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Analyzing Muffler Performance using the Transfer Matrix Method

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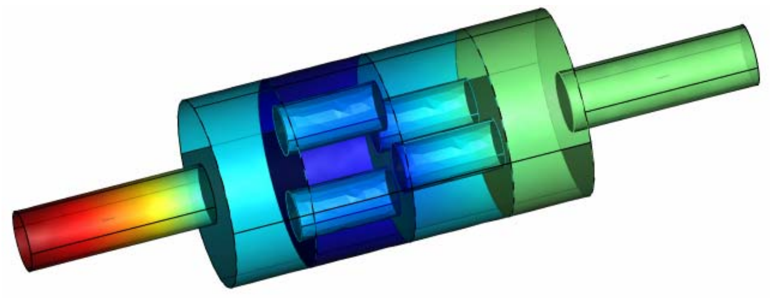
Dinex Emission Technology A/S



TRUCKS

VANS

BUSES

INDUSTRIAL

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Content

- The Transfer Matrix Method
- The Numerical Models
- Results
- Conclusion

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Exhaust Systems in General

- Exhaust gas transportation
- Noise reduction
- NOx, HC, PM reduction

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The Transfer Matrix Method

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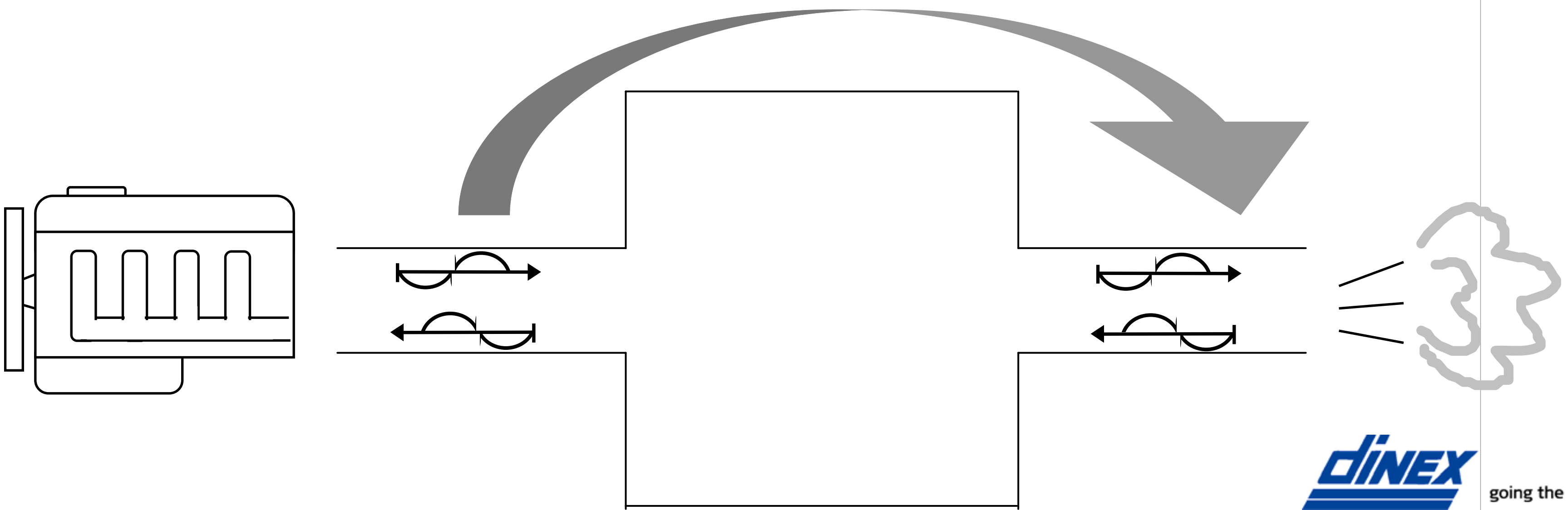
The Transfer Matrix

- The acoustical transfer properties of a system
- Plane wave decomposition in the connecting pipes



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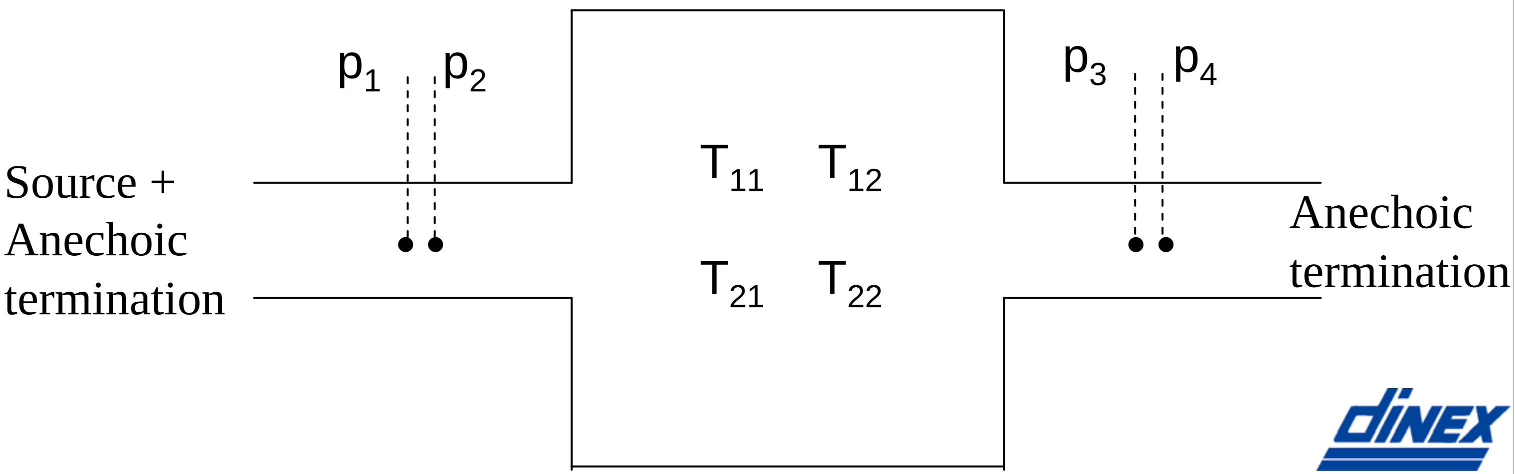
The Transfer Matrix Extraction

