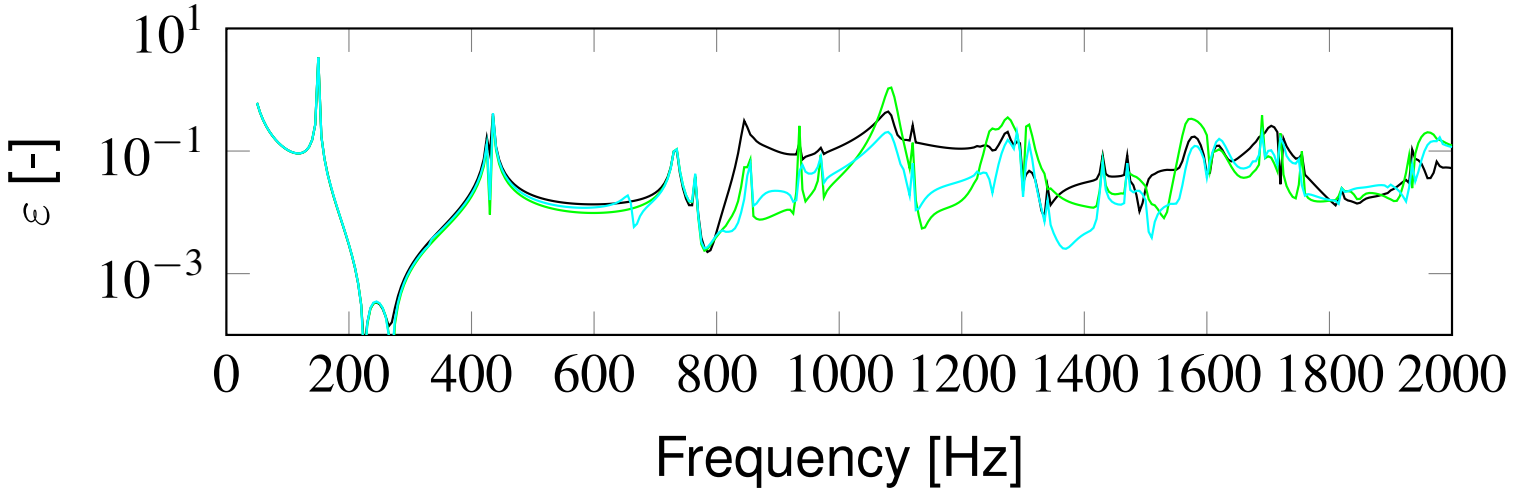
[1] J. Descheemaeker. Elastic characterization of porous materials by surface and guided acoustic wave propagation analysis. KU Leuven, Dept. of Physics, PhD. thesis, Leuven, 2011.

Transfer Matrix Method

Numerical example

WBM-TMpackage – (-0.05,-0.11,0.08)





