Fluid-Structure Acoustic Analysis with Bidirectional Coupling and Sound Transmission

Reinhard Helfrich

INTES GmbH, Stuttgart

info@intes.de

www.intes.de

INTES

INTES Ingenieurgesellschaft
für technische Software mbH

Privately held and independent Finite Element Technology company since 1984 located in Stuttgart, Paris, and Tokyo

Offering own FE analysis software PERMAS with VisPER, software development, and consulting services

Unified software for thermo-mechanics, vibro-acoustics, and optimization

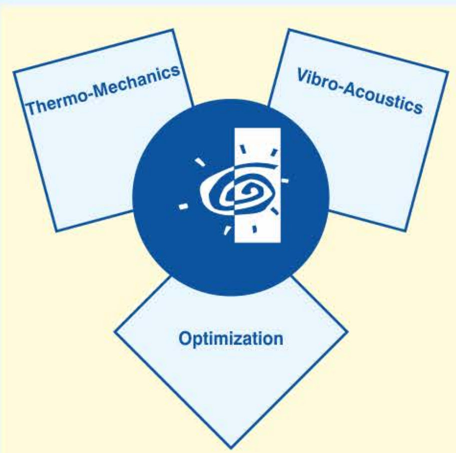
The Innovative Power of Simulation
PERMAS

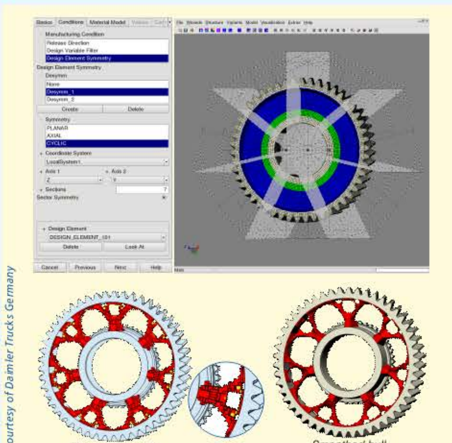
INTES

INTES GmbH
Schulze-Delitzsch-Str. 16
D-70565 Stuttgart
Phone +49-711-78499-0
Fax +49-711-78499-10
E-mail: info@intes.de
http://www.intes.de

PERMAS

VisPER





By courtesy of Daimler Trucks Germany

High performance computing by parallelization (multi-threading) and special algorithms (contact, MLDR, fluid-structure coupling)

Unified concepts like incompatible meshes, substructuring, submodelling

Simulation-driven design by integrated optimization (topology, shape, sizing, bead) with local and global methods

1984: Start of software industrialization and new developments in optimization, acoustics, and reliability

1989: Start of full re-design of software for higher speed of development and Nastran compatibility

1993: PERMAS Version 5 available, the new software basis for further development

2005: Start of VisPER development, a new graphical user interface for PERMAS

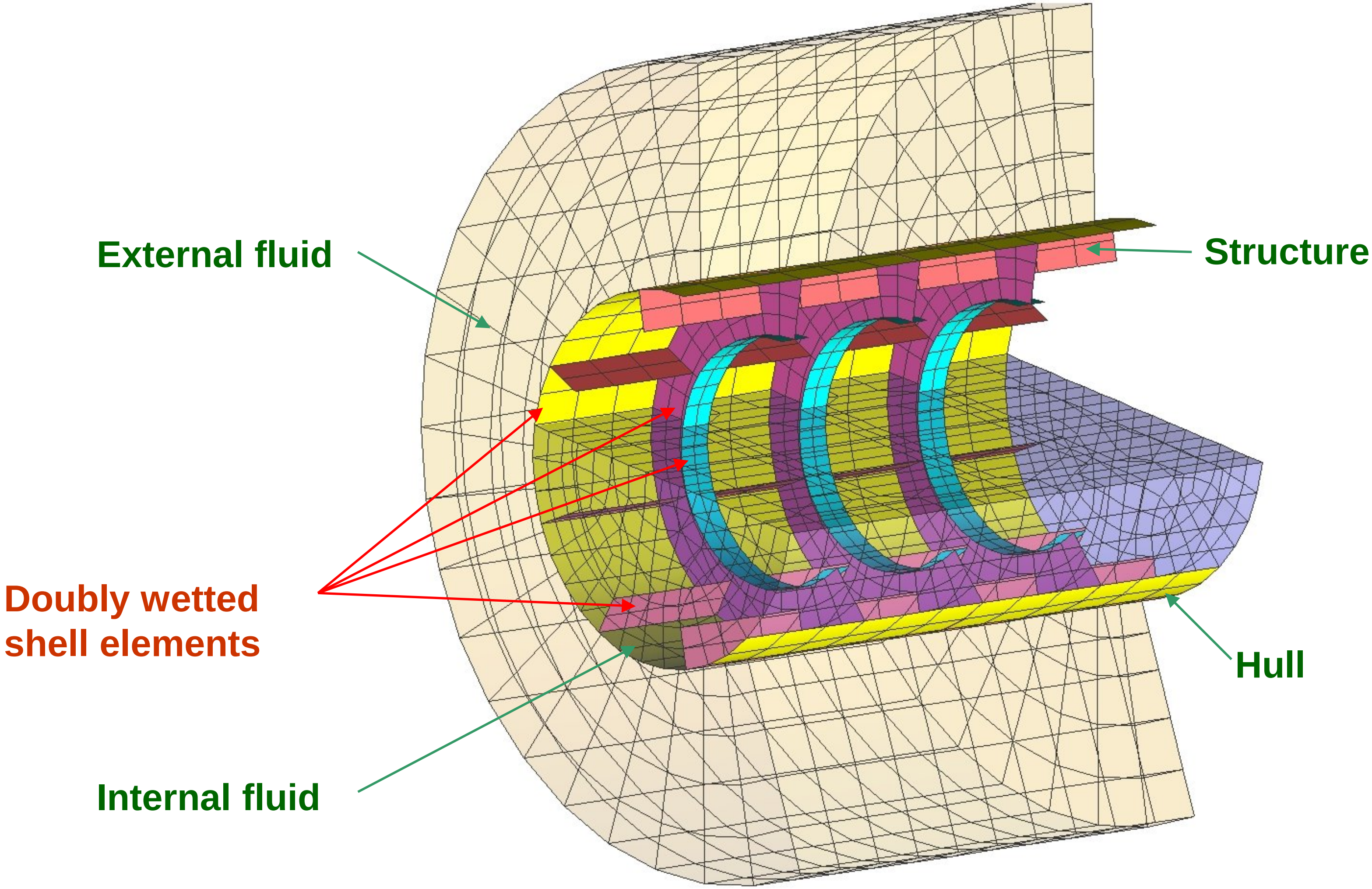
2008: VisPER Version 1

2010: PERMAS Version 13 and VisPER Version 2

Fluid-Structure Acoustics

- Methods like structural dynamics (vibrations)
- Application for fluids only (Acoustics) and for structures coupled with fluids (Fluid-Structure Acoustics)
- Extension of classical structural models by surrounding fluid models using a strong coupling
- The coupling is performed physically, i.e. the normal displacement of the structure is identical to the normal displacement of the fluid

Example for Fluid-Structure Acoustics



Fluid Model with Finite Elements

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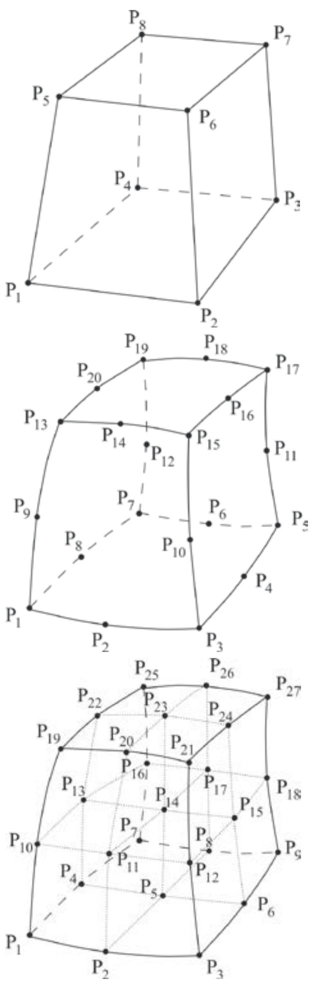
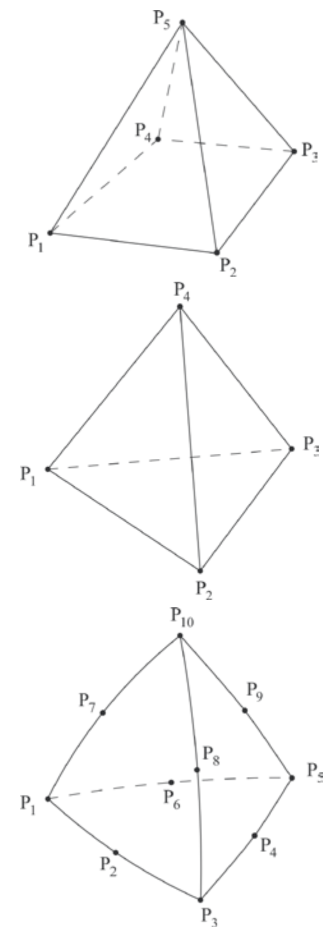
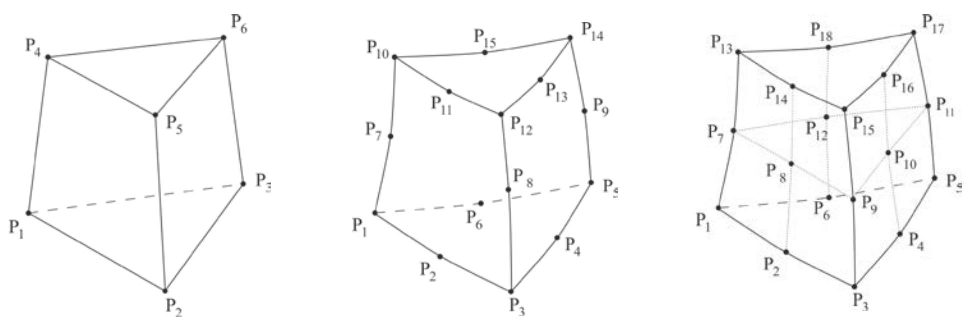
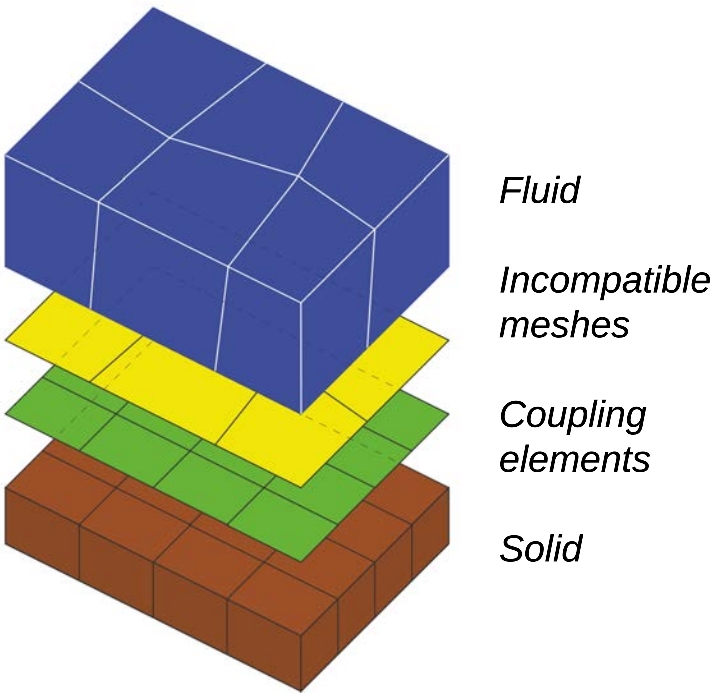


