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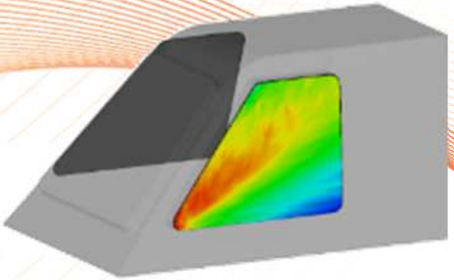
KSNVE 2014

Oct 30th & 31st

Wind Noise Benchmark BMT4

Preliminary Results

for Hyundai Motor Corporation

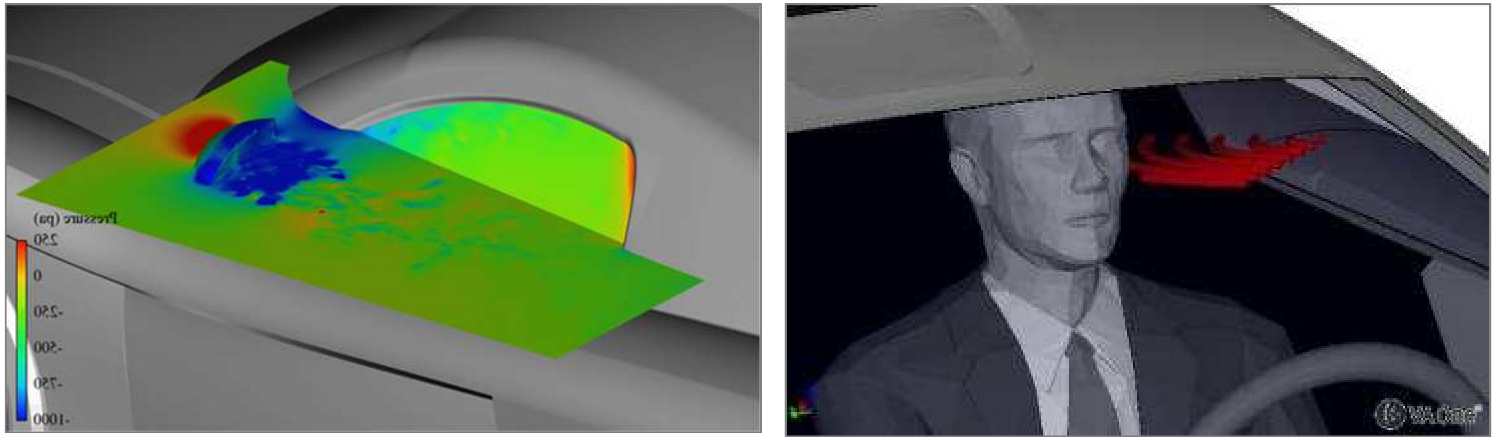


Denis Blanchet
Anton Golota
30th October 2014

www.esi-group.com

The challenge

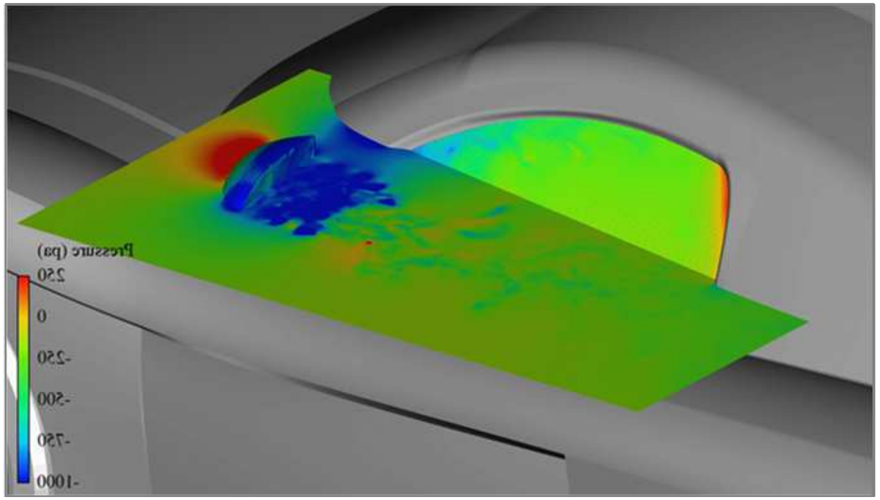
- Turbulent flow generates convective and acoustic pressure fluctuations on side glass,
- This energy can potentially be transfered inside a vehicle

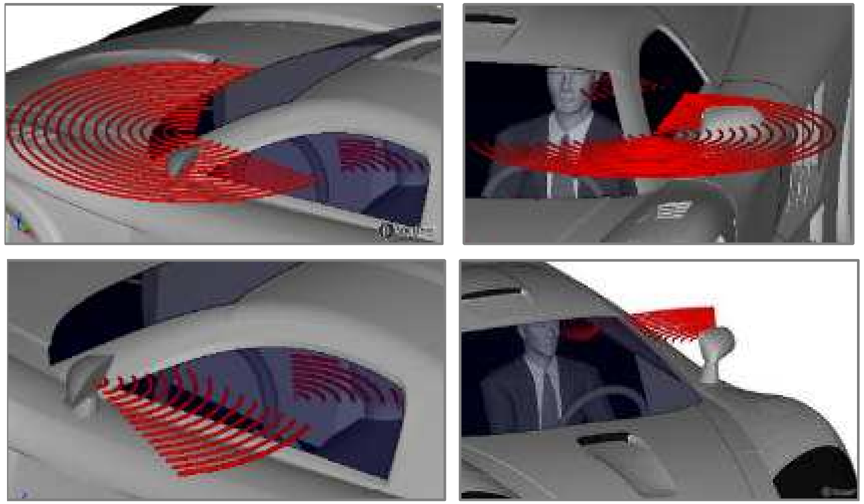


Physical mechanisms

① Pressure fluctuation on mirror

- Pressure fluctuations on mirror rear face and Apillar generate acoustic waves that propagate towards side glass
- Acoustic waves travel with specific heading
- Associated to a dipole source (surface terms)
- Waves travel through side glass to driver‘s ear

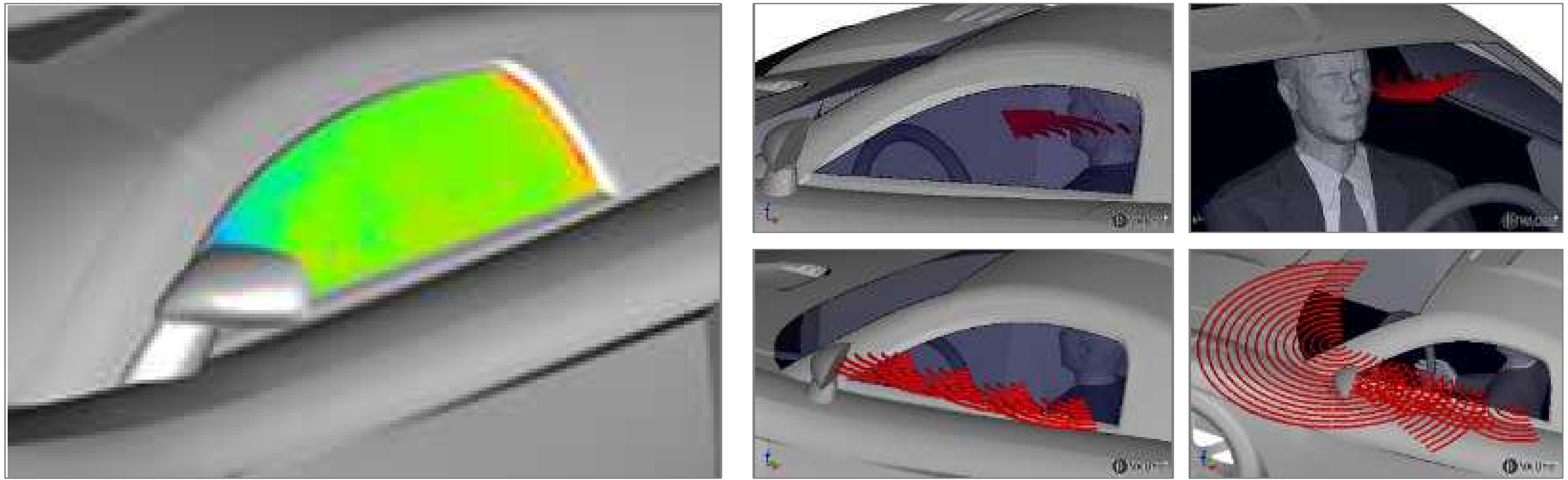




Physical mechanisms

② Pressure fluctuation on side glass

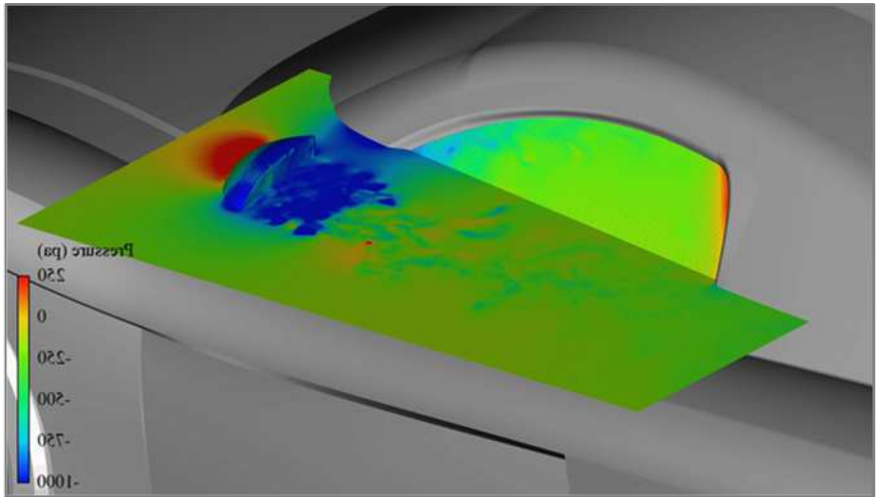
- Pressure field includes convective and acoustic component
- Acoustic comp. ~30-40 dB smaller than convective
- Both components contribute to SPL at driver‘s ear
- Pressure field generates acoustic waves away from side glass
- Interfere with incoming acoustic waves from A-Pillar and mirror
- Has negligeable impact on driver‘s ear SPL