Transfer Matrix Method

Numerical example

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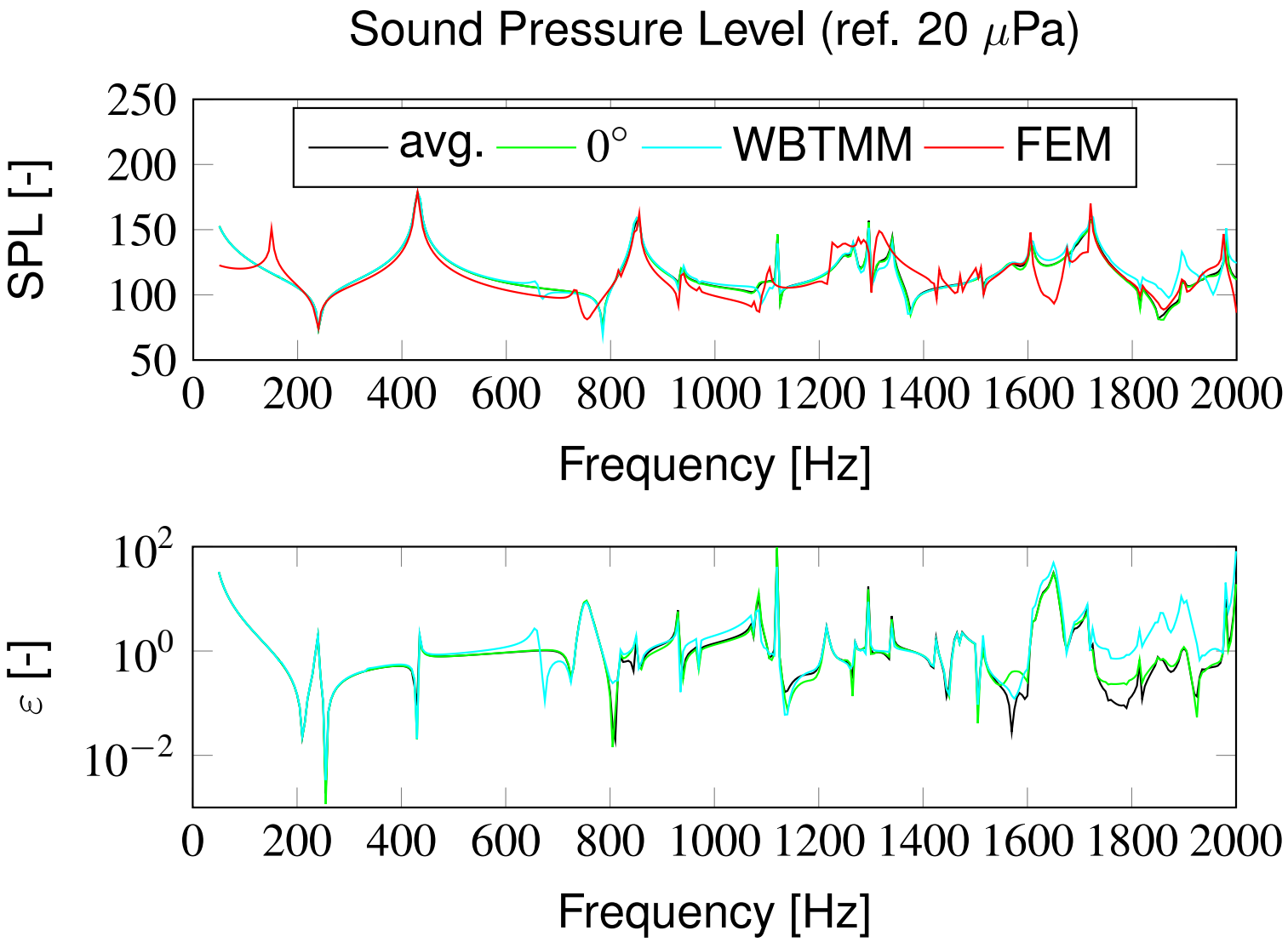
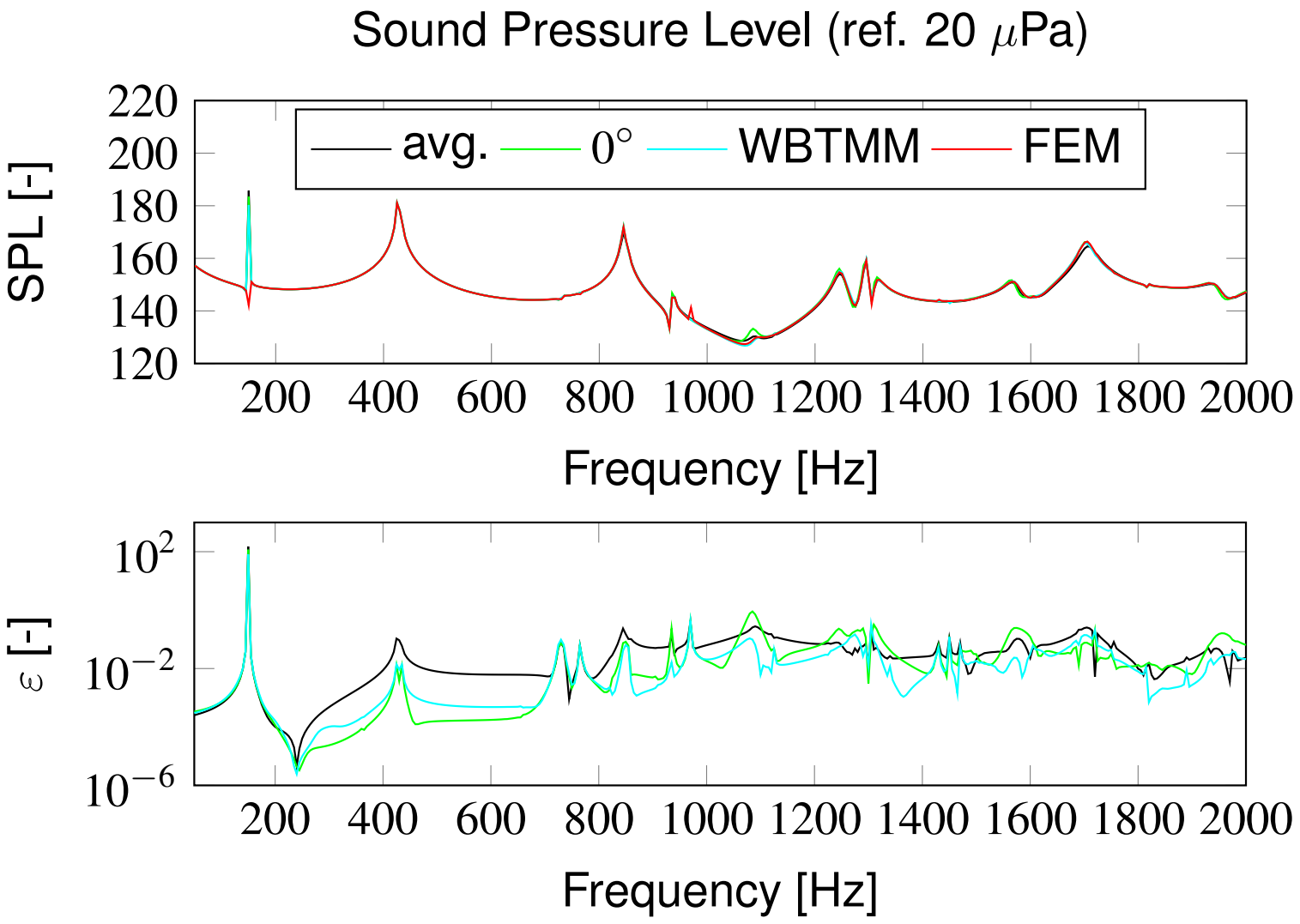