Acoustics	Fluid only	Fluid coupled with structure
Degrees of freedom	pressure variation	+ displacements
Element types	fluid, radiation bound. cond., surface waves, semi-infinite elements for added masses	+ coupling, structure
Material values	density, compressibility (also incompressible)	+ density, Young's modulus, Poisson's ratio





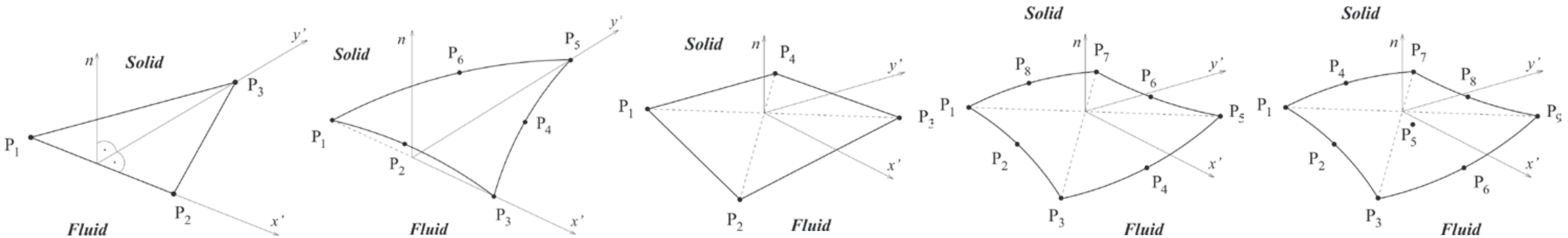
Coupling of Structure and Fluid



- **Fluid mesh and structural mesh** are usually not compatible.

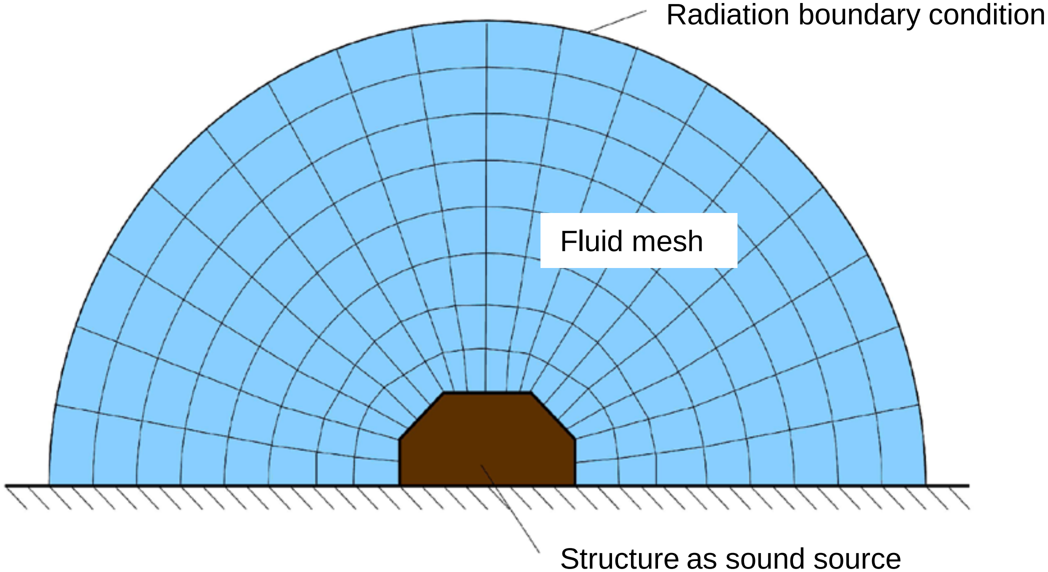
  Reasons:
  - Fluid and structure are meshed independently
  - Structural meshes are usually much finer than the coupled fluid mesh due to different sound velocities

- **Incompatible meshes** as standard feature are solving the different requirements



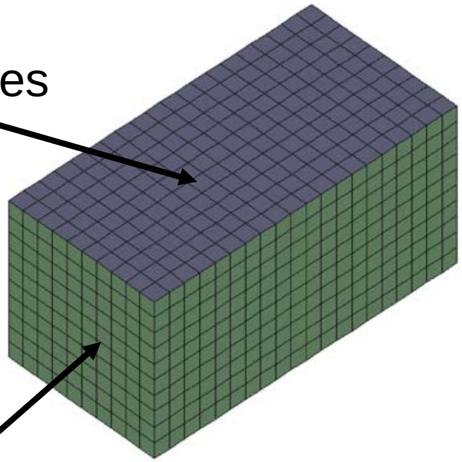
Sound Radiation

Anechoic boundaries are modeled by radiation boundary condition elements, e.g. spherical boundaries following Bayliss-Turkel

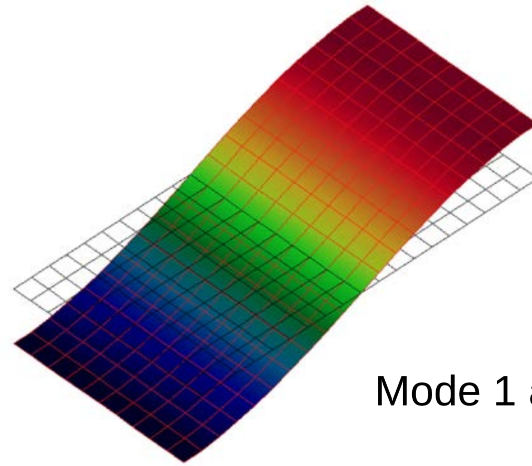


Surface Waves

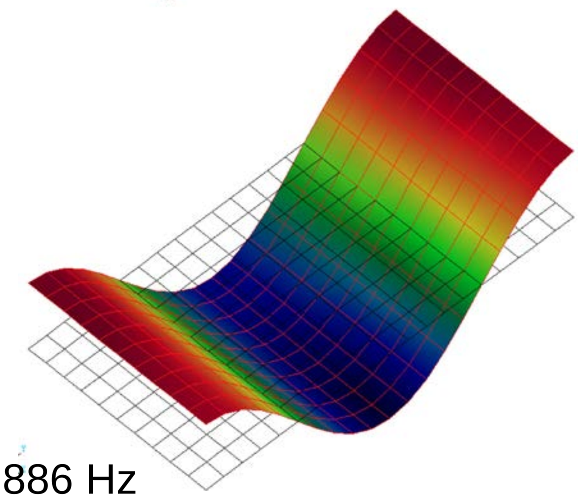
Surface waves



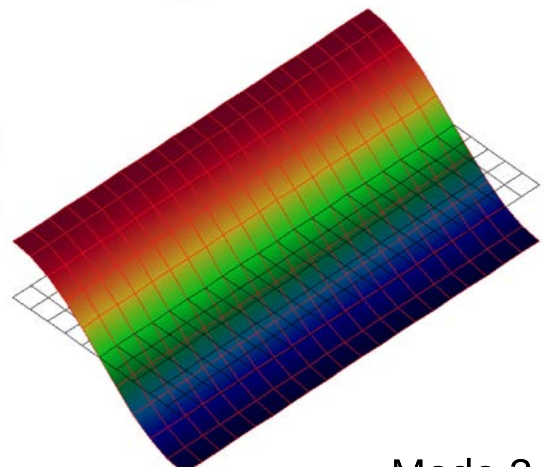
Fluid elements



Mode 1 at 0.599 Hz



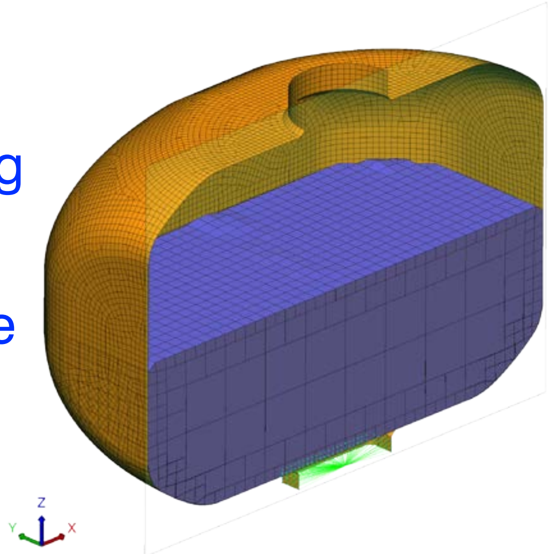
Mode 2 at 0.886 Hz

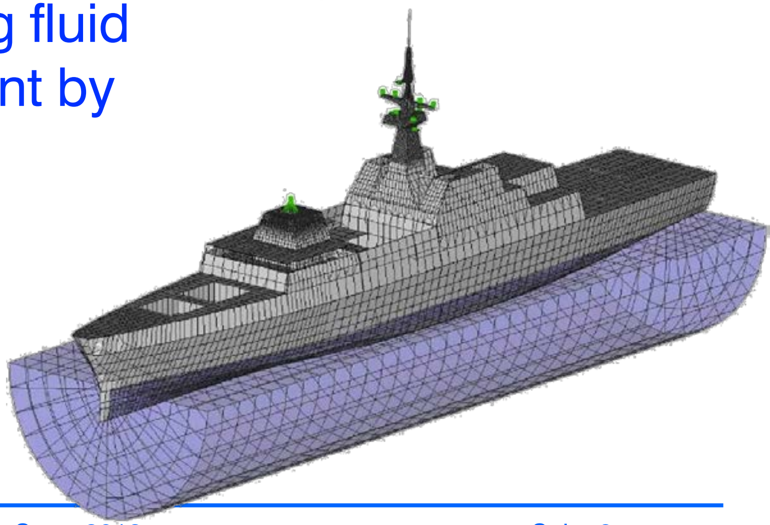


Mode 3 at 0.886 Hz

Added Mass

- It is frequently sufficient for structural dynamic analysis to include just the mass of a surrounding or enclosed fluids (like surrounding water of ships or enclosed fluids in a tank).
- To this end, the fluid mass distribution has to be determined correctly.
- This can be achieved by modeling the fluid.
- Even an infinitely expanded surrounding fluid (like for a ship) can be taken into account by semi-infinite elements.