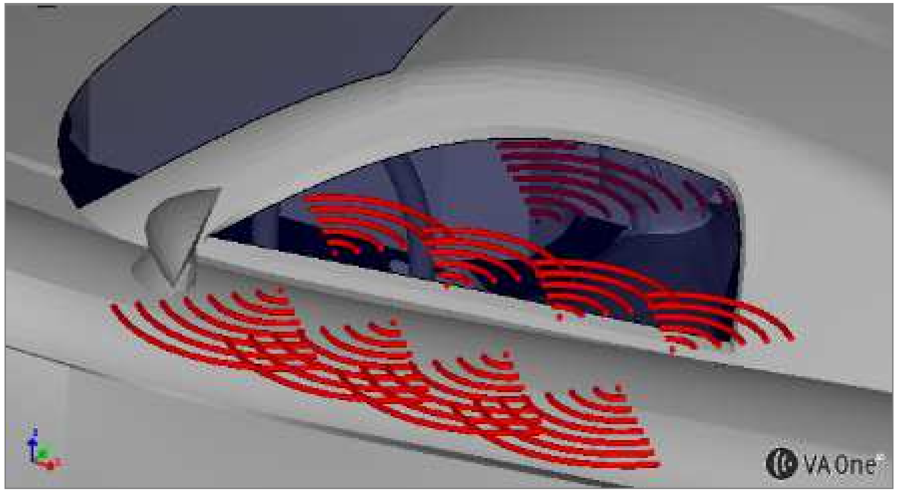


Physical mechanisms

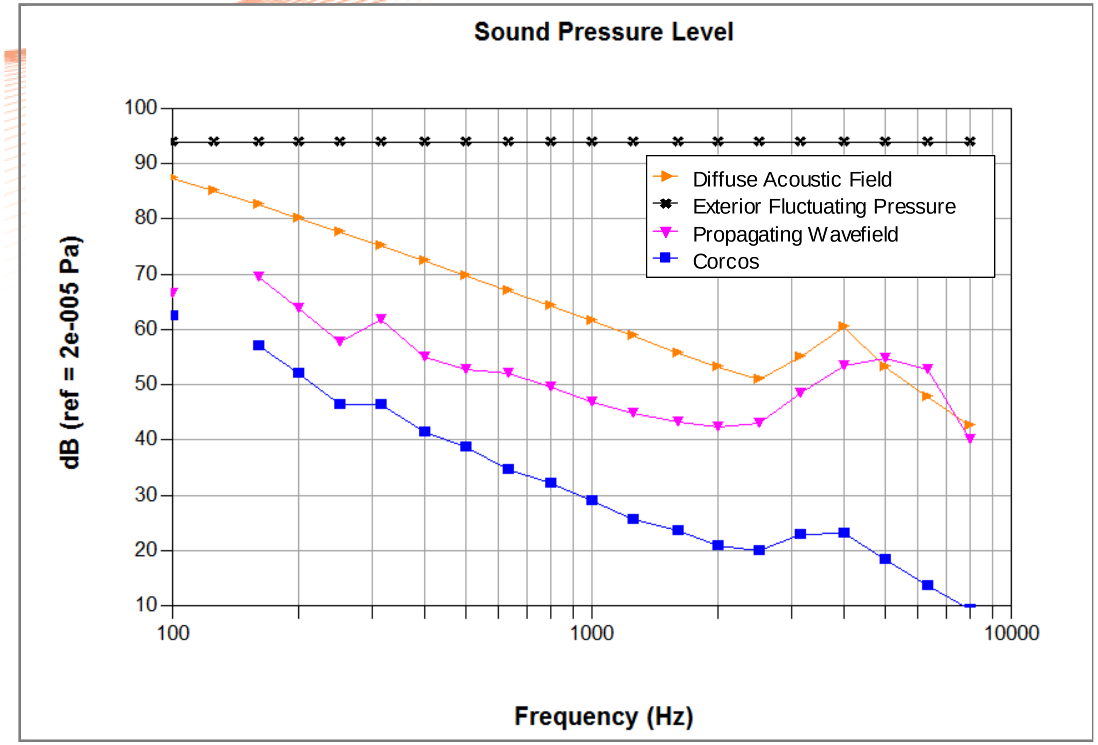
③ Acoustic sources within eddies

- Eddies generate acoustic sources associated with quadripole acoustic sources
- Close proximity to side glass
- At automobile speed, this term is negligeable





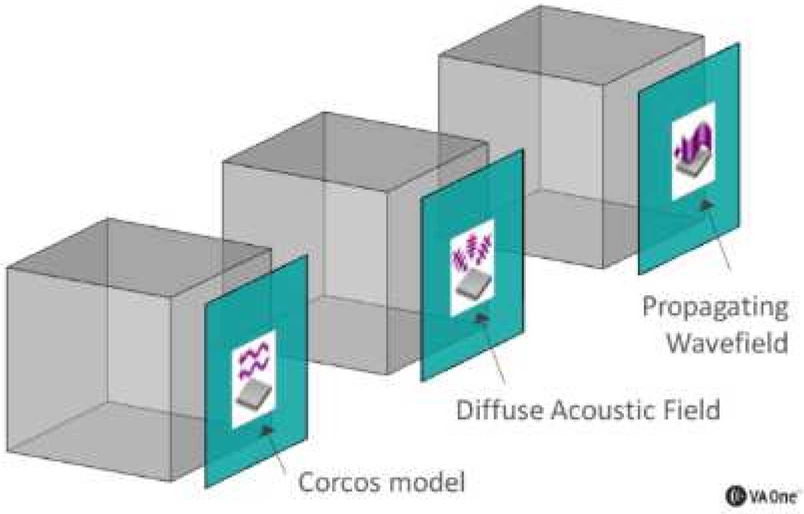
Effect of cross-correlation function



Glass panel of 1 m^2 and thickness 3.5 mm in contact with a 1 m^3 acoustic cavity and excited by:

i) TBL (Turbulent Boundary Layer : Corcos , 40 m/s mean flow)
ii) DAF (Diffuse Acoustic Field)
iii) PWF (Propagating Wave Field)

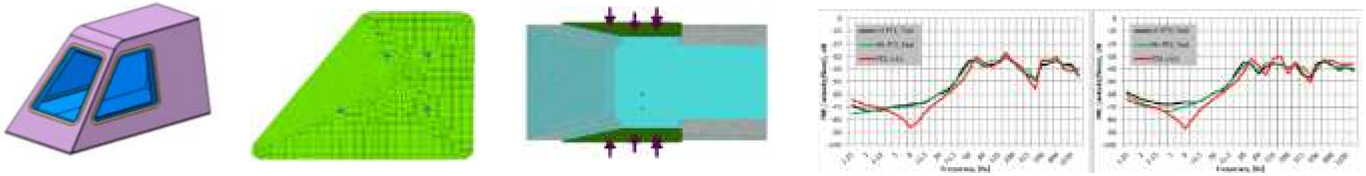
Note that the Turbulent Corcos load yield approximately 30 dB lower SPL than the DAF, and 10 to 30 dB compared to the PWF due to the different spatial correlation characteristics of each load.