p_1, p_2, p_3, p_4 → $T_{11}, T_{12}, T_{21}, T_{22}$

1. Symmetric matrix
2. Reciprocity requires det(T)=1

Advantage:
Solving the FEM problem only once



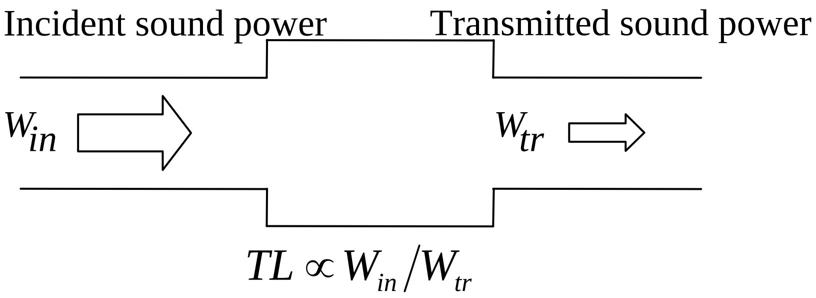
Evaluation Parameters

Transmission loss (source **in**dependent)

Insertion loss (source dependent)

Evaluation parameters

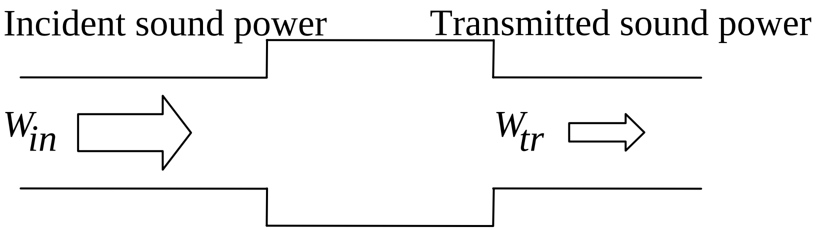
Transmission loss (source **in**dependent)



Insertion loss (source dependent)

Evaluation parameters

Transmission loss (source **in**dependent)



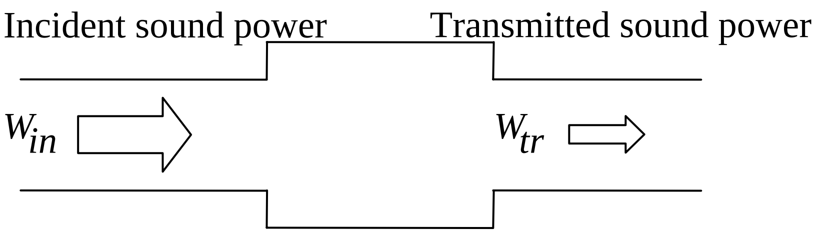
$$TL \propto W_{in} / W_{tr}$$

$$TL = 10\log\left(\frac{1}{4}\left|T_{11} + T_{12}\frac{S}{\rho c} + T_{21}\frac{\rho c}{S} + T_{11}\right|^2\right)$$

Insertion loss (source dependent)

Evaluation parameters

Transmission loss (source **in**dependent)



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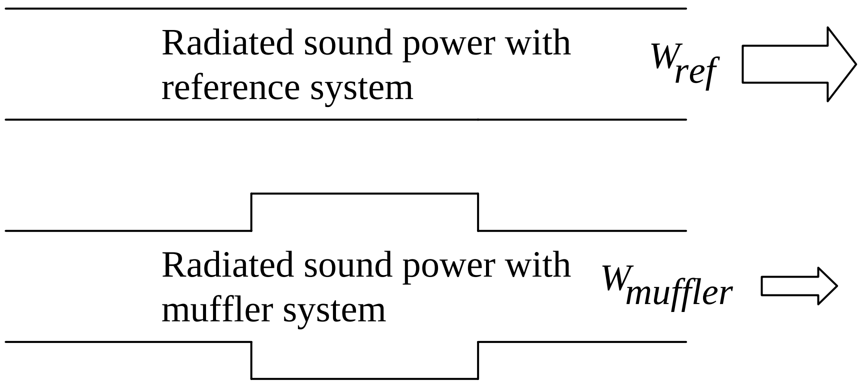
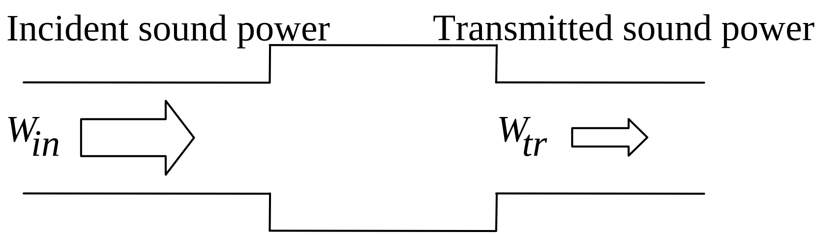


$$IL \propto W_{ref} / W_{muffler}$$

Evaluation parameters

Transmission loss (source **in**dependent)