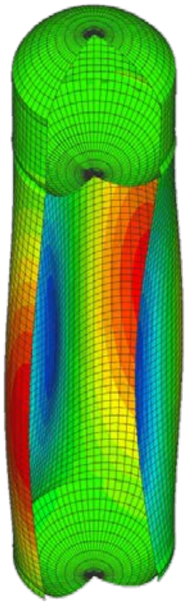


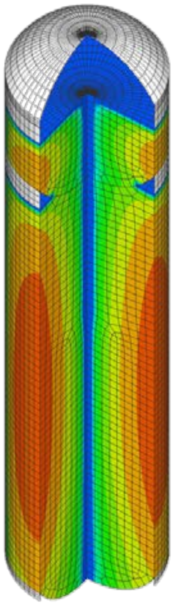


Eigenvalues and Mode Shapes

Acoustics	Fluid only	Fluid coupled with structure
Real eigenvalues and eigenmodes	yes	coupled, with energy distribution
Additional static modes	yes	yes
Dynamic Condensation	Craig-Bampton	dry (only for displacement dof) or wet (also pressure dof)

Displacement



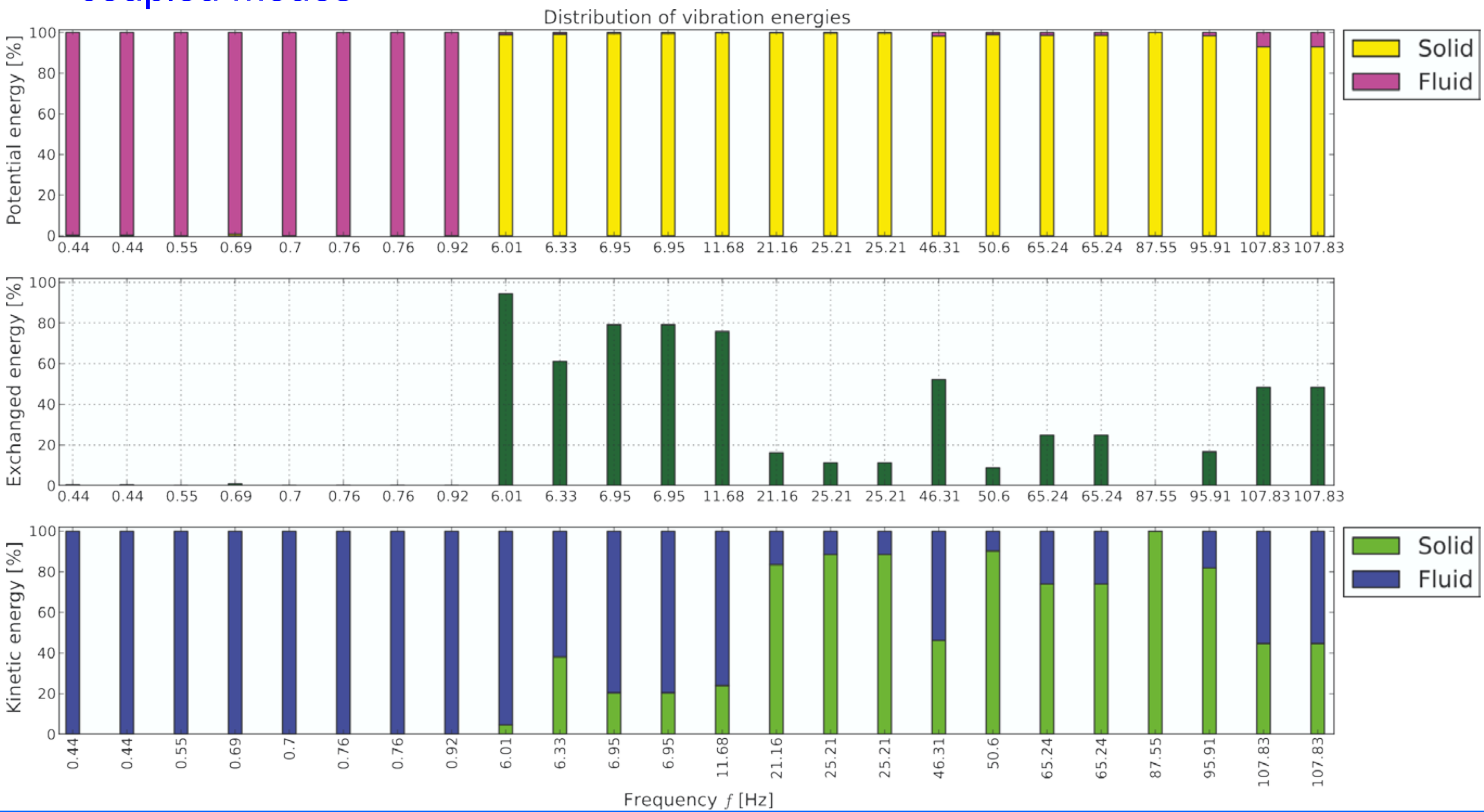


Pressure distribution

Real coupled eigenmode of a rocket tank

Energy Distribution in Coupled Eigenmodes

- Partitioning of energy in fluid and structure for coupled eigenmodes
- enables the identification of structure-dominant, fluid-dominant, and strongly coupled modes

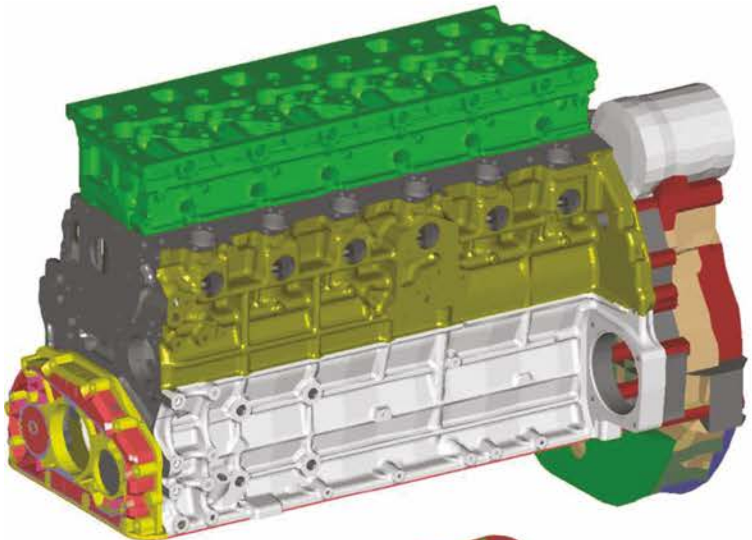


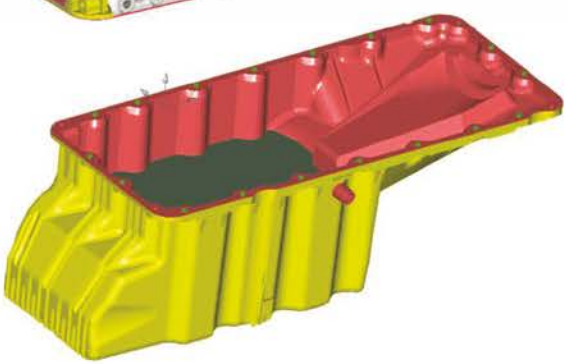
Dynamic Condensation

There are two available options for dynamic condensation of coupled fluids and structures:

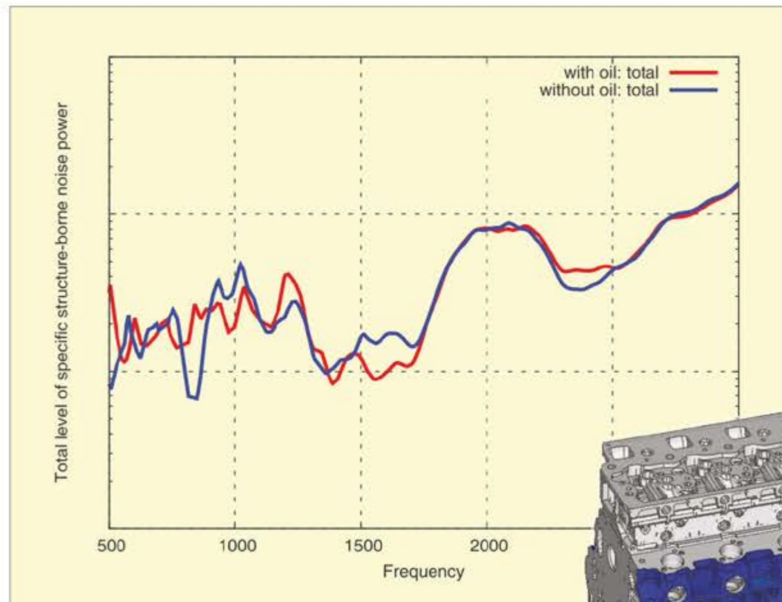
- **‘Wetted‘ Condensation**
  - Separate calculation of fluid modes and structural modes in different substructures. The external modes are displacement modes and pressure modes.
  - The final solution step is a coupled vibration analysis.
- **‘Dry’ Condensation**
  - In the substructures, a coupled eigenvalue problem is solved, i.e. the fluid part will be isolated. The external modes are coupled modes (without pressure dof).
  - The final solution step is a structural vibration analysis, because no pressure dof exist any more.
  - Facilitates the use of acoustic components in larger structural components (but the possibility remains to calculate pressure of the condensed fluid).

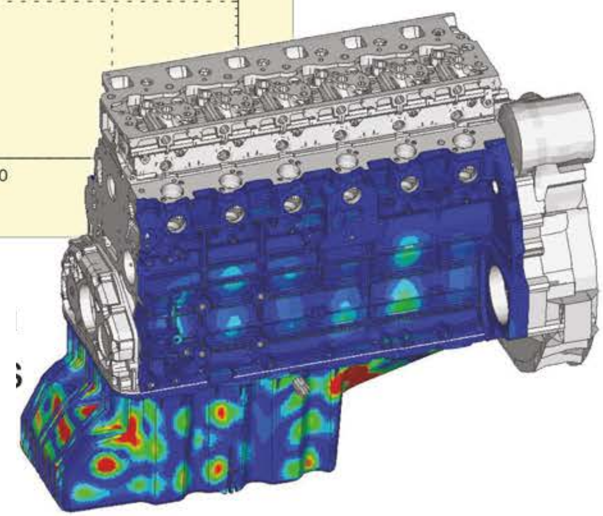
Engine with Attached Parts





Specific sound radiation power to indicate structrue-borne sound



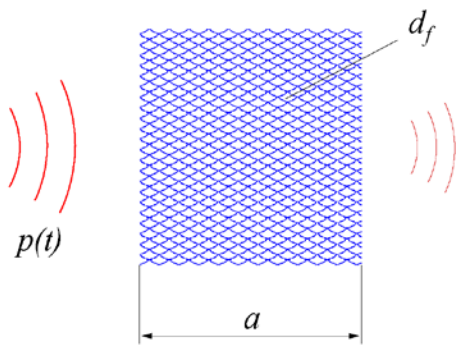


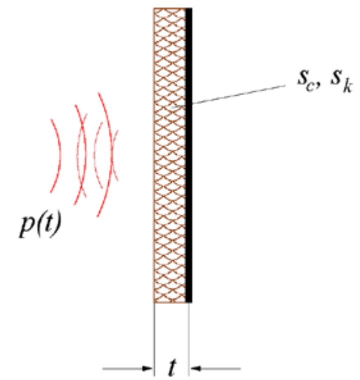
Influence of the oil in the oil pan on the structure-borne sound of engine block and oil pan