Outline

Overview of available approaches

Validation of Vibro-Acoustic models



Validation of aero-vibro-acoustic (AVA) models

Conclusions

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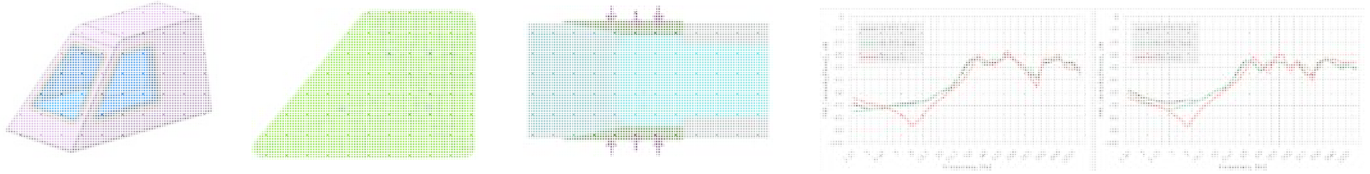
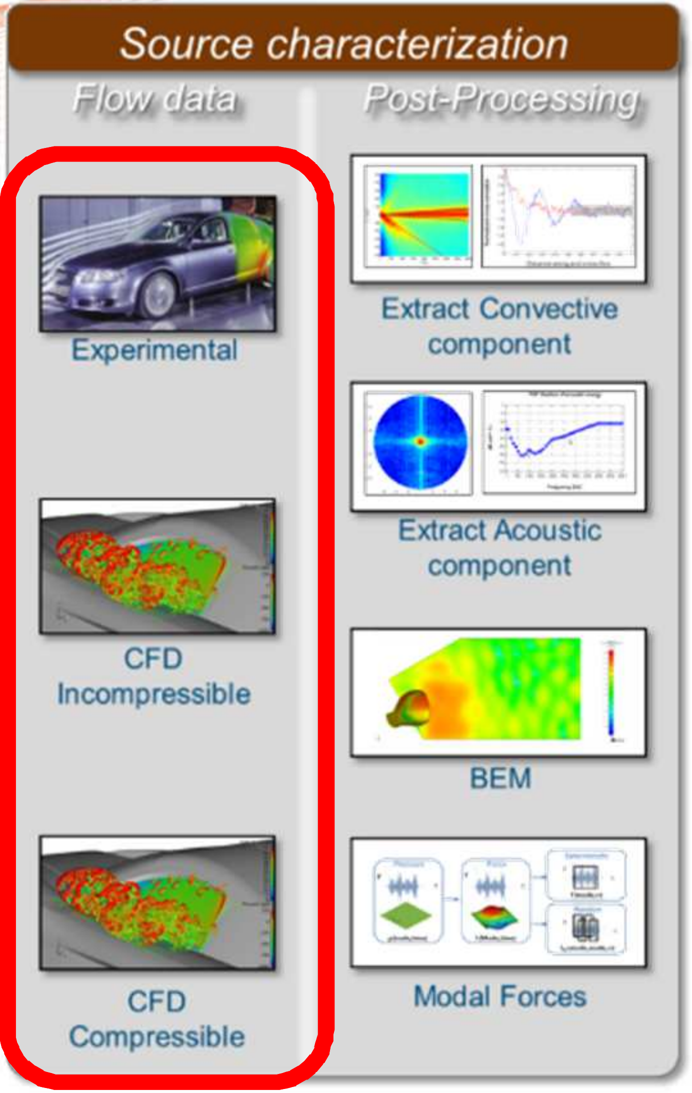
Validation of Vibro-Acoustic models



Validation of aero-vibro-acoustic (AVA) models

Conclusions

Source characterization



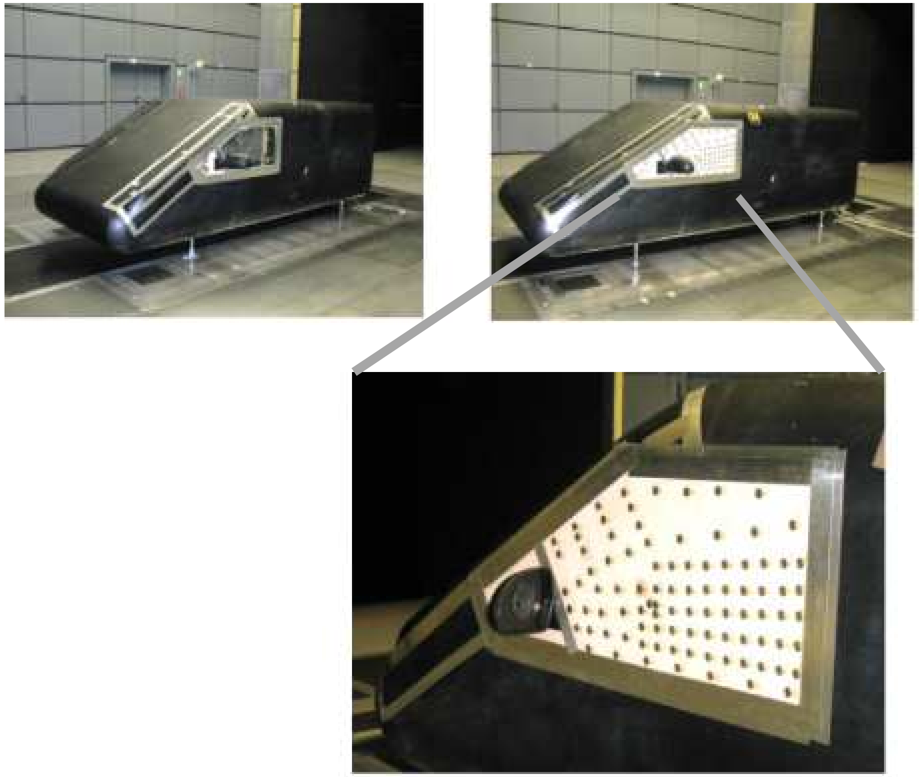
Source characterization

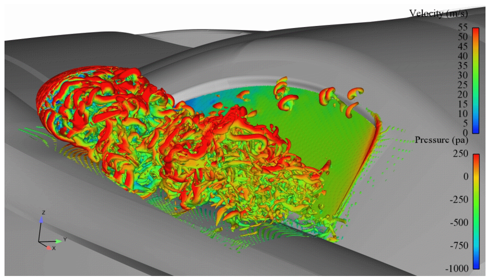
Flow data

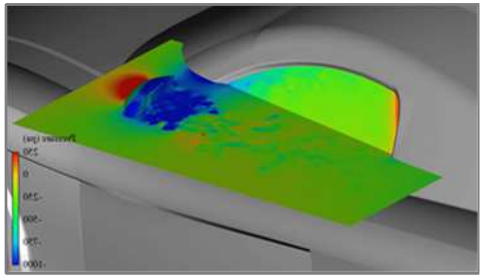
- Experimental
- CFD Incompressible
- CFD Compressible

Post-Processing

- Extract Convective component
- Extract Acoustic component
- BEM
- Modal Forces







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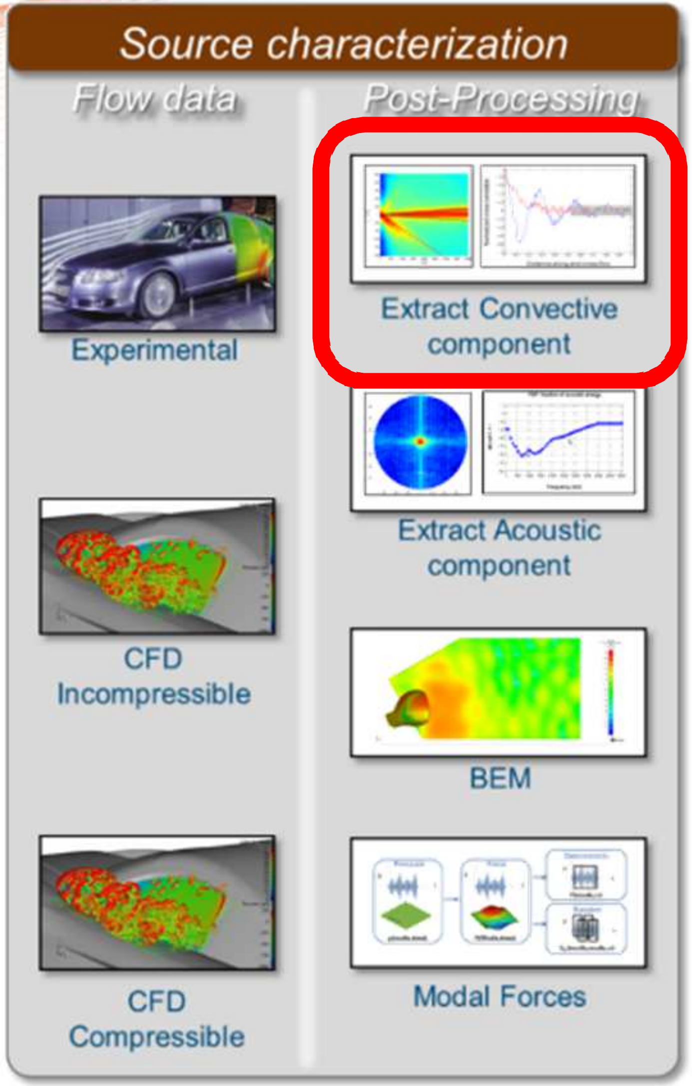
Source characterization