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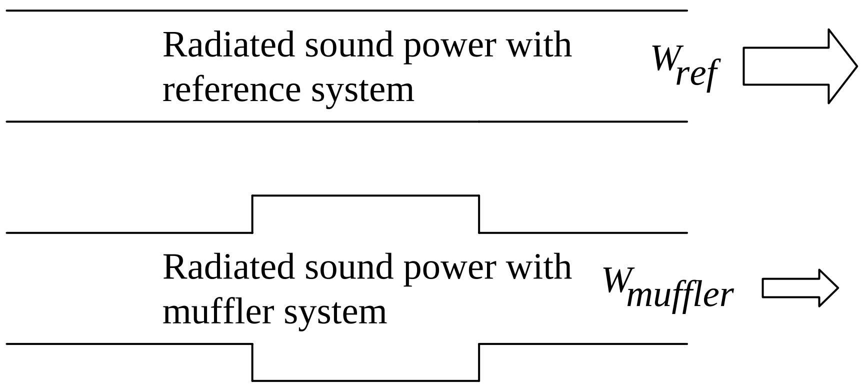
Insertion loss (source dependent)



$$IL \propto W_{ref} / W_{muffler}$$

$$IL = 10 \log\left(\frac{\left| T_{11}Z_{a,r} + T_{12} + Z_{a,s} + (T_{21}Z_{a,r} + T_{22}) \right|^2}{\left| T_{11}'Z_{a,r} + T_{12}' + Z_{a,s} + (T_{21}'Z_{a,r} + T_{22}') \right|^2} \right)$$

The Numerical Model

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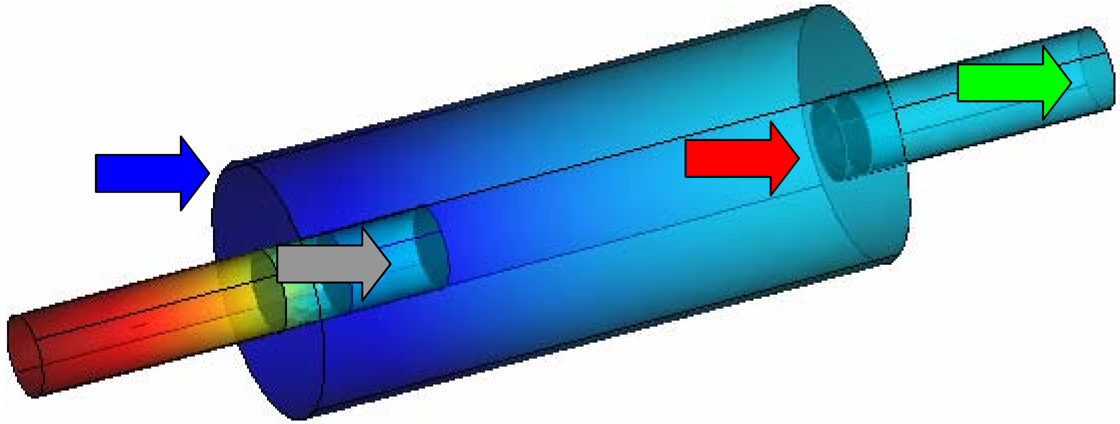
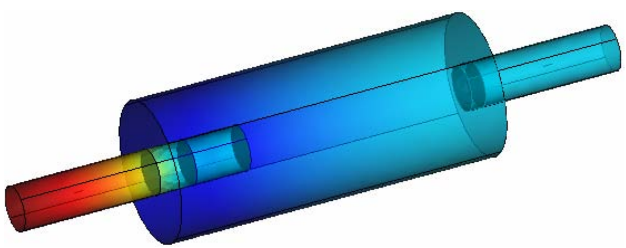
Boundary Conditions

- Solid walls (sheet metal)
- Coupling boundaries conditions (wave propagation from one medium to another)
- Radiation conditions (reflection free ends)
- Impedance conditions (perforated plates)



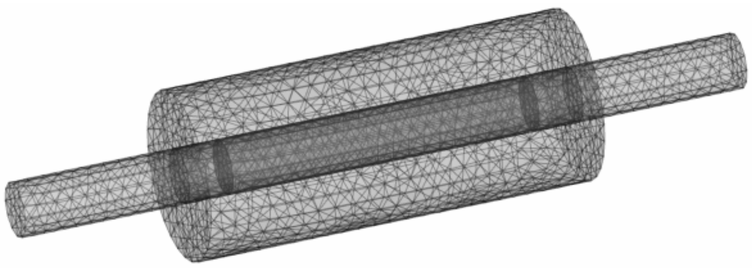
Subdomain Conditions

- Air
  - Defined by the speed of sound and the density
- Absorptive material
  - Defined by the apparent density and average fiber diameter
  - Based on theory by Delany and Bazley, Bies and Hansen
- Ceramic structure (Diesel Particulate Filter)
  - Preliminary described by general damping