All pictures by courtesy of Daimler AG

Dynamic Response

Acoustics	Fluid only	Fluid coupled with structure
Damping	absorption at surfaces and in fluid volume	+ any structural damping
Modal dynamic response	in frequency and time domain	in frequency and time domain
Direct dynamic response	in frequency domain	in frequency domain





Absorption in fluid volume

$$\boldsymbol{V}_f = -d_f \dot{\boldsymbol{u}}_f$$

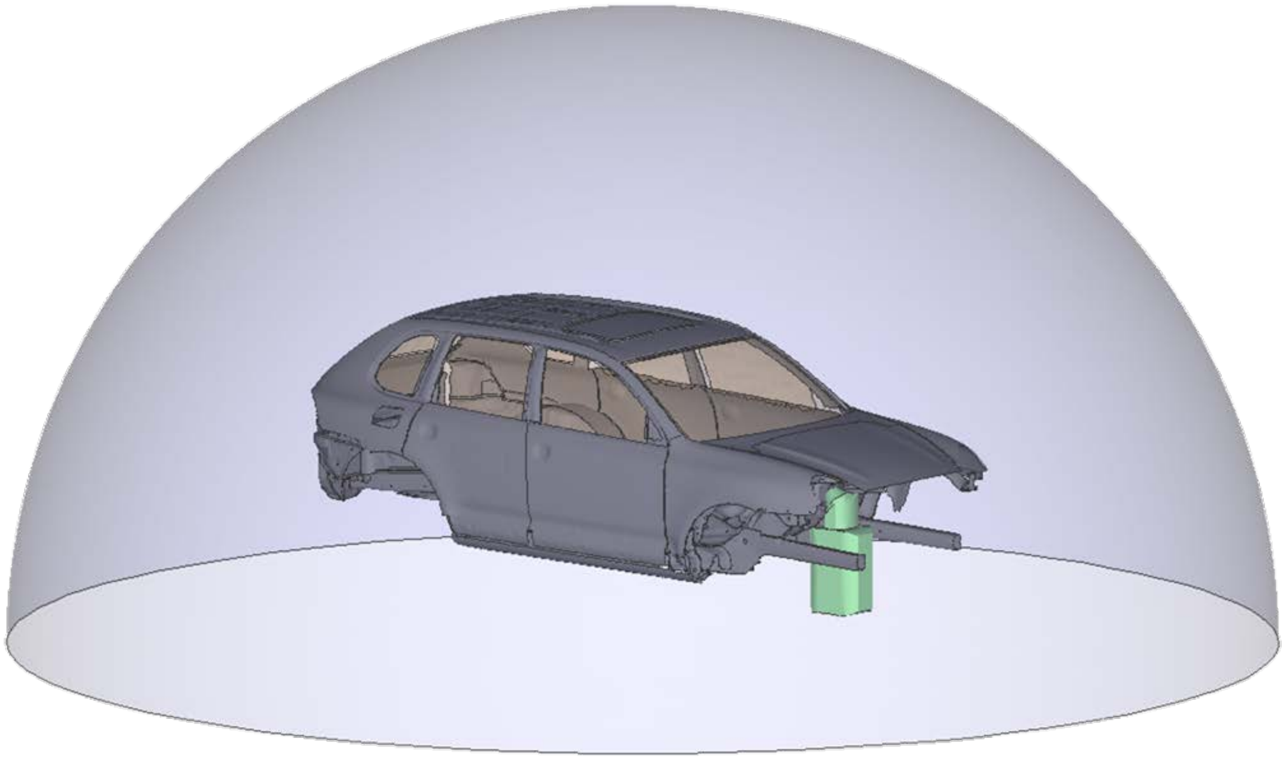
Absorption at surface

Normal impedance

$$\dot{u}_n = s_c p + s_k \dot{p}$$

Assumption: $\lambda \gg t$

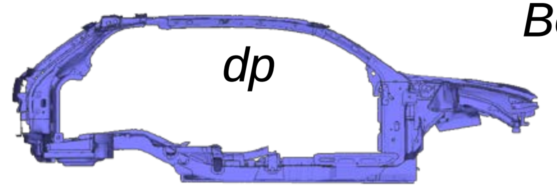
Interior Noise of an SUV



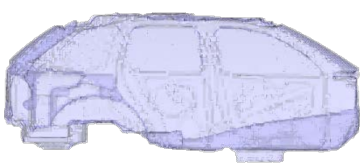
Introduction

- Structure-borne and air-borne sound excitation for Body-in-White (BIW) and Trimmed Body (TB)
- Comparison of measurement (performed by Autoneum, Winterthur, Switzerland) and calculation (performed by INTES)

Body in White Vehicle

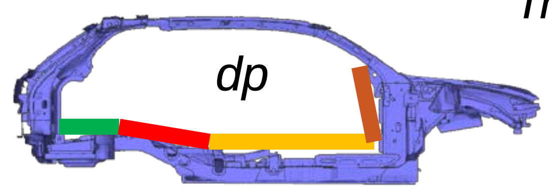


Body in White (BIW)

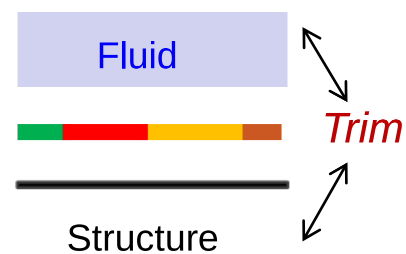


Interior Fluid

Trimmed Vehicle



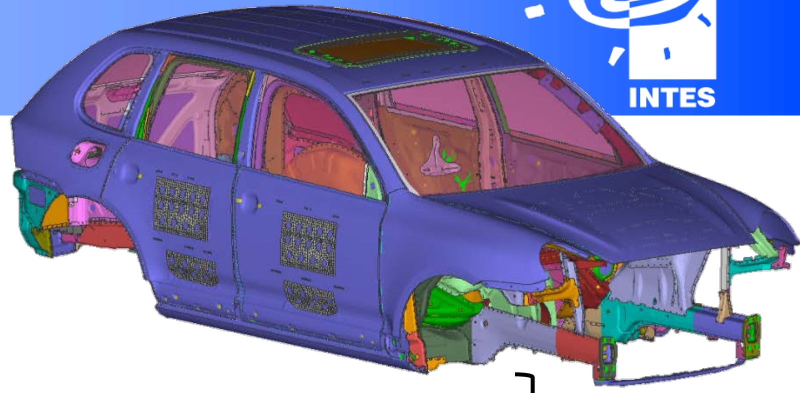
Trimmed Body



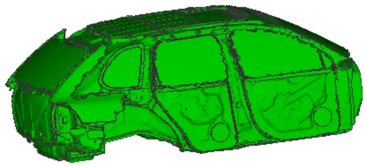
Transfer Matrix Method

Structure Model and Fluid-Structure Model

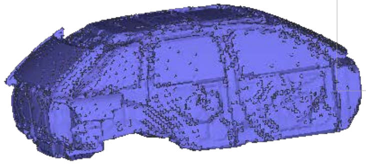
DISP DOF: 2 900 367
PRES DOF: 502 696



FS coupling to inner fluid

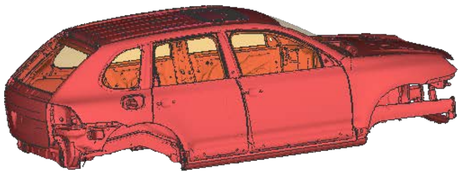


Inner fluid

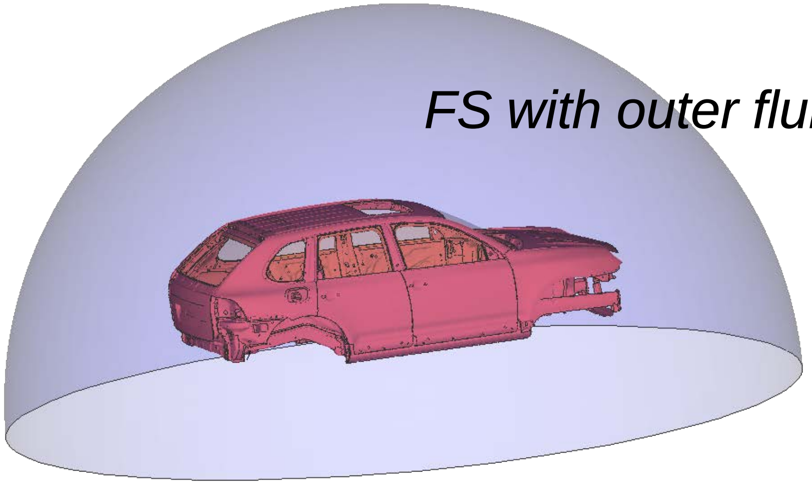


FS with inner fluid

Structure model



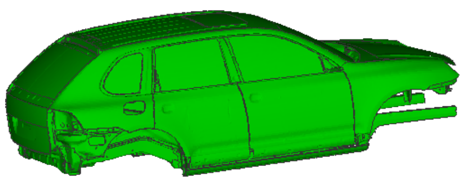
Outer fluid and radiation boundary condition



FS with outer fluid

FS Model

FS coupling to outer fluid

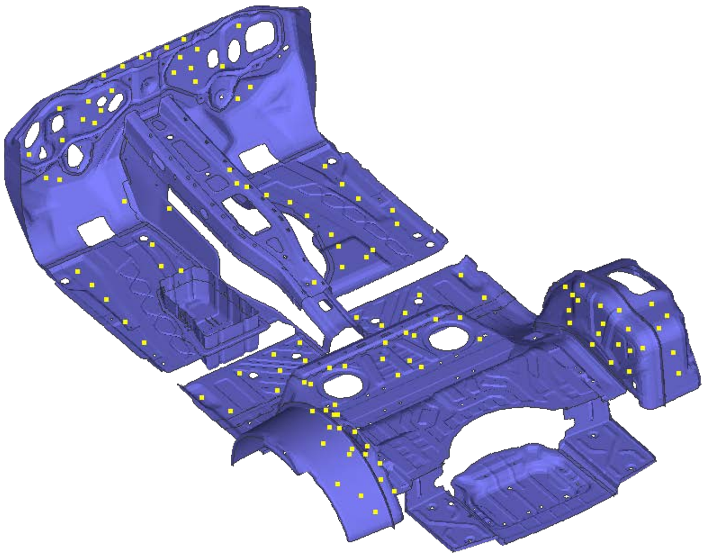


Measurement Points

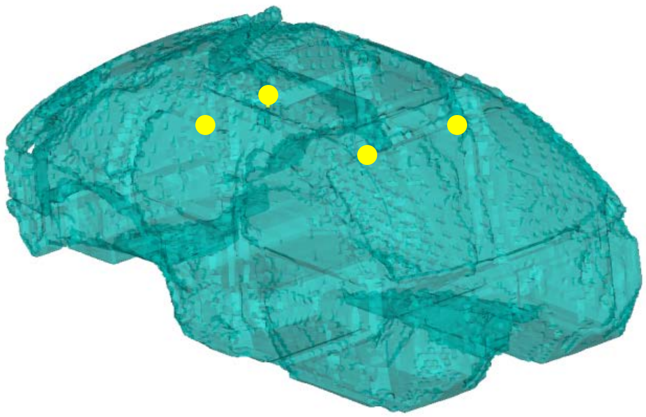
- The measurement points are located as follows:

  1) Dash (Left and right)
  2) Floor (left and right, front and behind)
  3) Tunnel (left, top and right)
  4) Wheelhouse (left and right)
  5) Four microphones in the interior fluid

Accelerometer positions

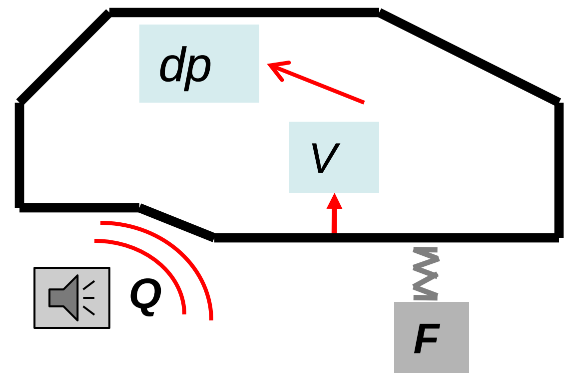


Microphones



Structure- and Air-borne Excitations

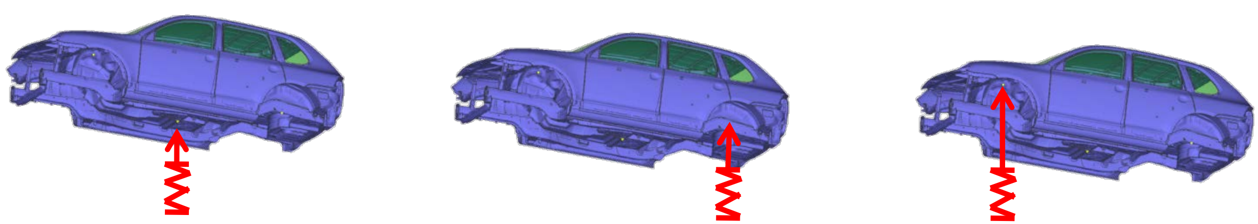
- Type of calculation: Eigenvalue analysis
  Modal Frequency Response



- Excitations (Sine sweep from 5 up to 500 Hz):

1) Structure-borne

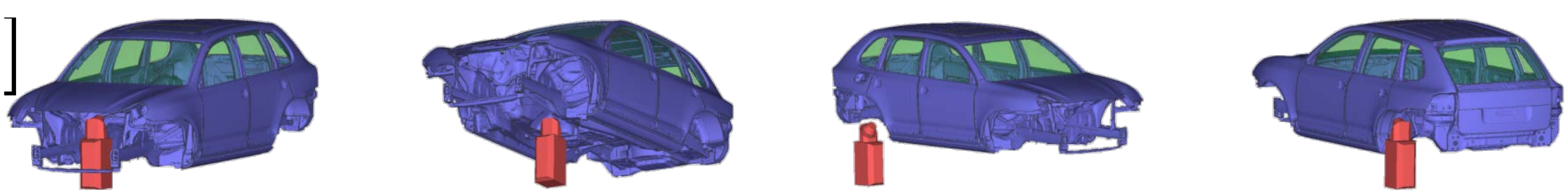
$$F\left[N\right]$$



Gear Box Bridge   Rear Axis Subframe   Structure Dome Left

2) Air-borne

$$\dot{Q}\left[mm^3/s^2\right]$$



Engine Bay   Gear Box   Rear Muffler   Wheelhouse

Measured Quantities

- Measured quantities for the correlation:
  v/F – Transfer functions (RMS normal velocity / input force)
  p/F – Transfer functions (RMS microphone SPL / input force)
  v/Q – Transfer functions (RMS normal velocity / volume velocity acoustic source)
  p/Q – Transfer functions (RMS microphone SPL / volume velocity acoustic source)

$$v_{RMS} = 20\log_{10}\left(\frac{\sqrt{\frac{\sum_{i=1}^{N} v_i^2}{N}}}{v_0}\right) \qquad p_{RMS} = 20\log_{10}\left(\frac{\sqrt{\frac{\sum_{i=1}^{N} p_i^2}{N}}}{p_0}\right)$$

$$v_0 = 1000\ \text{mm/s} \qquad p_0 = 2.10^{-11}\ \text{MPa}$$

- The correlation between simulation and measurement is evaluated using „Frequency Response Assurance Criterion“ (FRAC).

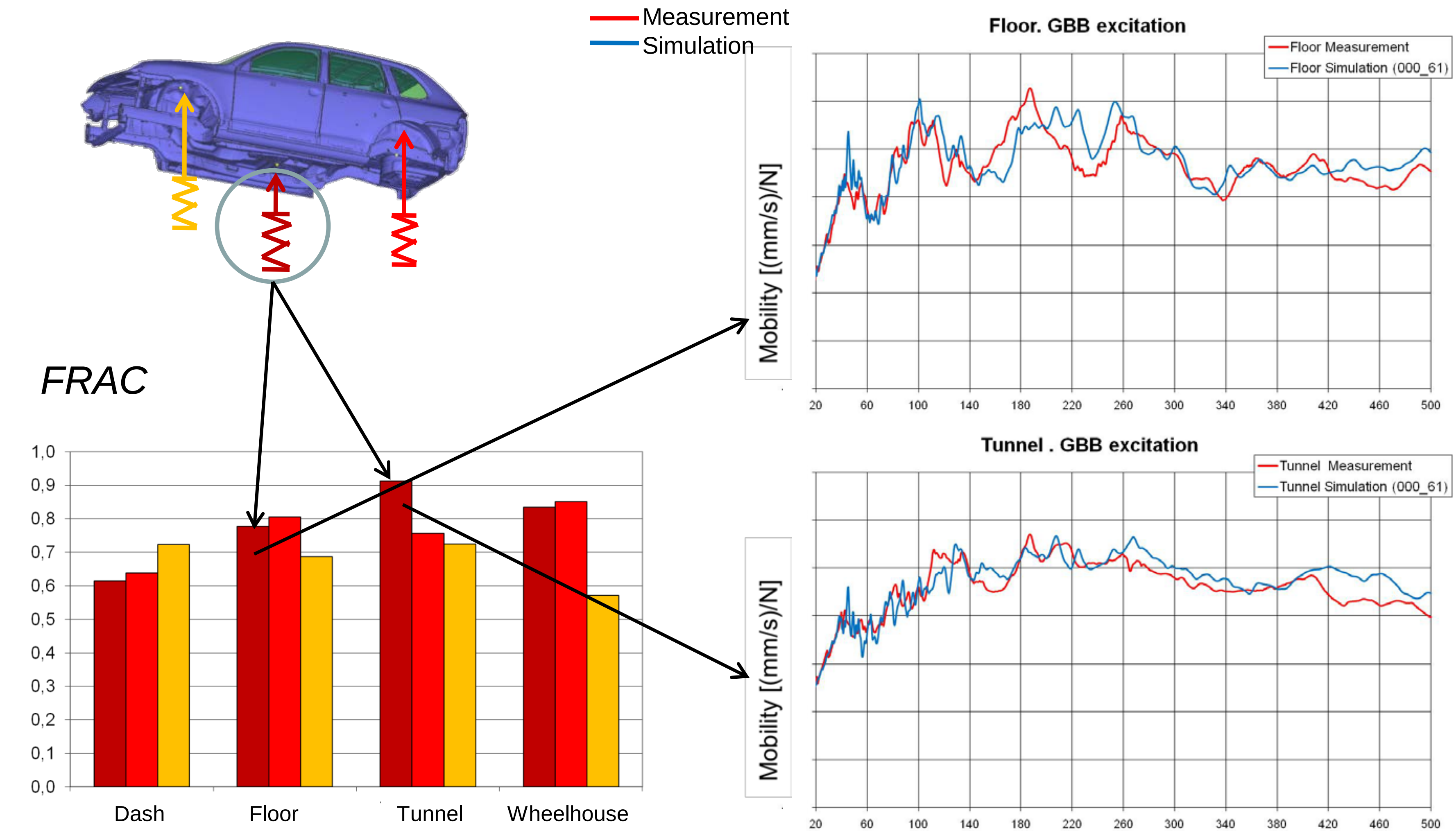
$$FRAC = \frac{\left(\sum_{f_i}^{f_{\max}} FRF_{meas}(f_i) FRF_{cal}(f_i)\right)^2}{\sum_{f_i}^{f_{\max}} FRF_{meas}^2(f_i) \sum_{f_i}^{f_{\max}} FRF_{cal}^2(f_i)} \qquad FRF_\alpha(f_i)$$

$$\alpha = meas, cal$$

Comparison Structure-Borne Sound BIW Measurement/Simulation

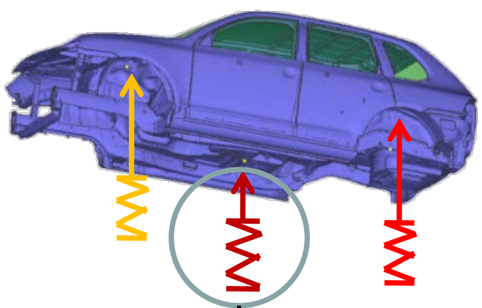
Structure excitations

v/F Response in frequency domain [Hz]