ISMA2012



Source characterization

Flow data

Post-Processing

Experimental

Extract Convective component

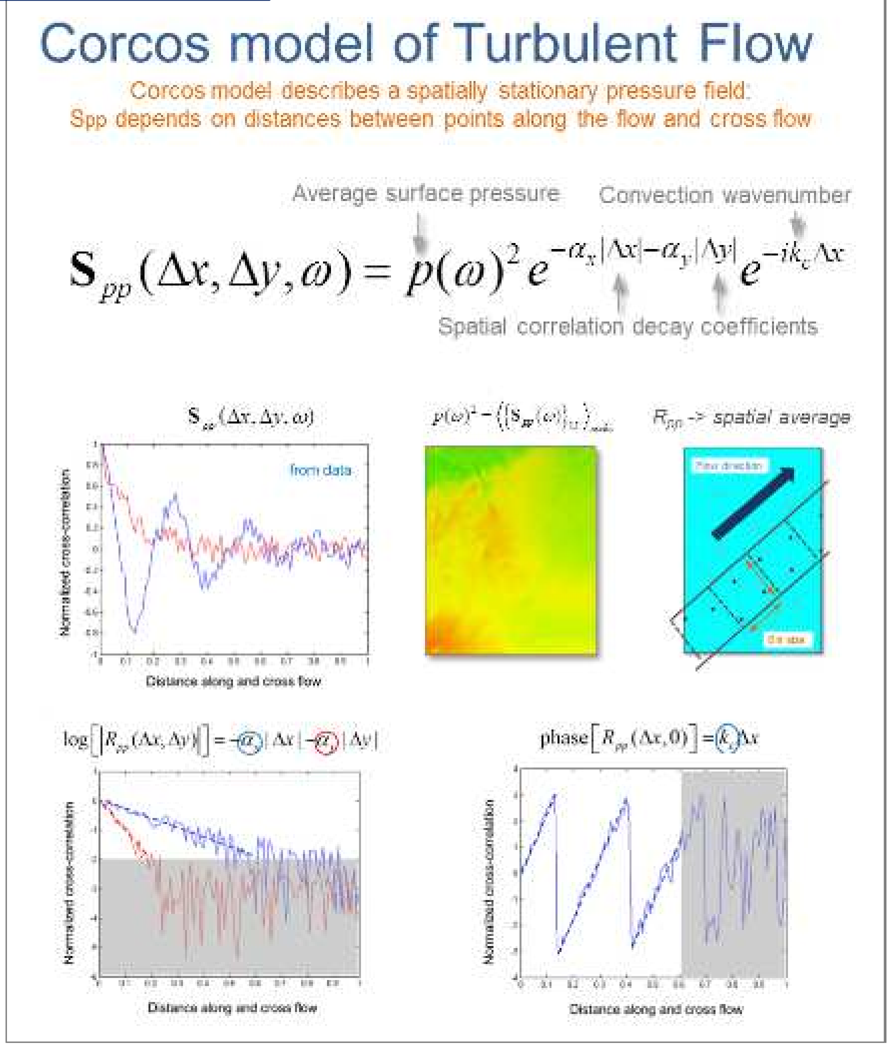
CFD Incompressible

Extract Acoustic component

BEM

CFD Compressible

Modal Forces



Corcos model of Turbulent Flow

Corcos model describes a spatially stationary pressure field:
Spp depends on distances between points along the flow and cross flow

Average surface pressure

Convection wavenumber

$$\mathbf{S}_{pp}(\Delta x, \Delta y, \omega) = p(\omega)^2 e^{-\alpha_x|\Delta x| - \alpha_y|\Delta y|} e^{-ik_c \Delta x}$$

Spatial correlation decay coefficients

$\mathbf{S}_{pp}(\Delta x, \Delta y, \omega)$

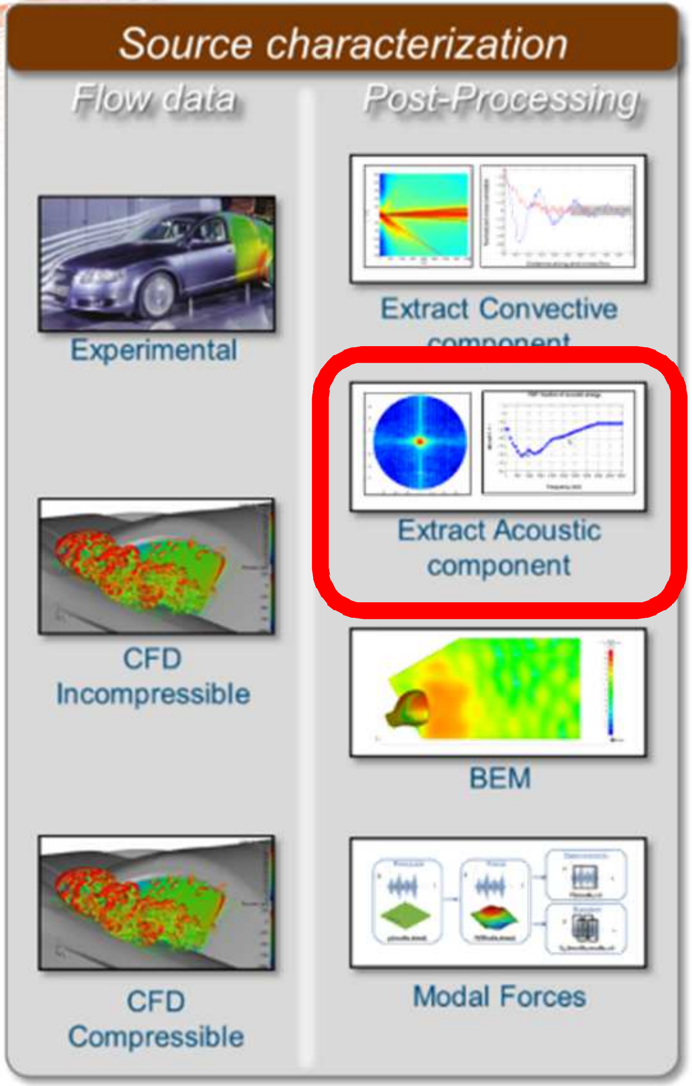
$p(\omega)^2 - \langle\{\mathbf{S}_{pp}(\omega)\}_{ii}\rangle_{nodes}$

R_{pp} -> spatial average

$$\log\left[\left|R_{pp}(\Delta x, \Delta y)\right|\right] = -\alpha_x|\Delta x| - \alpha_y|\Delta y|$$

$$\text{phase}\left[R_{pp}(\Delta x, 0)\right] = k_c \Delta x$$

Source characterization



Source characterization

Flow data

Post-Processing

Experimental

Extract Convective component

Extract Acoustic component

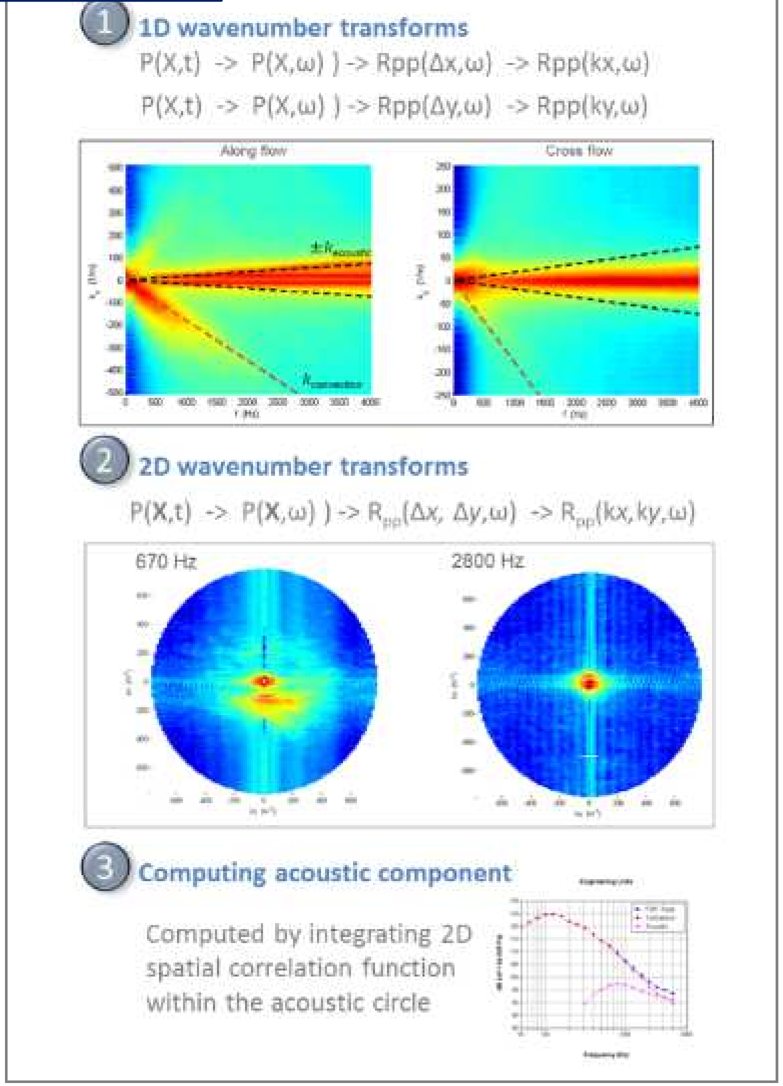
CFD Incompressible

BEM

CFD Compressible

Modal Forces

ISMA2012



① **1D wavenumber transforms**

P(X,t) -> P(X,ω)) -> Rpp(Δx,ω) -> Rpp(kx,ω)