Simulation Setup

- Maximum element size = $\lambda/5$ = 34 mm
- 24.000 elements, 38.000 DOF
- PARDISO solver
- 100 discrete frequencies



The Results

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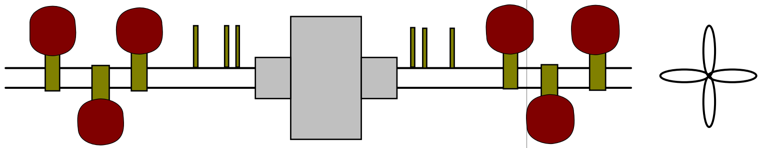
The Measurement Setup

- The two source method
  - Up and down stream source direction

- Flow speed up to 30 m/s (cold air)
  - Corresponds to 160 kW engine @ rated speed



The Test Objects

- Reflection muffler
  - Simple expansion chamber
  - Quarter wave resonator
- Absorption muffler
- Perforated muffler
  - Hole size: Ø3, Ø4, Ø8, Ø12
  - Porosity: 10 – 40 %
- Automotive exhaust
  - Diesel Particulate Filter
  - Hybrid muffler

The reflection muffler

The absorption muffler

The perforated muffler

Automotive exhaust

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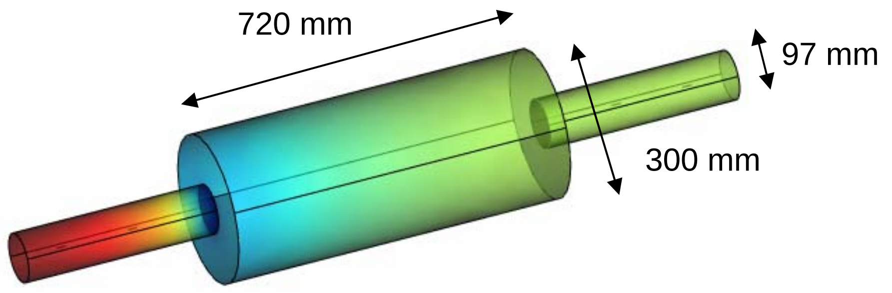
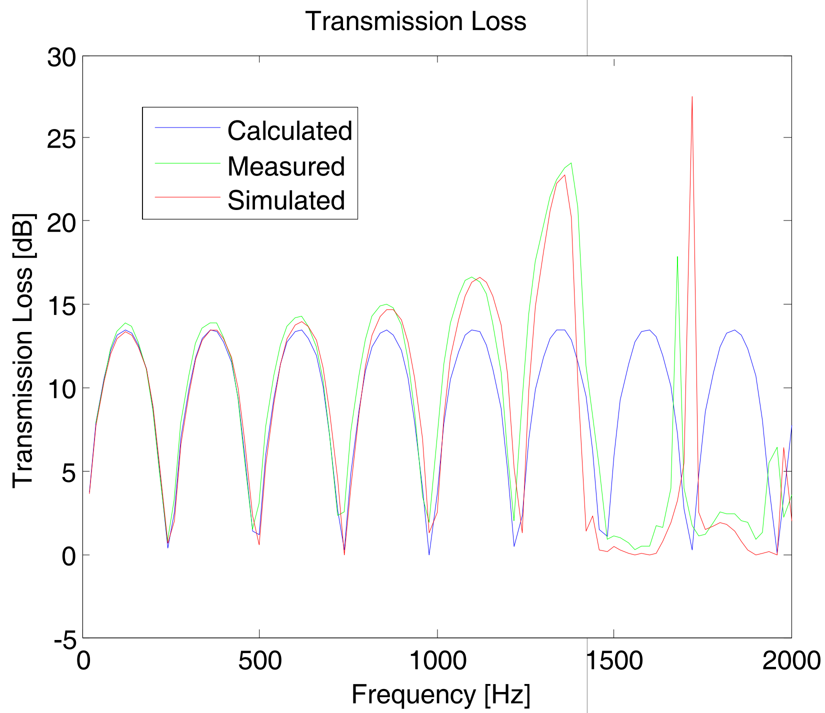
The Reflective Muffler

Comparison

- Good correlation
- Peak offset due to inaccurate lengths, temperatures, densities
- First axisymmetric higher-order mode will propagate above 1400 Hz.
- First TL peak corresponds to a quarter muffler length