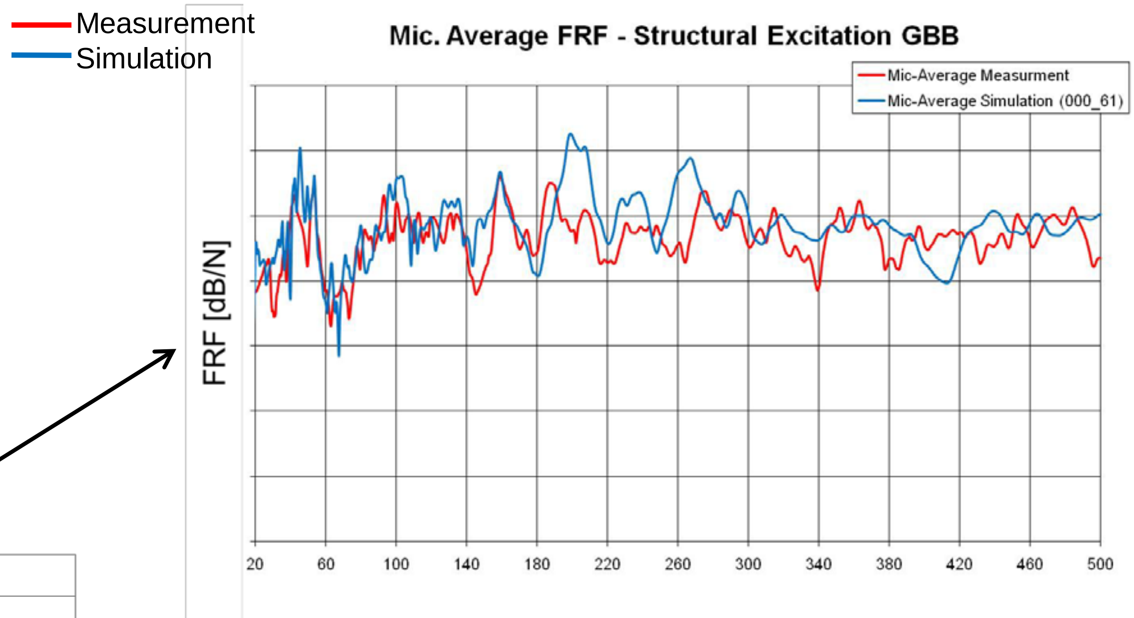


Comparison Structure-Borne Sound BIW Measurement/Simulation

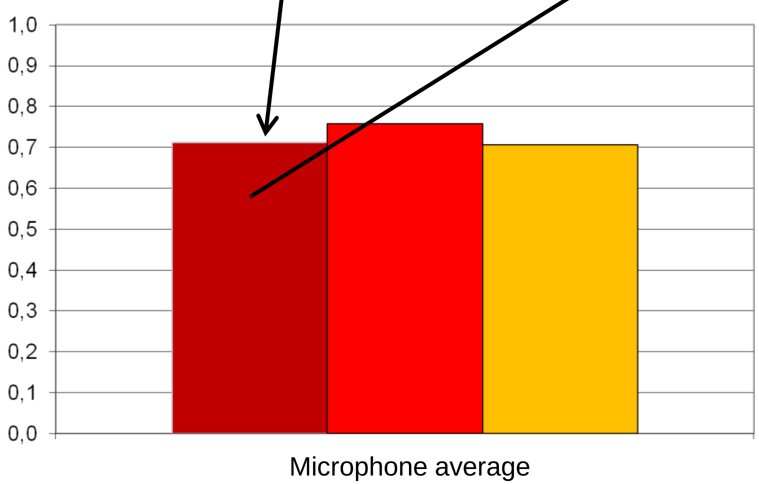
Structure excitations



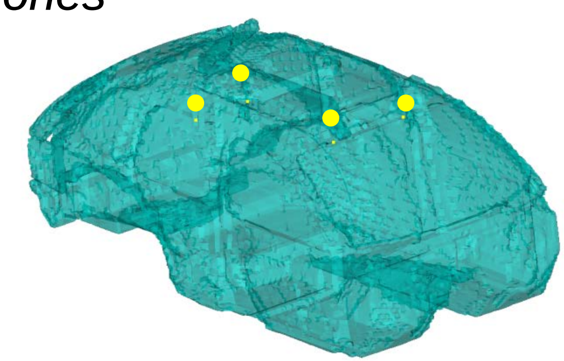
p/F Response in frequency domain [Hz]



FRAC



Microphones

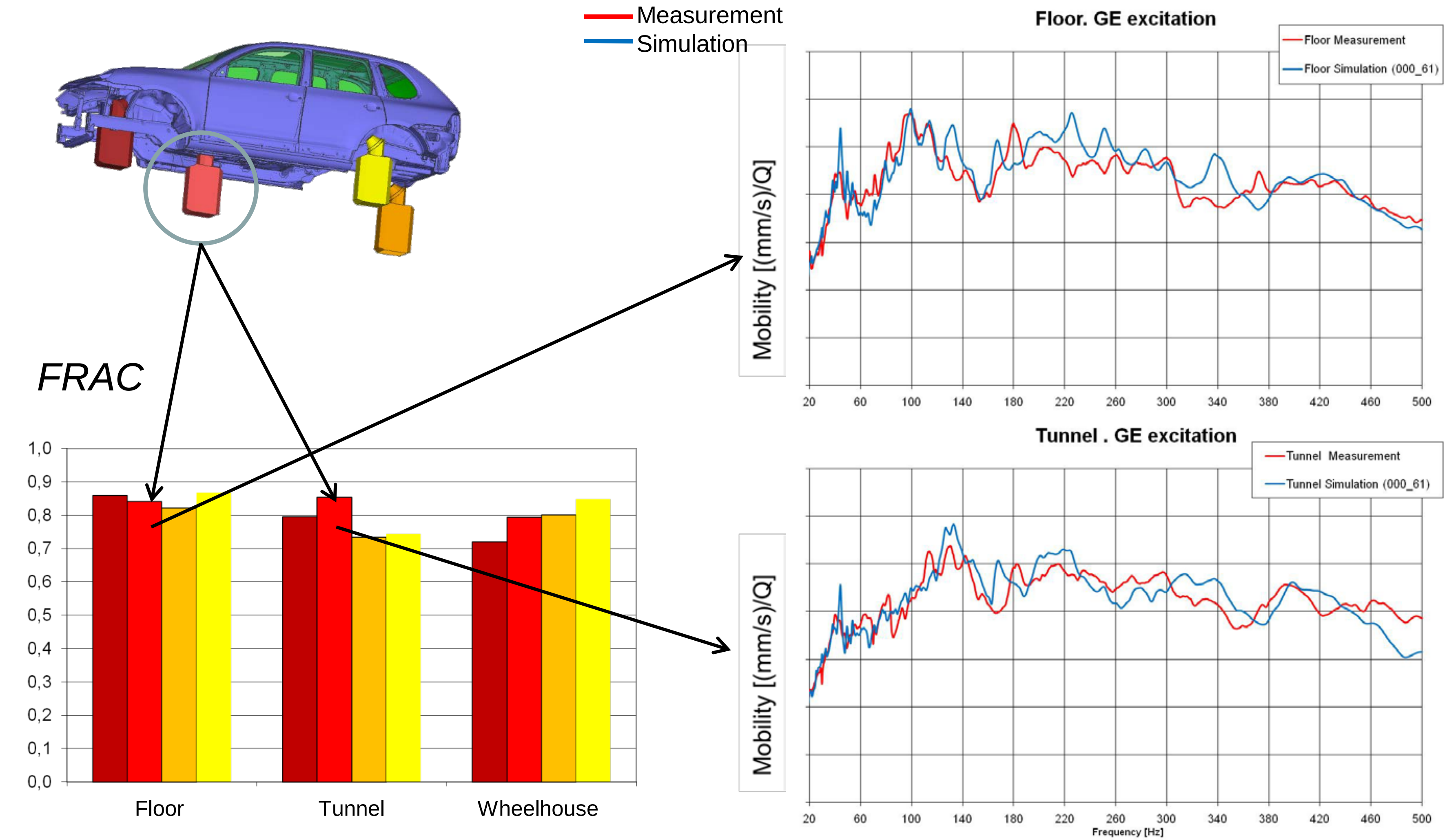


Comparison Air-Borne Sound BIW Measurement/Simulation

INTES

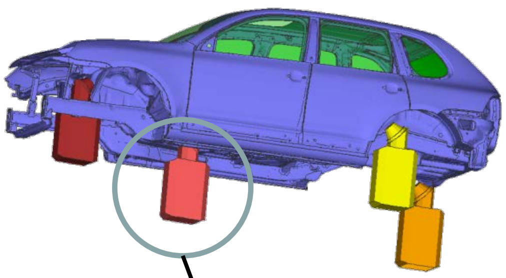
Acoustic excitations

v/Q Response in frequency domain [Hz]

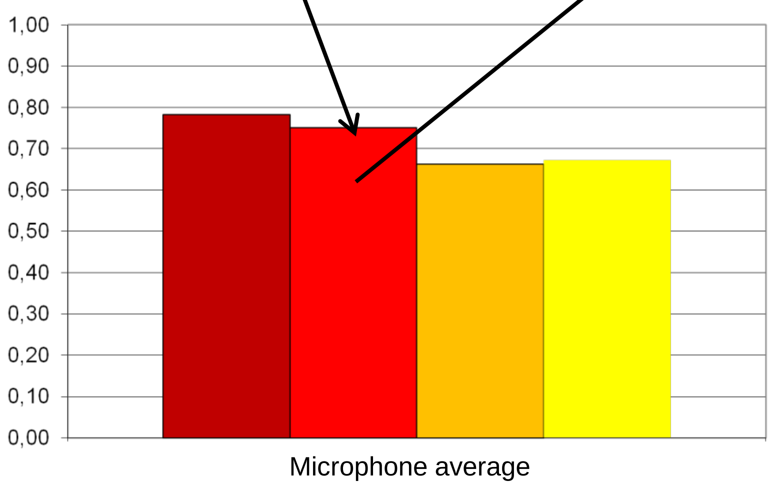


Comparison Air-Borne Sound BIW Measurement/Simulation

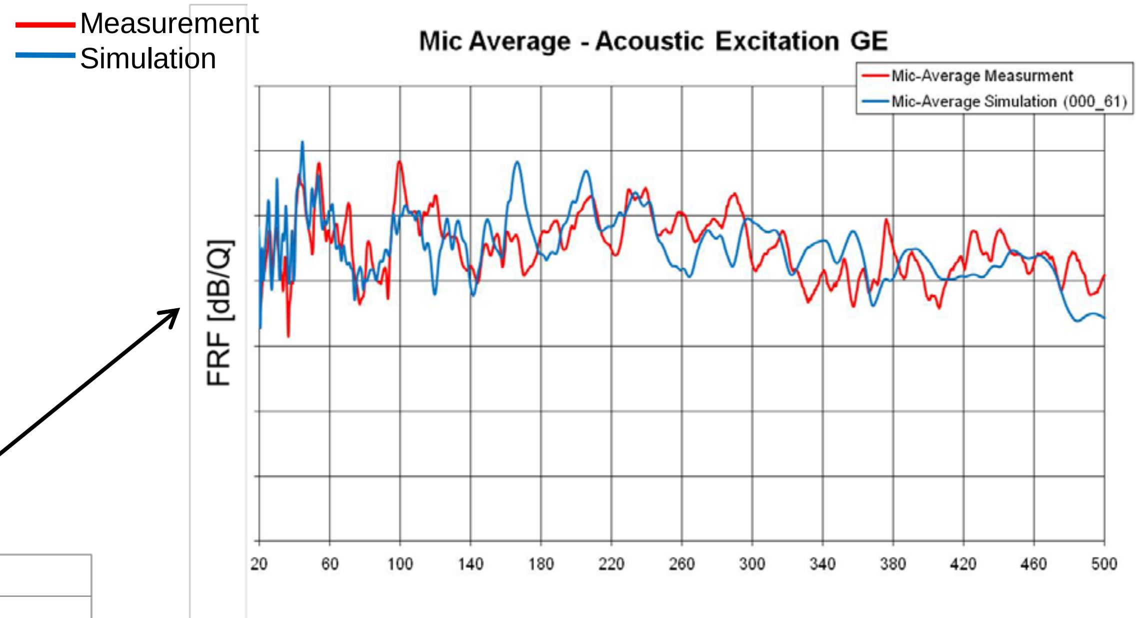
Acoustic excitations



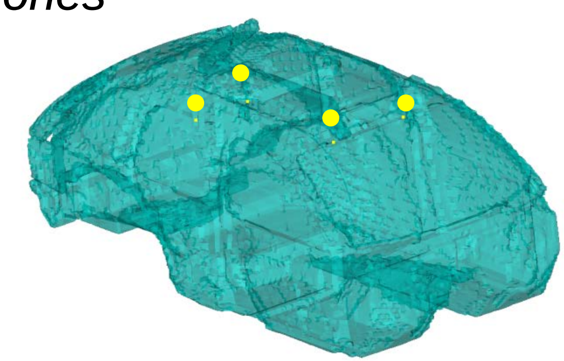
FRAC



p/Q Response in frequency domain [Hz]