Transfer Matrix Method

Numerical example

WBM-TMM-WBM – (-0.05,-0.11,0.08)



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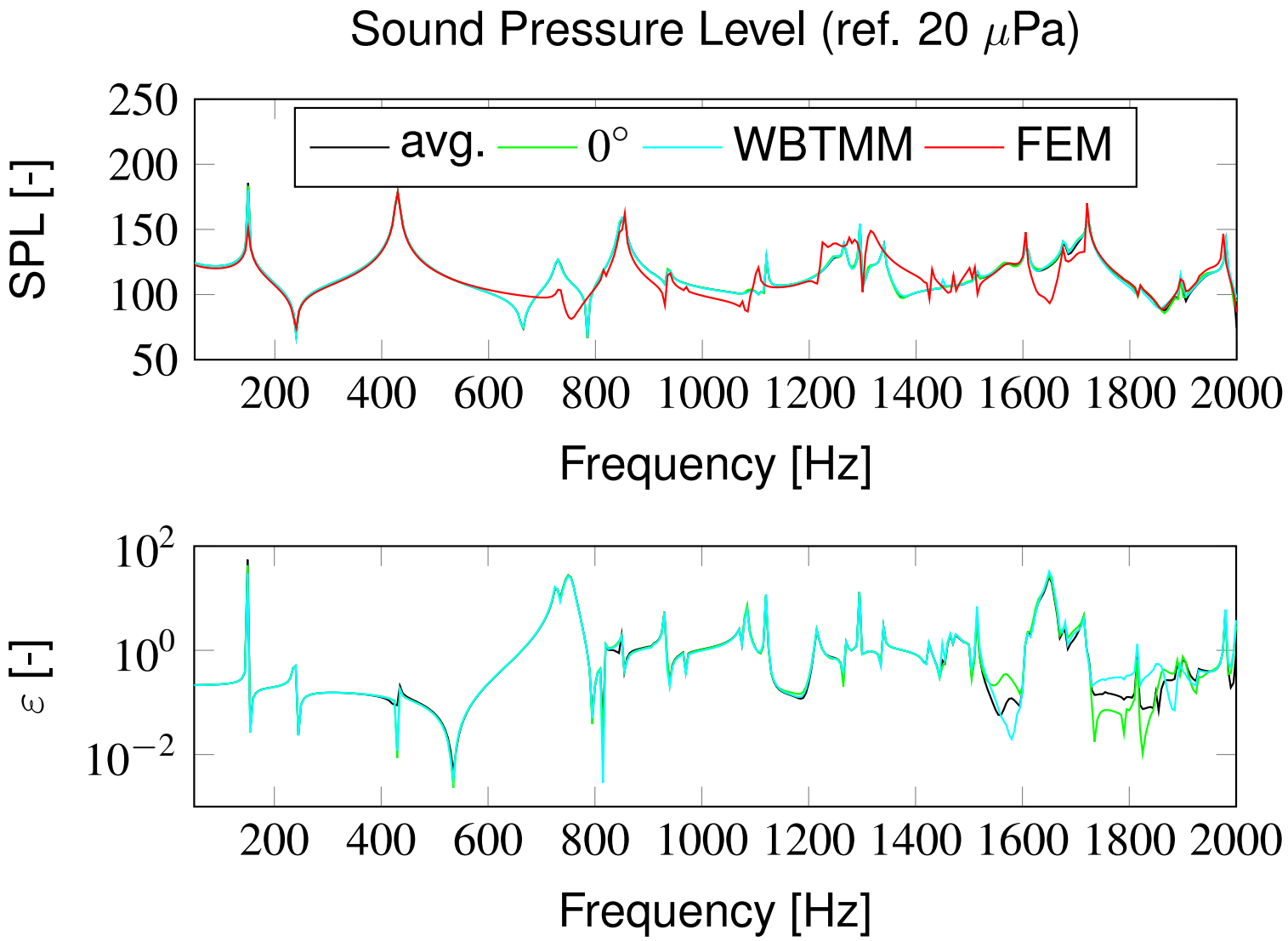

Transfer Matrix Method

Numerical example

TMM has its limitations!

- Less TMM $\rightarrow$ Better predictions
- Why? Boundary conditions!
  - Simply supported plate
  - Poroelastic layer glued to plate
  - Sliding edges solid phase

$\rightarrow$ Be careful with TMM in vibro-acoustic calculations!

For narrowband predictions:

- Use explicit models
- But remember Hybrid FE-WBM
  - Efficient WBM for acoustics
  - Flexible FEM for damping treatment

Outline

Conclusions

Hybrid FE-WBM

- Synergy of WBM and FEM
  - WBM: Efficiency
  - FEM: Geometrical flexibility
- Hybrid $(\mathbf{u}^s, p^f)$ FE-WBM
  - Faster for same accuracy
  - More accurate for same effort
- Still large part of solving time for FE submatrices

WBTMM

- More efficient use of TMM in WBM
  - Wave function dependent θ
  - Source/location dependent θ
- Better, but no miracle solution! (BC's)

Further extensions

- Modal/CMS methods for multilayers

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Conclusions

Questions?

Contact information

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