P(X,t) -> P(X,ω)) -> Rpp(Δy,ω) -> Rpp(ky,ω)

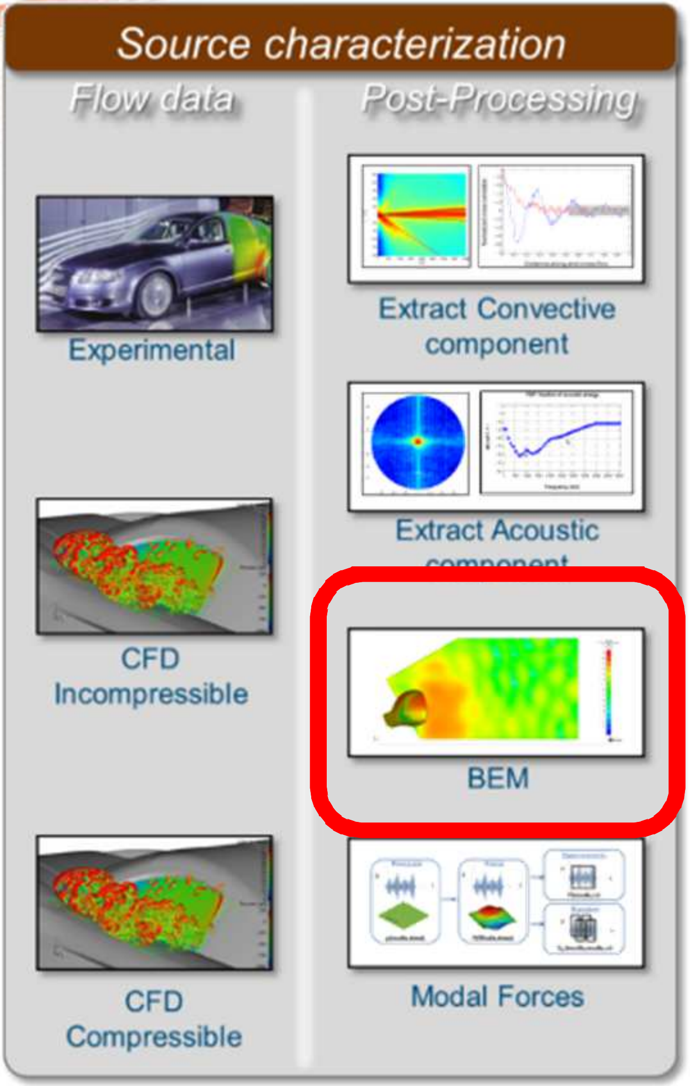
② **2D wavenumber transforms**

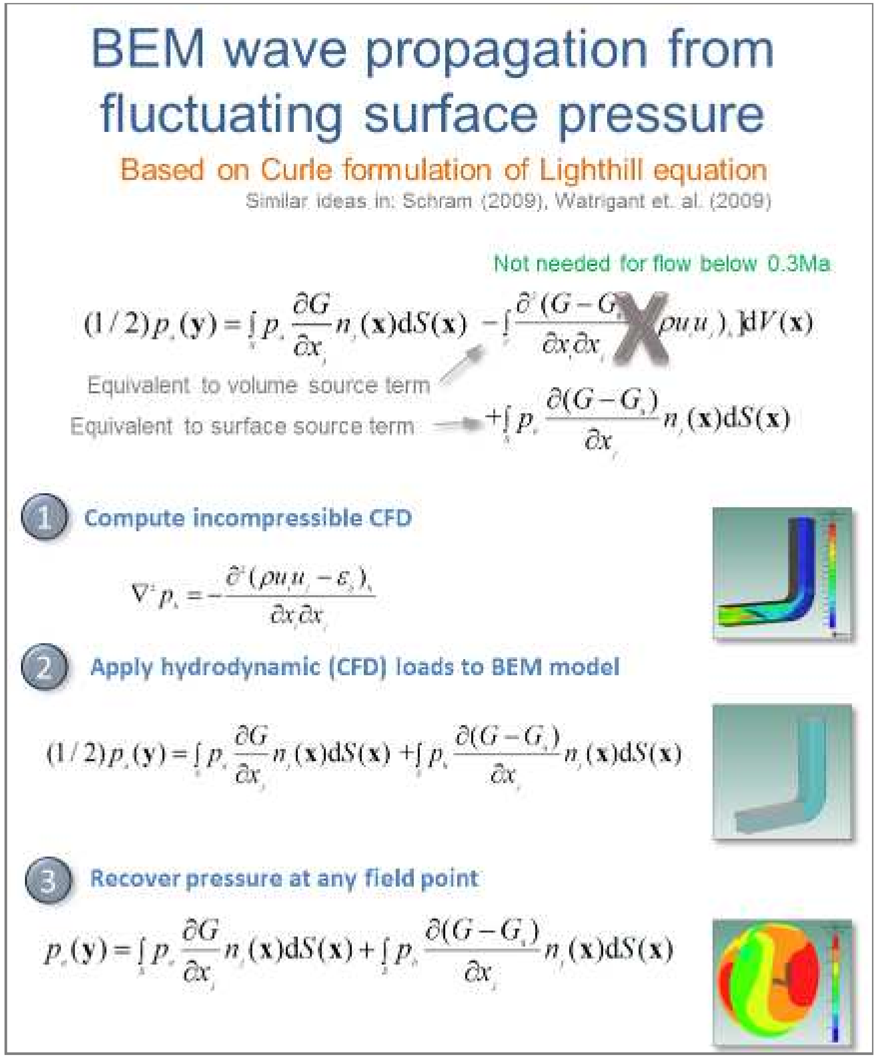
$P(\mathbf{X},t) \rightarrow P(\mathbf{X},\omega)\ ) \rightarrow R_{pp}(\Delta x, \Delta y,\omega) \rightarrow R_{pp}(kx,ky,\omega)$

③ **Computing acoustic component**

Computed by integrating 2D spatial correlation function within the acoustic circle

Source characterization





BEM wave propagation from fluctuating surface pressure

Based on Curle formulation of Lighthill equation

Similar ideas in: Schram (2009), Watrigant et. al. (2009)

Not needed for flow below 0.3Ma

$$(1/2)p_a(\mathbf{y}) = \int_S p_a \frac{\partial G}{\partial x_j} n_j(\mathbf{x})\mathrm{d}S(\mathbf{x}) - \cancel{\int_V \frac{\partial^2 (G-G_s)}{\partial x_i \partial x_j} (\rho u_i u_j)_s \mathrm{d}V(\mathbf{x})}$$

Equivalent to volume source term

Equivalent to surface source term

$$+\int_S p_s \frac{\partial (G-G_s)}{\partial x_j} n_j(\mathbf{x})\mathrm{d}S(\mathbf{x})$$

① Compute incompressible CFD

$$\nabla^2 p_s = -\frac{\partial^2 (\rho u_i u_j - \varepsilon_{ij})_s}{\partial x_i \partial x_j}$$

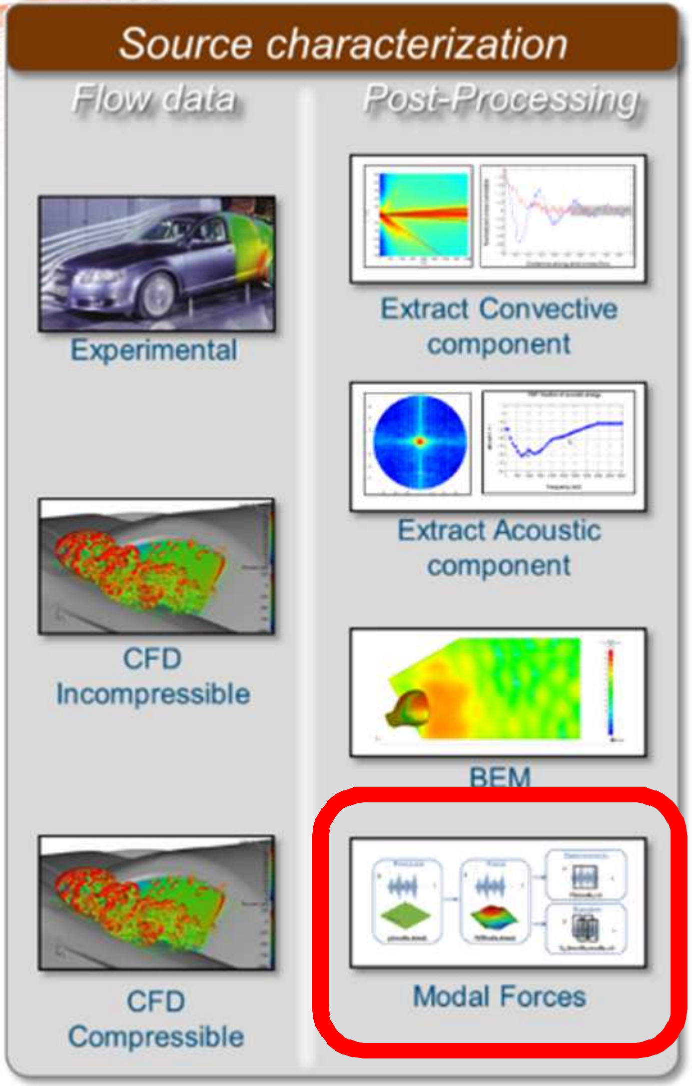
② Apply hydrodynamic (CFD) loads to BEM model