Microphones

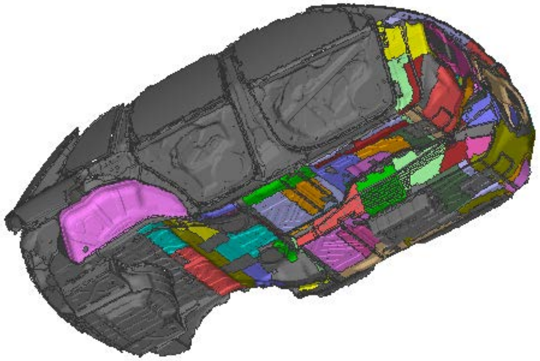


Trimmed Body (TB)

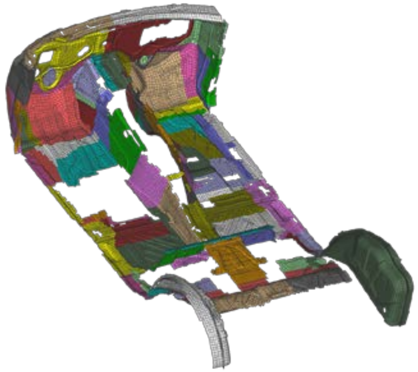
- There, 80 trimmed regions were considered

Kinematical fluid-structure coupling

Fluid-structure trim configuration



Trim configuration consist of 80 different regions



- The physical description of the trim material (and the derived impedance matrices) is directly made for the coupling elements (using a software from Autoneum, Winterthur, Switzerland) .

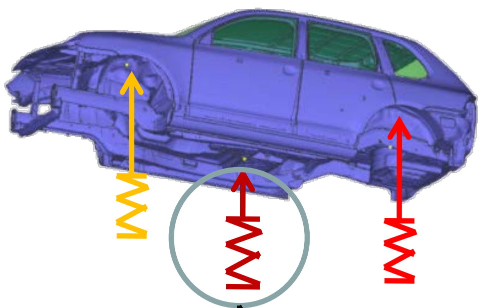
Comparison Structure-Borne Sound TB Measurement/Simulation

Structure excitations

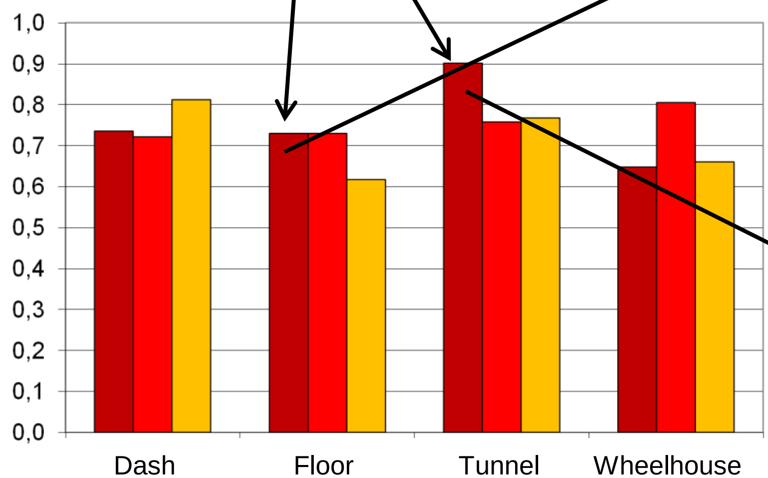
v/F Response in frequency domain [Hz]

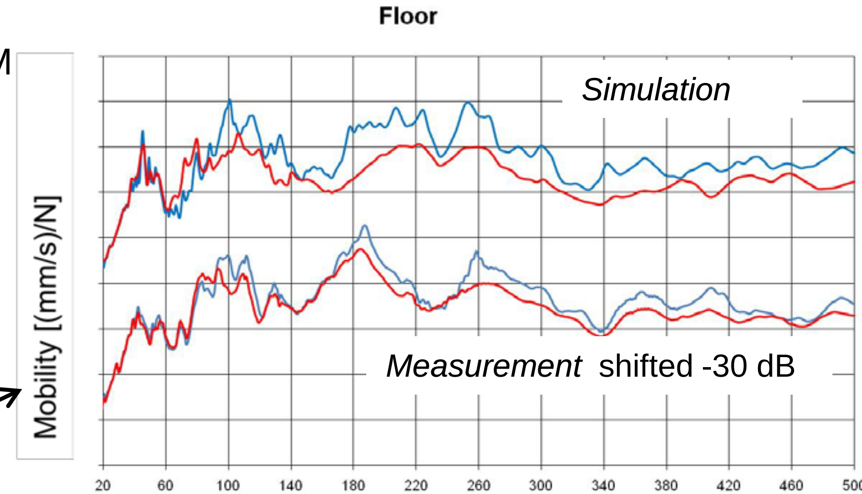
BIW

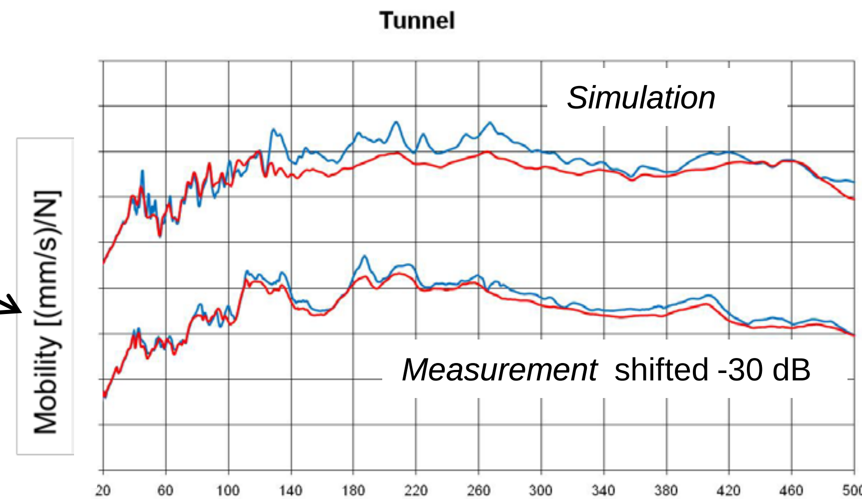
TRIM



FRAC

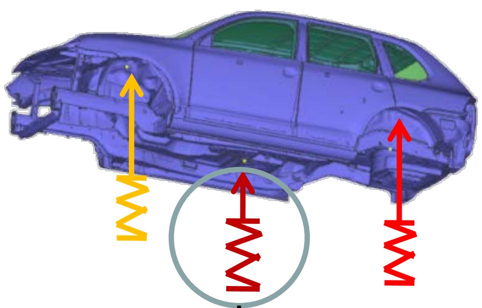




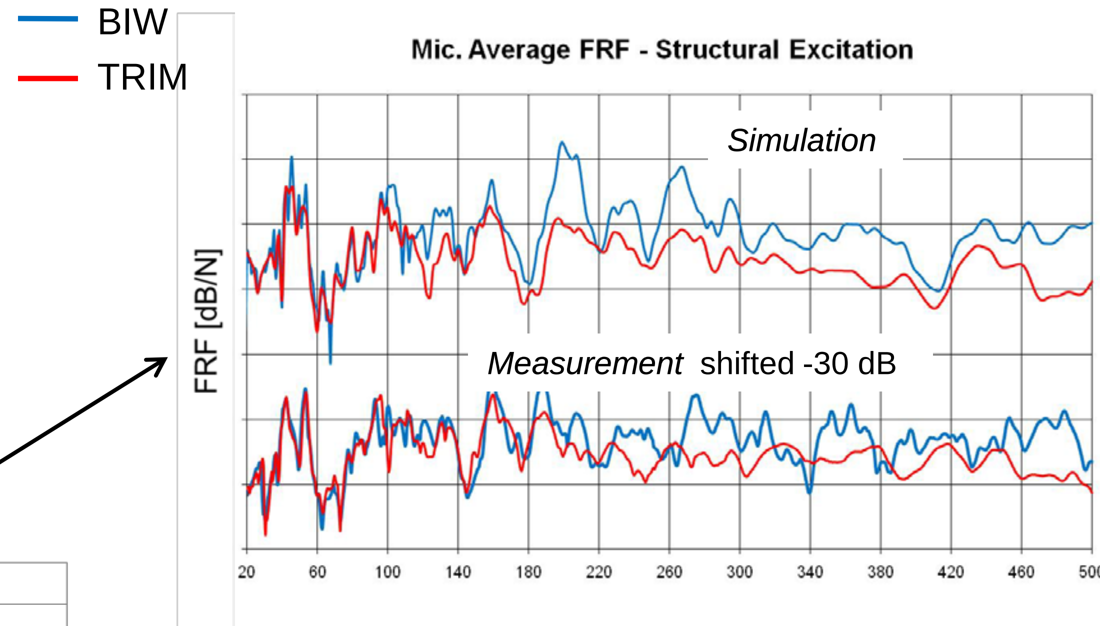


Comparison Structure-Borne Sound TB Measurement/Simulation

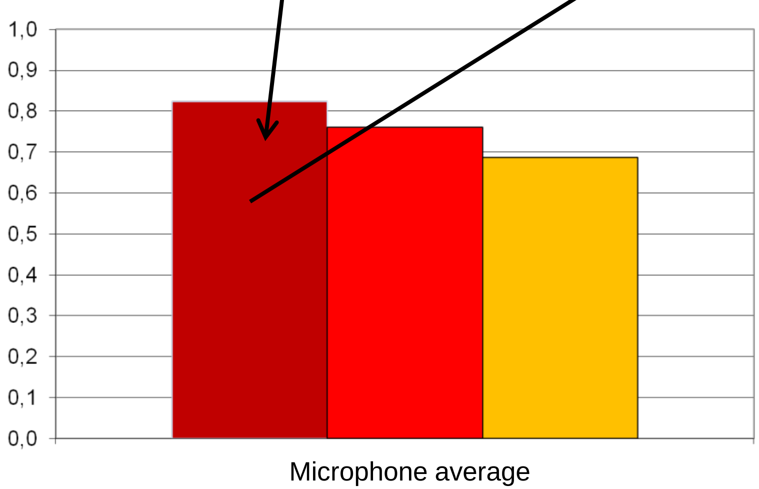
Structure excitations



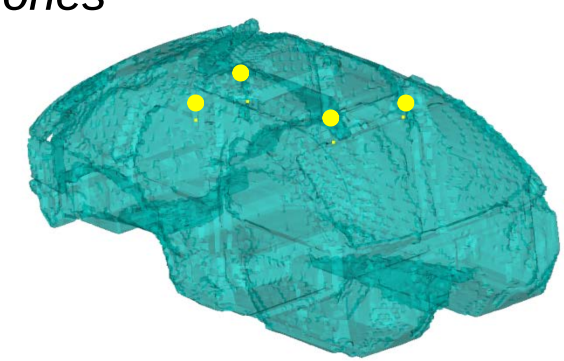
p/F Response in frequency domain [Hz]