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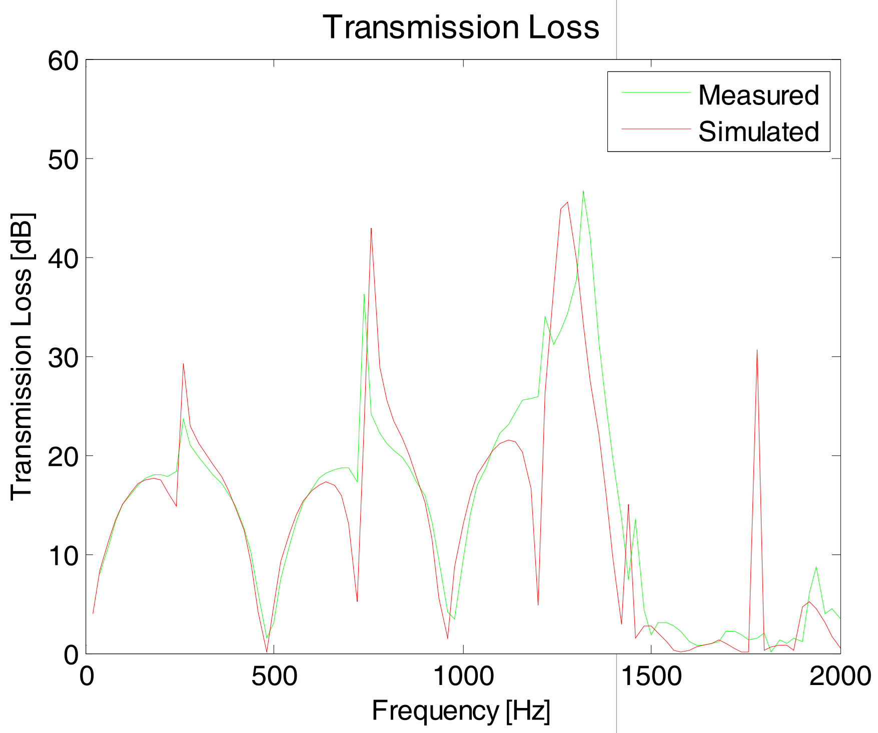
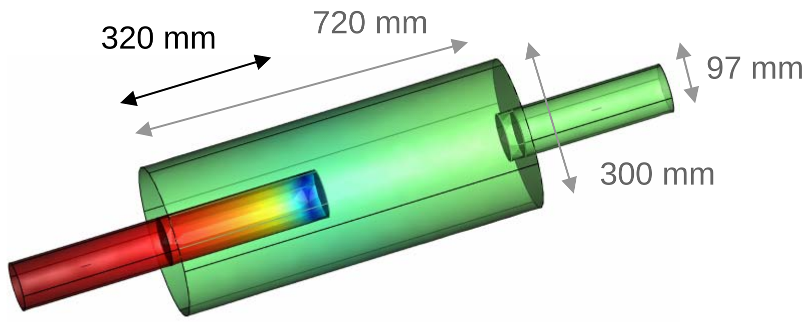
The Quarter Wave Resonator

Comparison

- Again good correlation
- The first peak corresponds to a quarter pipe length.
- The 500 Hz minima could be eliminated by a pipe of 1/8 of the muffler length.

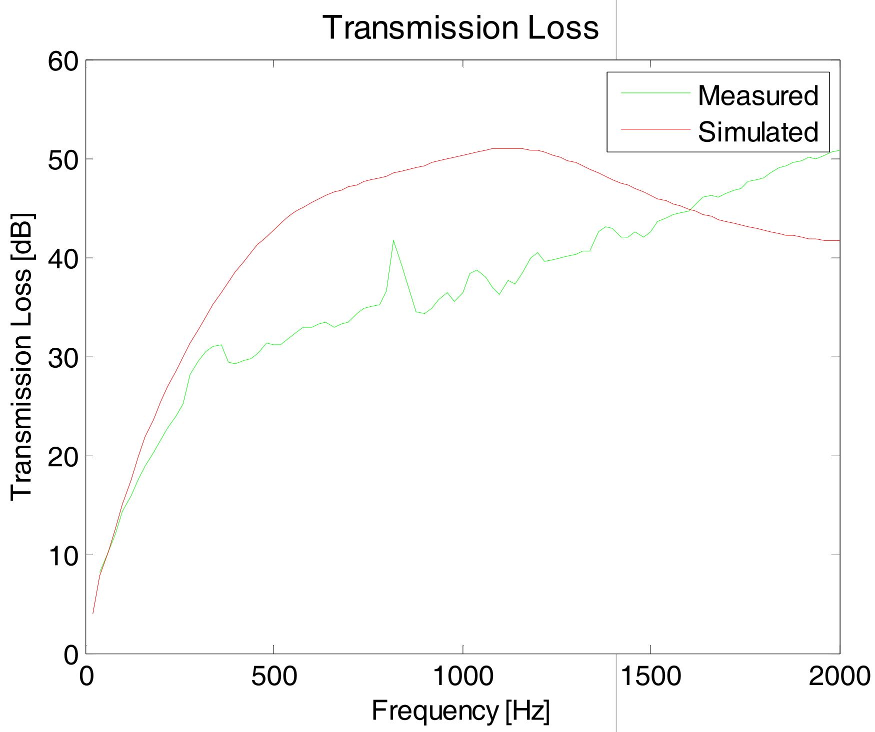


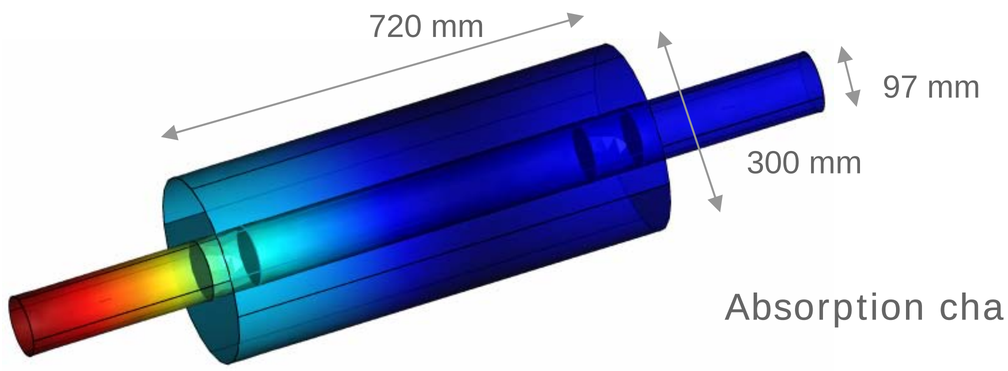


The Absorption Muffler

Comparison

- Good low frequency correlation
- Mid & high frequency differences
  - Inaccurate Delany & Bazley model
  - Too large sub-domain