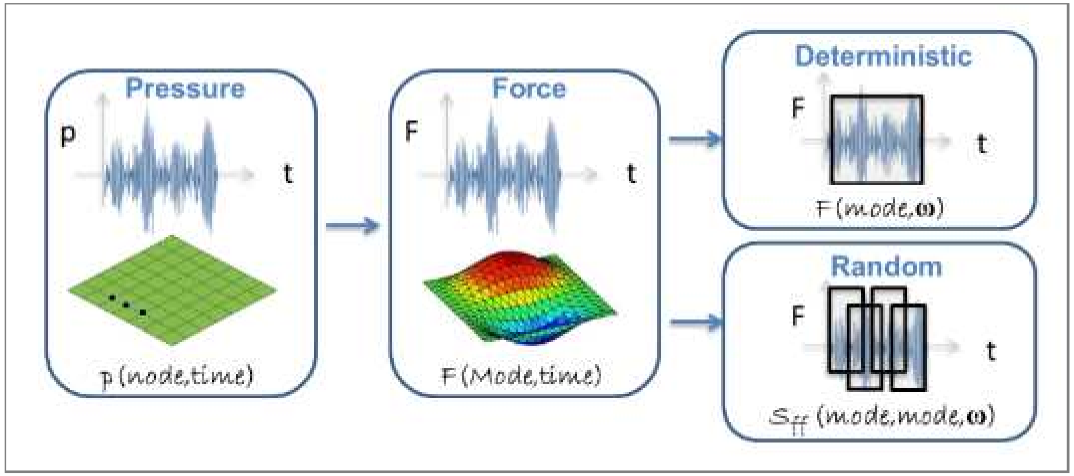
$$(1/2)p_a(\mathbf{y}) = \int_S p_a \frac{\partial G}{\partial x_j} n_j(\mathbf{x})\mathrm{d}S(\mathbf{x}) + \int_S p_s \frac{\partial (G-G_s)}{\partial x_j} n_j(\mathbf{x})\mathrm{d}S(\mathbf{x})$$

③ Recover pressure at any field point

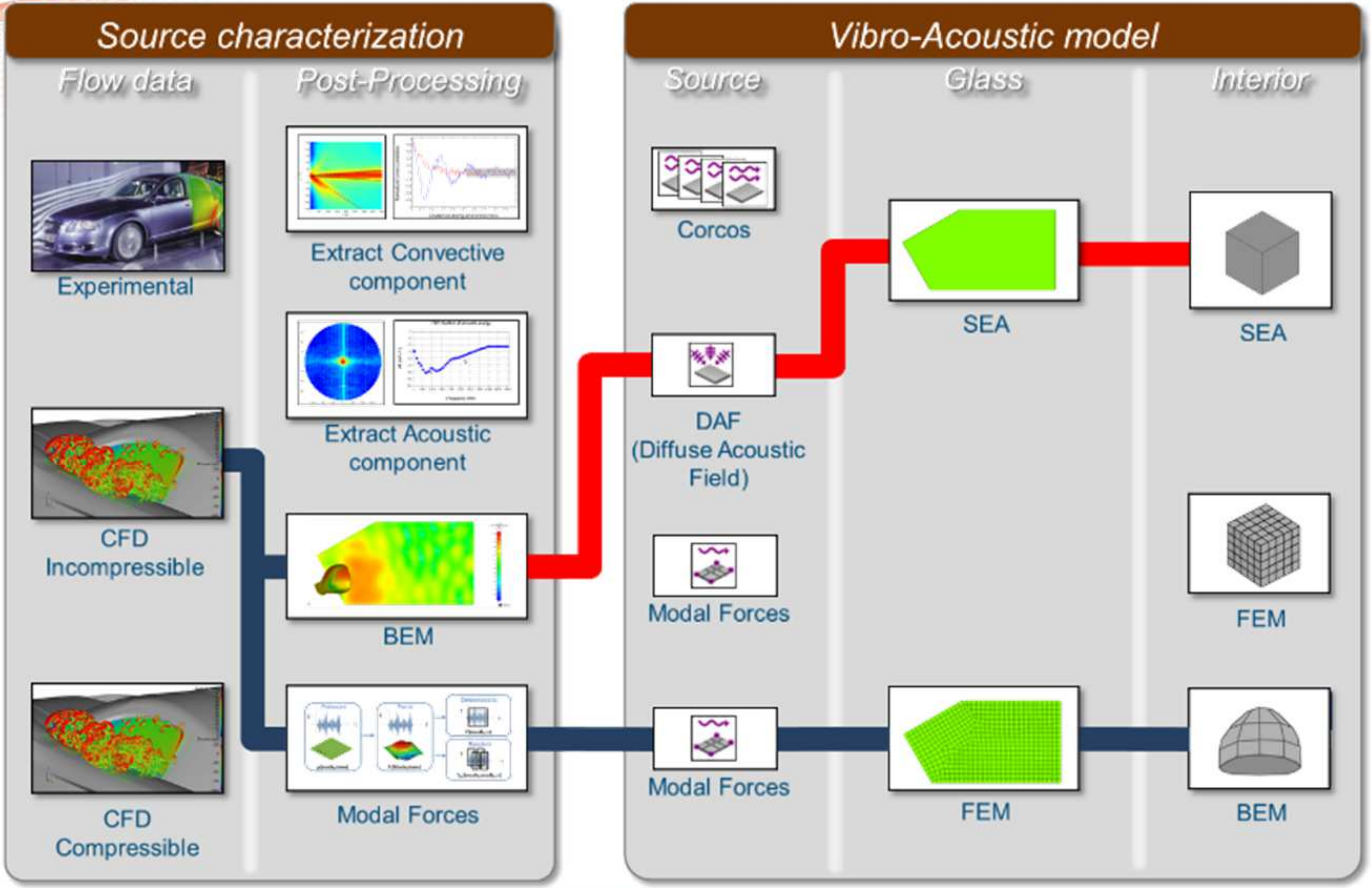
$$p_a(\mathbf{y}) = \int_S p_a \frac{\partial G}{\partial x_j} n_j(\mathbf{x})\mathrm{d}S(\mathbf{x}) + \int_S p_s \frac{\partial (G-G_s)}{\partial x_j} n_j(\mathbf{x})\mathrm{d}S(\mathbf{x})$$

Source characterization





Methods used



🟦 Convective component 🟥 Acoustic component 🟩 Both components

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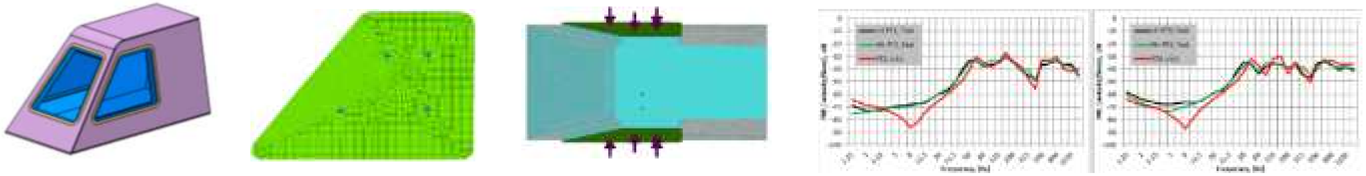

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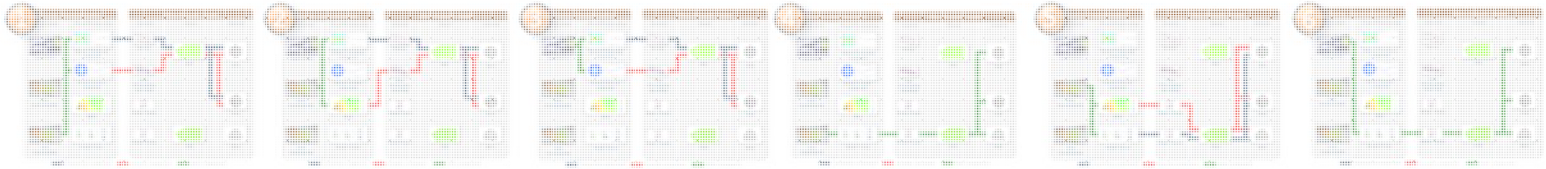
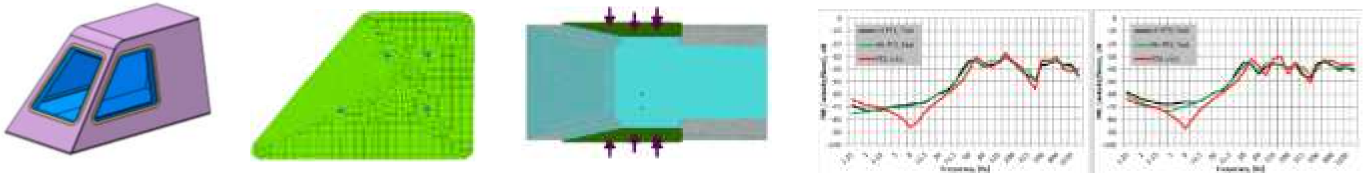