FRAC

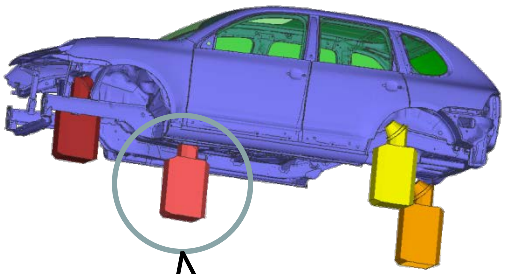


Microphones



Comparison Air-Borne Sound TB Measurement/Simulation

Acoustic excitations



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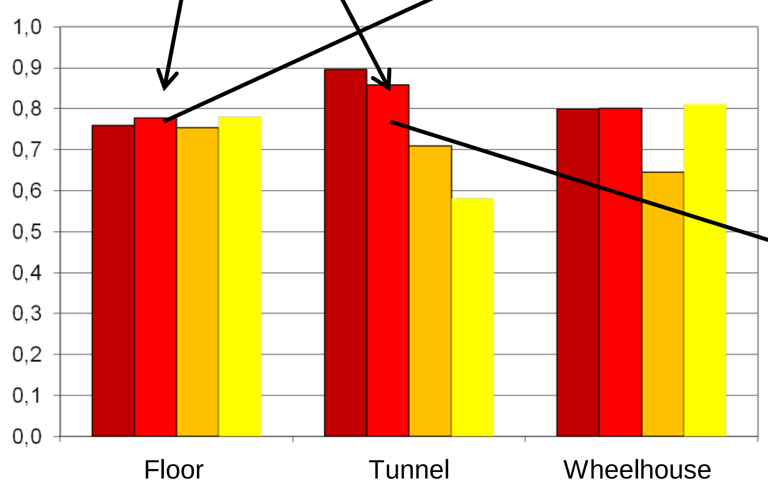
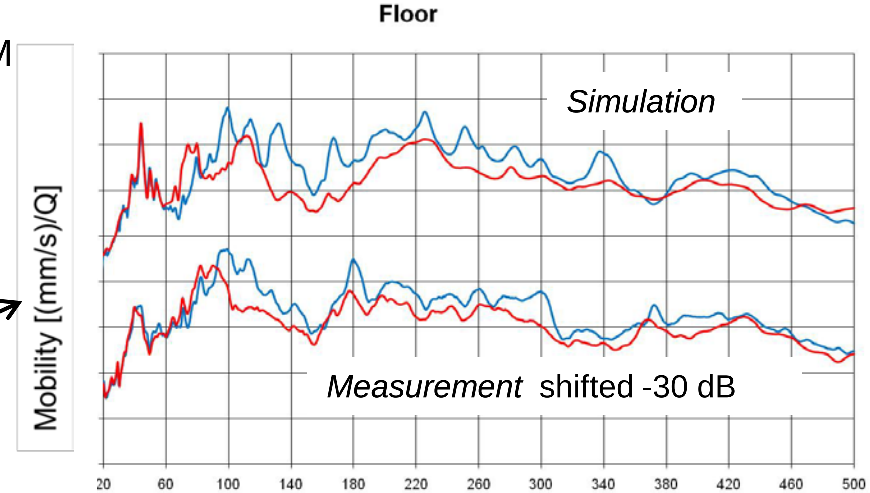
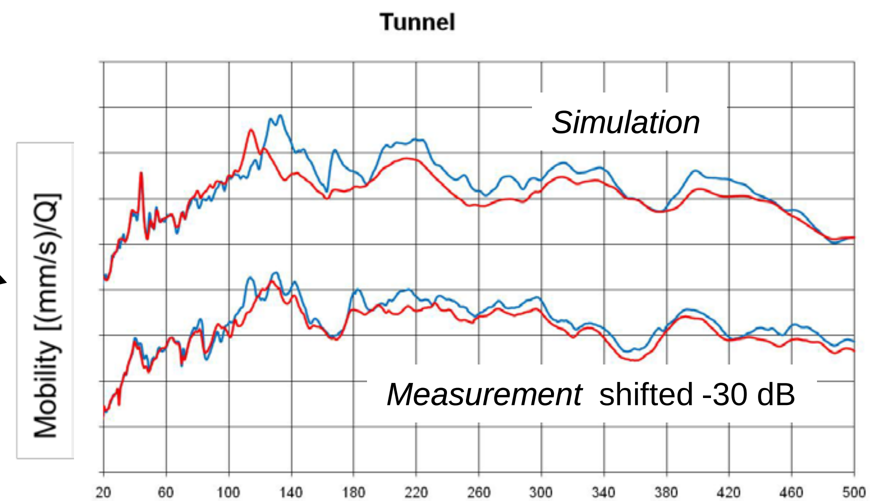


v/Q Response in frequency domain [Hz]

BIW

TRIM

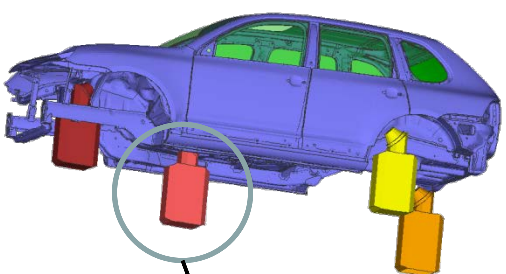




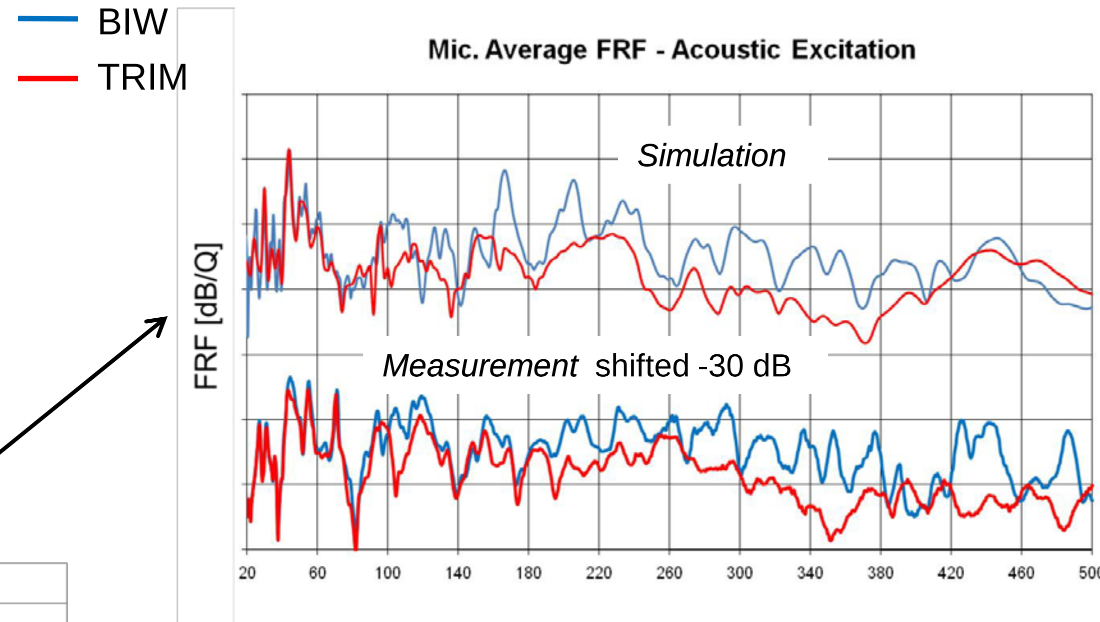
Comparison Air-Borne Sound TB Measurement/Simulation

INTES

Acoustic excitations



p/Q Response in frequency domain [Hz]



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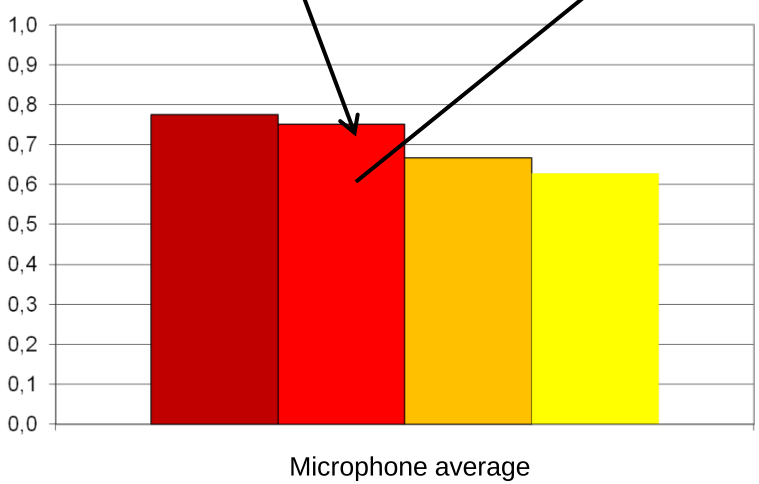
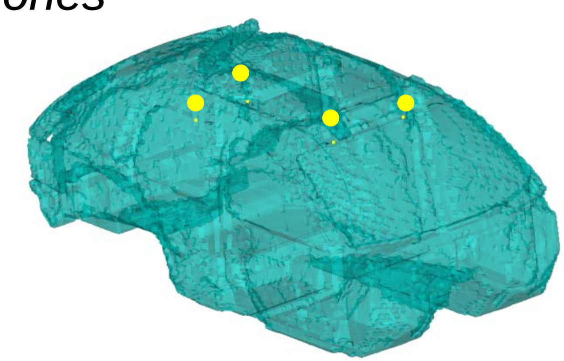


Microphones



Summary

- Acoustic analysis as extension of structural dynamics
- by a bidirectional coupling of pressure and displacement degrees of freedom
- for all fluids (gas and liquid)
- Direct and efficient computation of coupled real eigenfrequencies and mode shapes
- Dynamic condensation to displacement degrees of freedom only (‘dry‘ condensation) e.g. for subsequent MBS simulations
- Modal and direct dynamic response analysis in time and frequency domain
- Interior and exterior fluids in one model enabling sound transmission analysis