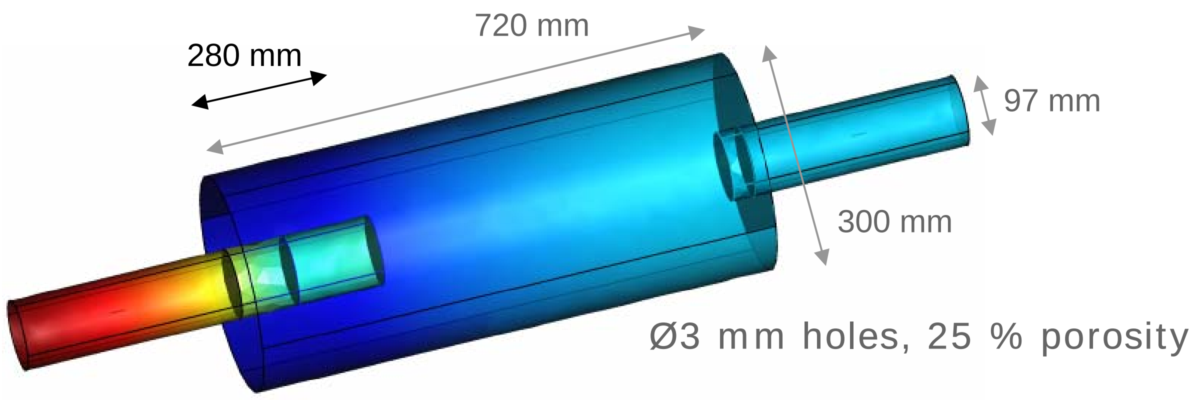


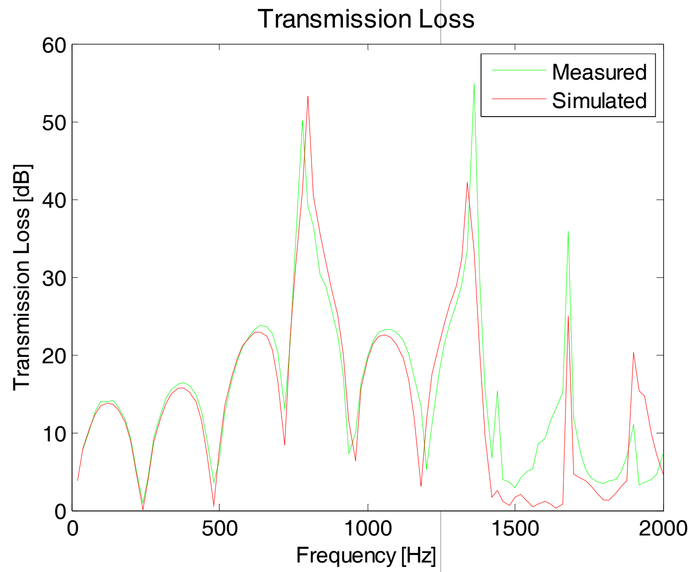
Absorption chamber – 5000 Rayls/m

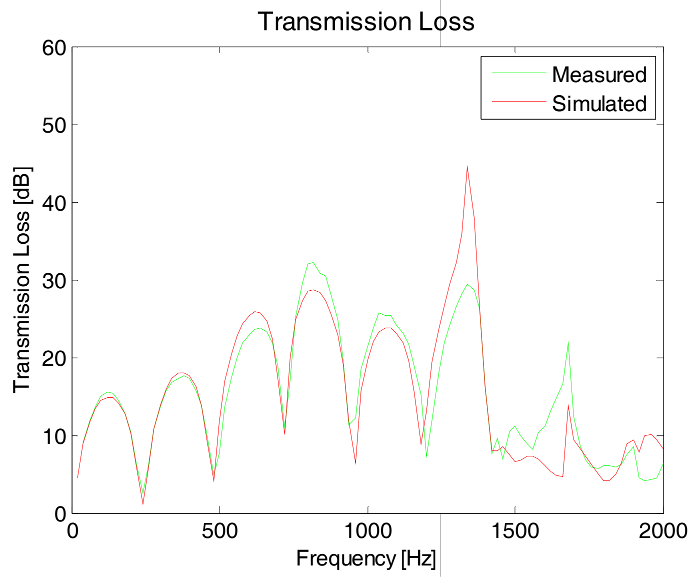
The Plug Flow Muffler

Comparison

- 0 m/s flow speed
  - Good correlation
  - 800 Hz peak due to 80 mm extended inlet
- 30 m/s flowspeed
  - Good correlation
  - 1350 Hz peak not affected in simulation
  - Peaks limited by losses due to flow