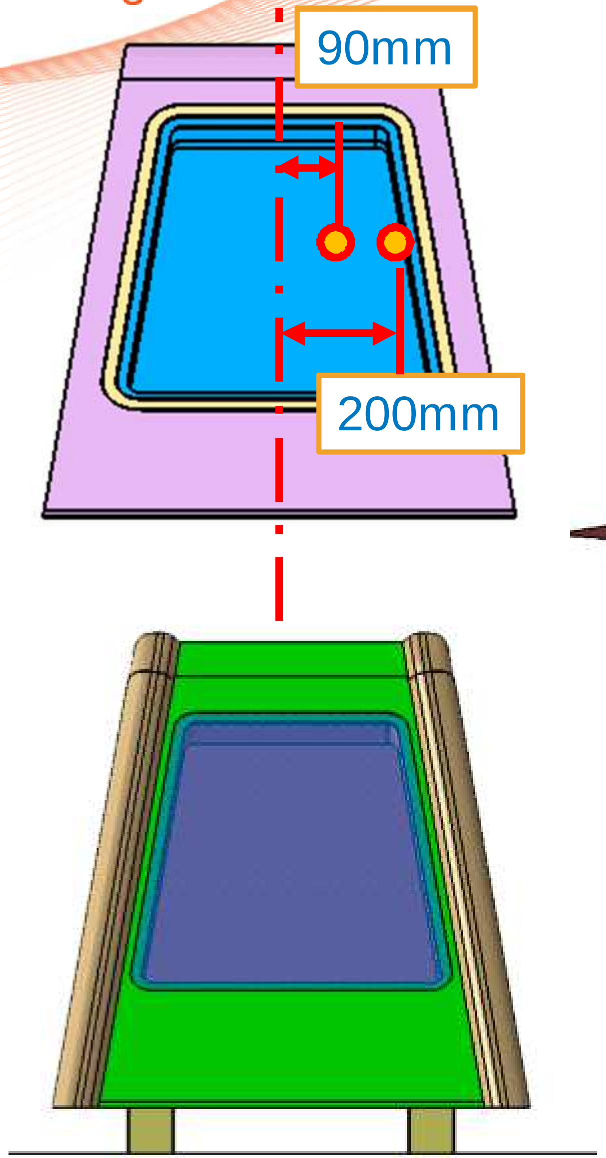
Validation of Vibro-Acoustic models

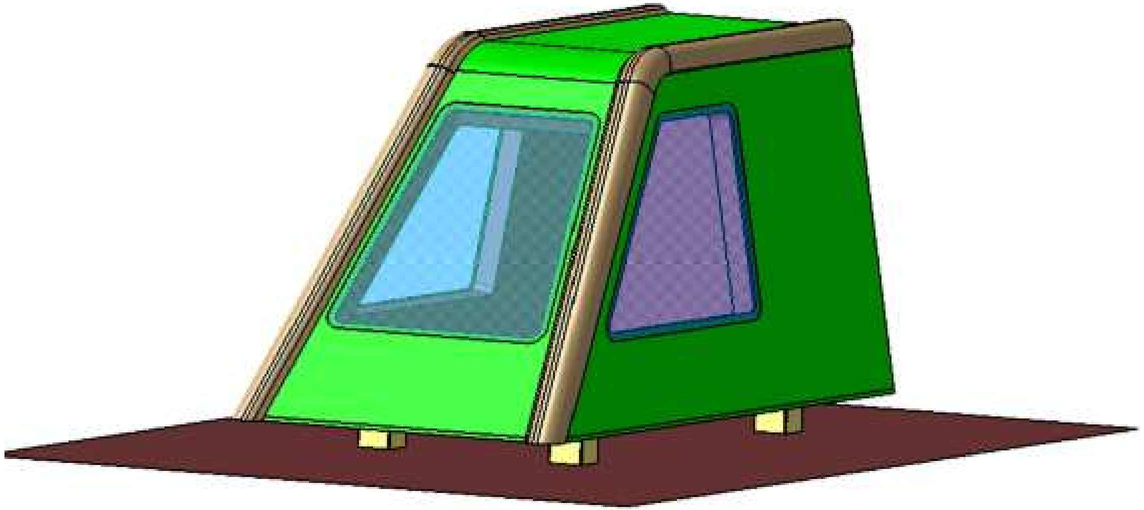


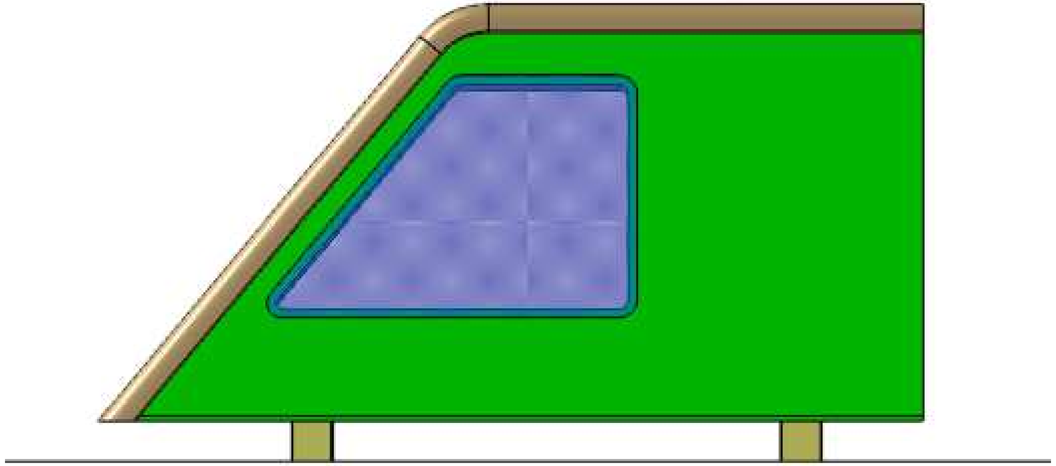
Validation of aero-vibro-acoustic (AVA) models