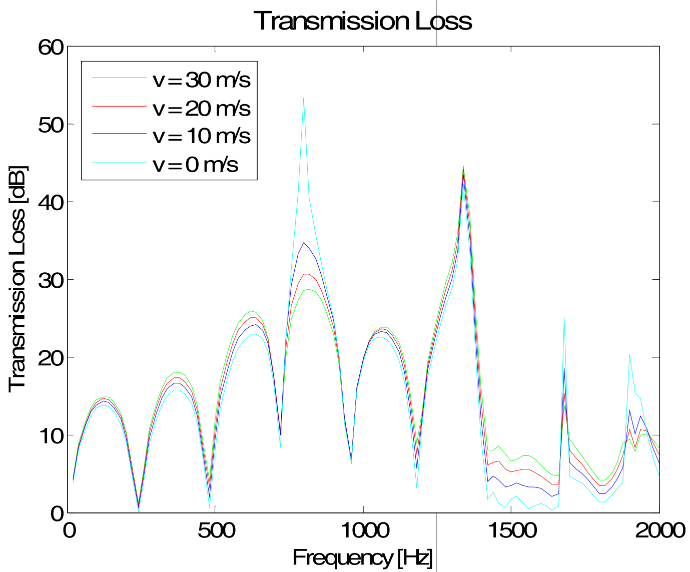


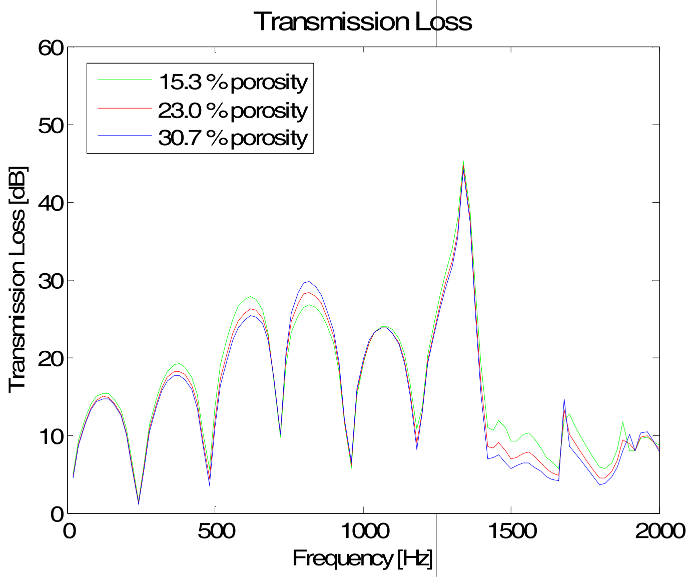


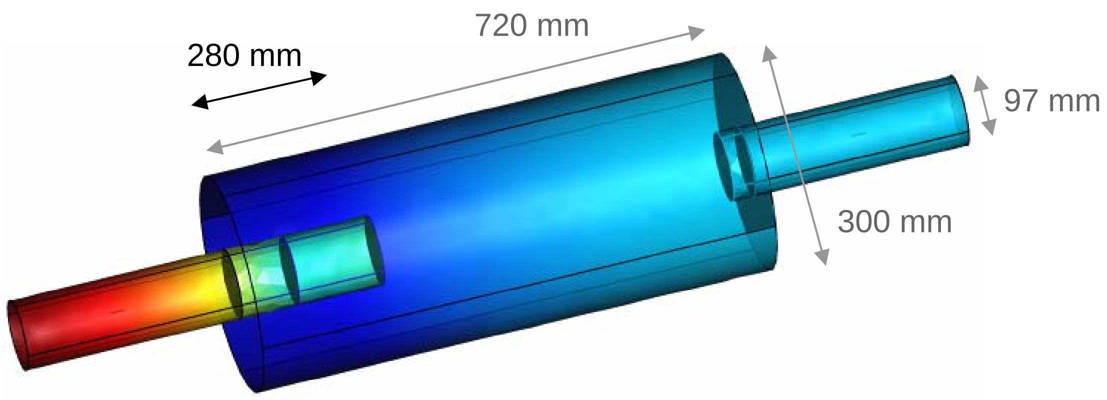
The Plug Flow Muffler

Simulations

- Flow speed variations (Ø3, 25 %)
  - Flow smoothes the peaks and dips
- Porosity variations (Ø4, 30 m/s)
  - Same effect as changing the flow speed
  - Porosity is important, not hole size

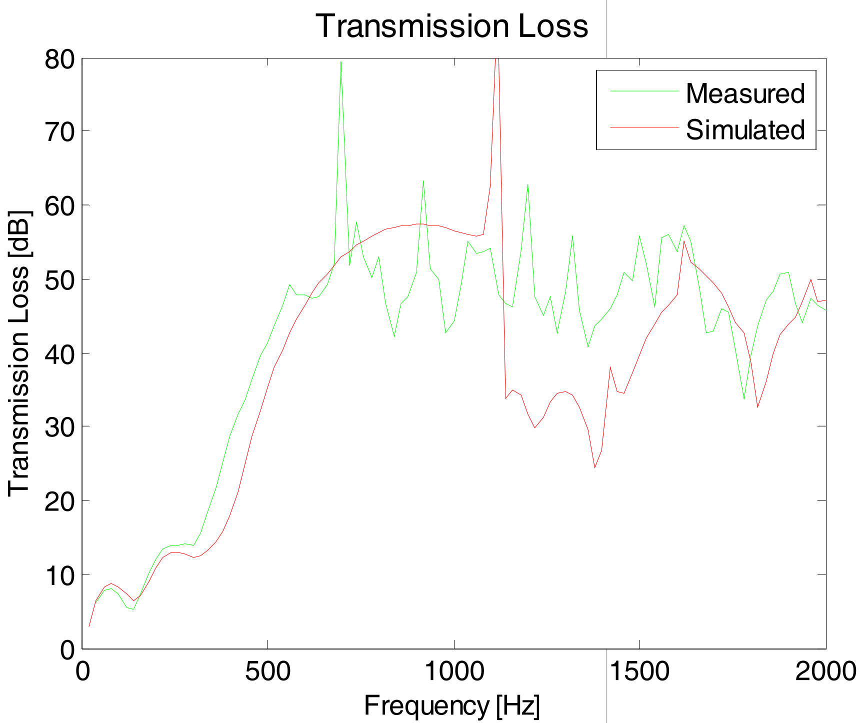


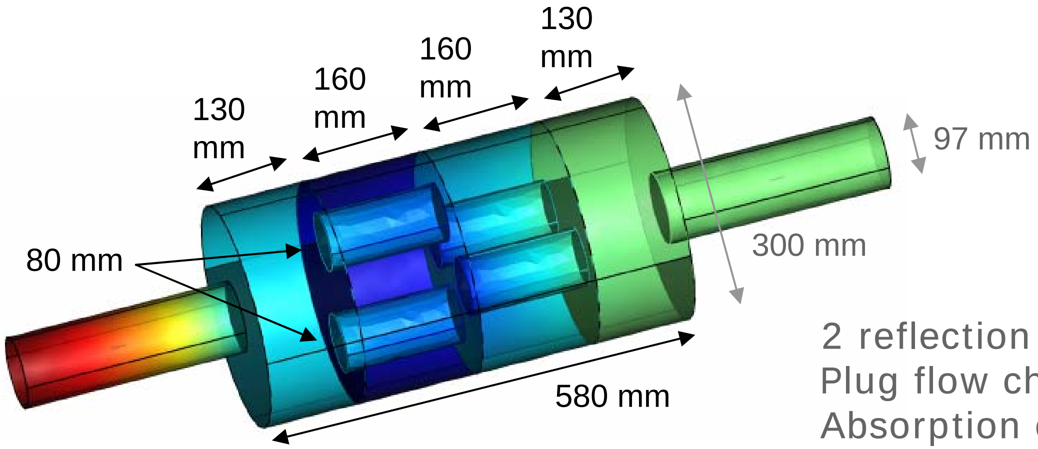




The Hybrid Muffler
Comparison at 0 m/s

- Good correlation up to 700 Hz
- Difference due to
  - Inaccurate Delany & Bazley model
  - Slightly different lengths
  - Additional small features of in the real exhaust





2 reflection chambers
Plug flow chamber – Ø3, 30 %
Absorption chamber – 5000 Rayls/m

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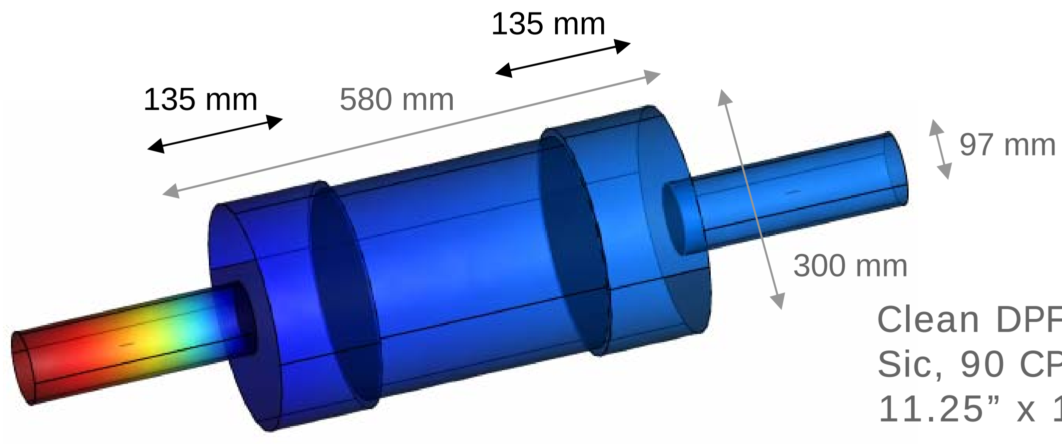
The Diesel Particulate Filter

Comparison at 0 m/s

- No correlation (general damping)
- Additional simulations proved the model against measurements made by KTH



Clean DPF
Sic, 90 CPSI
11.25” x 12”

Conclusion

- Successful transfer matrix approach
  - One run
  - Insertion loss calculation possible
- Model validation
  - Reflective and plug flow muffler
  - Absorptive and ceramic
- Simulation approach
  - Frequency limitations by pipe diameter
  - Short setup time
  - Easy redesign

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Future work

- Pressure loss and mean flow distribution simulation
  -> backpressure result

- Source impedance measurements
  -> Insertion loss results

Questions?

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Appendix

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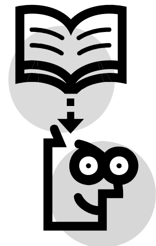
Benefits



- Of acoustic simulation of exhaust systems
  - Reduced cost price and development time
  - Increased performance and knowledge
  - Minimizing material consumption
  - Simplifying construction and production

- Of using the Transfer Matrix approach
  - Modular approach
  - Transmission loss calculation
  - Insertion loss calculation

Limitations

- Upper frequency is 2 kHz $f < \frac{1.84c}{\pi D}$
  - D is the duct diameter
  - f is the frequency
  - c is the speed of sound
- Exhaust system length max 15 m
- Max 150 dB re 20 µPa
- Constant temperature
- Zero mach number