Conclusions

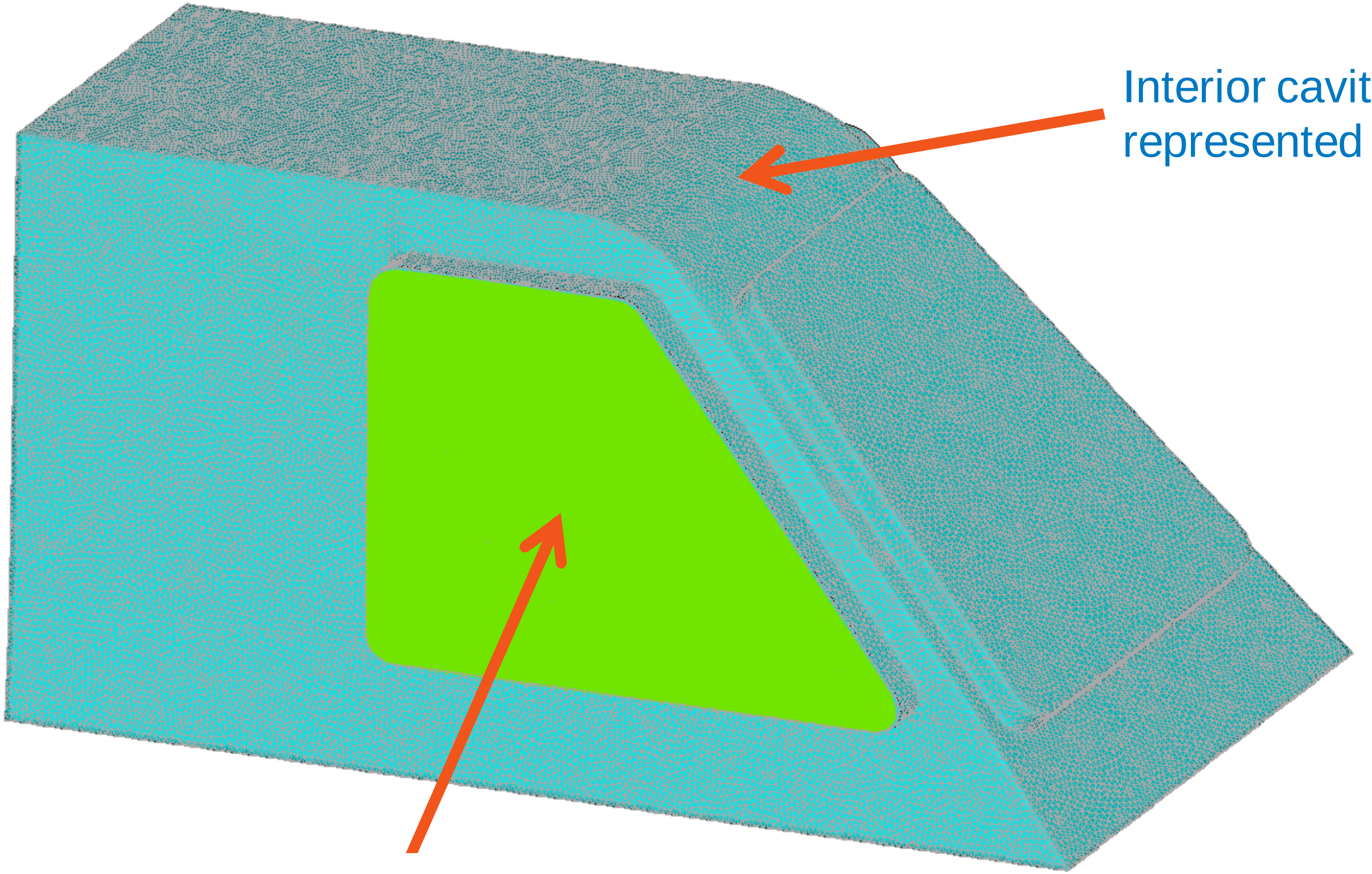
Description of structure







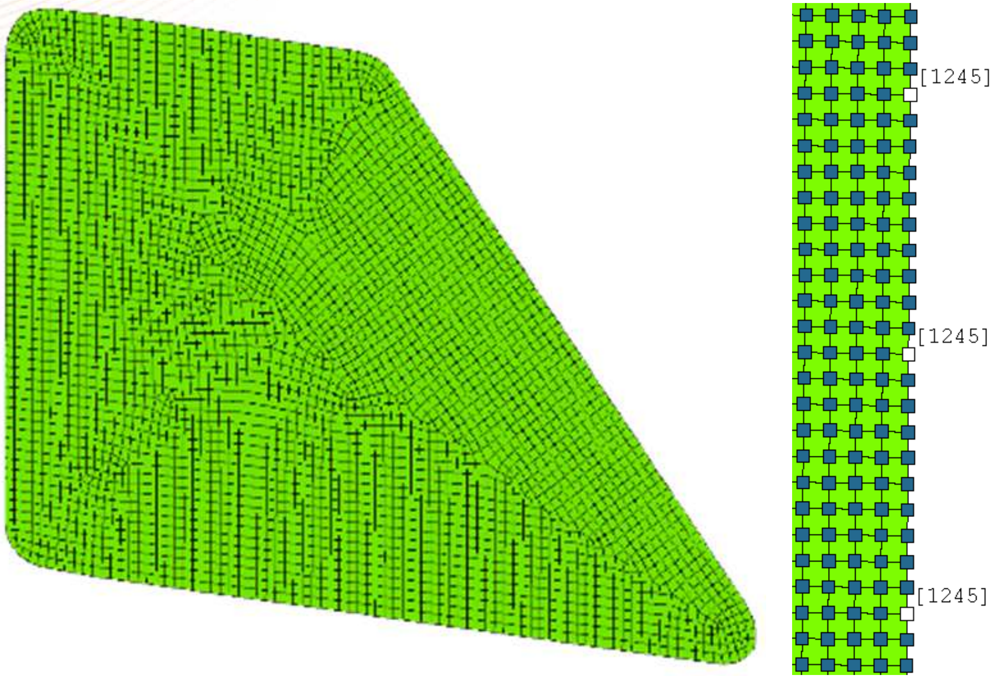
VA One model

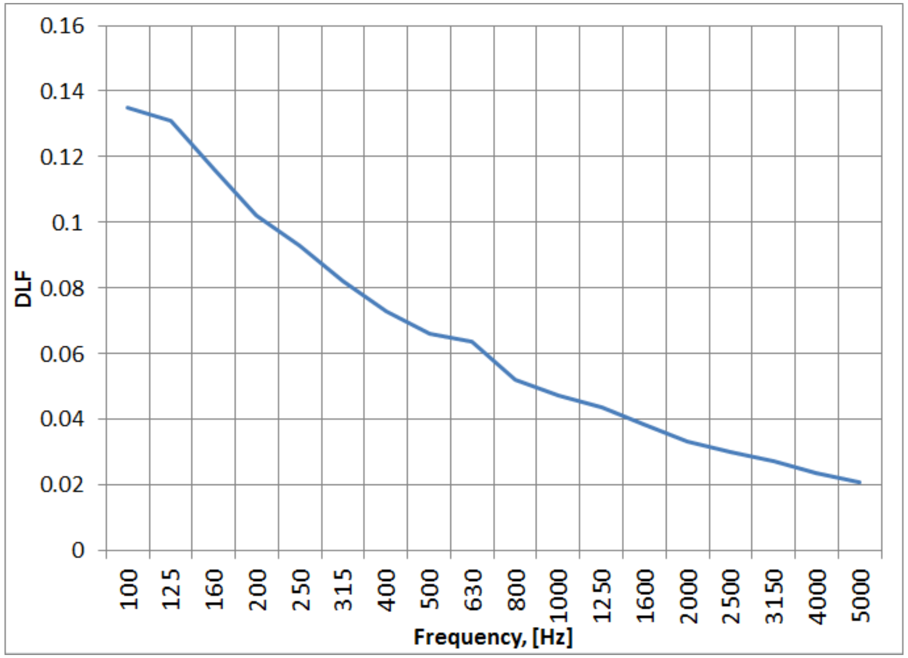


Interior cavity is represented with BEM

Side Glass is represented as a FE Structural Subsystem

FE glass model

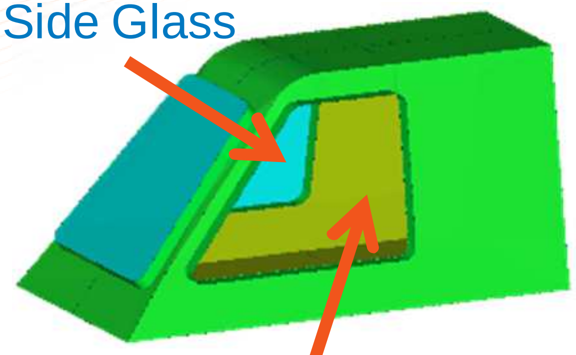




- Quad mesh
- Element size is 10 mm
- Mixed boundary condition applied on every 9th node on edge of Side Glasses
- Damping Loss Factor estimated from modal damping

Model for obtaining interior damping

Noise Control Treatment on interior SEA walls used to predict interior damping.



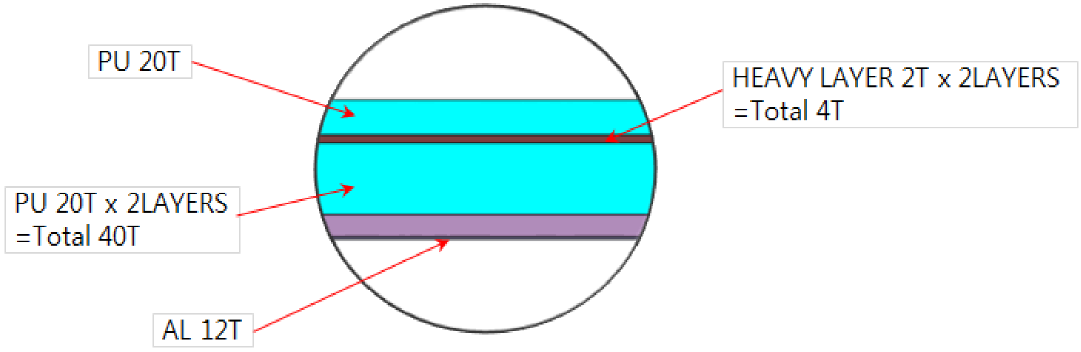
Side Glass

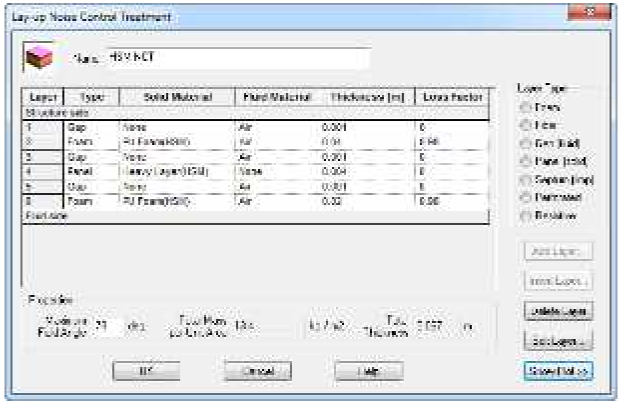
Noise Control Treatment

PU FOAM*	
Density (kg/m^3)	90
Tensile Modulus (Pa)	10000
Shear Modulus (Pa)	3703.7
Flow Resistivity (MKS Rayls/m)	68300
Poisson's Ratio	0.35
Loss Factor	0.98
Porosity	0.879
Tortuosity	3.31
Thermal Length (μm)	0.00012174
Viscous Length (μm)	0.0009483

Heavy Layer**	
Density (kg/m^3)	2000
Tensile Modulus (Pa)	40000000
Shear Modulus (Pa)	13790000
Poisson's Ratio	0.4503

*From HSM_Property_Info(from 2013 BMT).ppt
** From HSM_BEM_110KPH_yaw0.va1



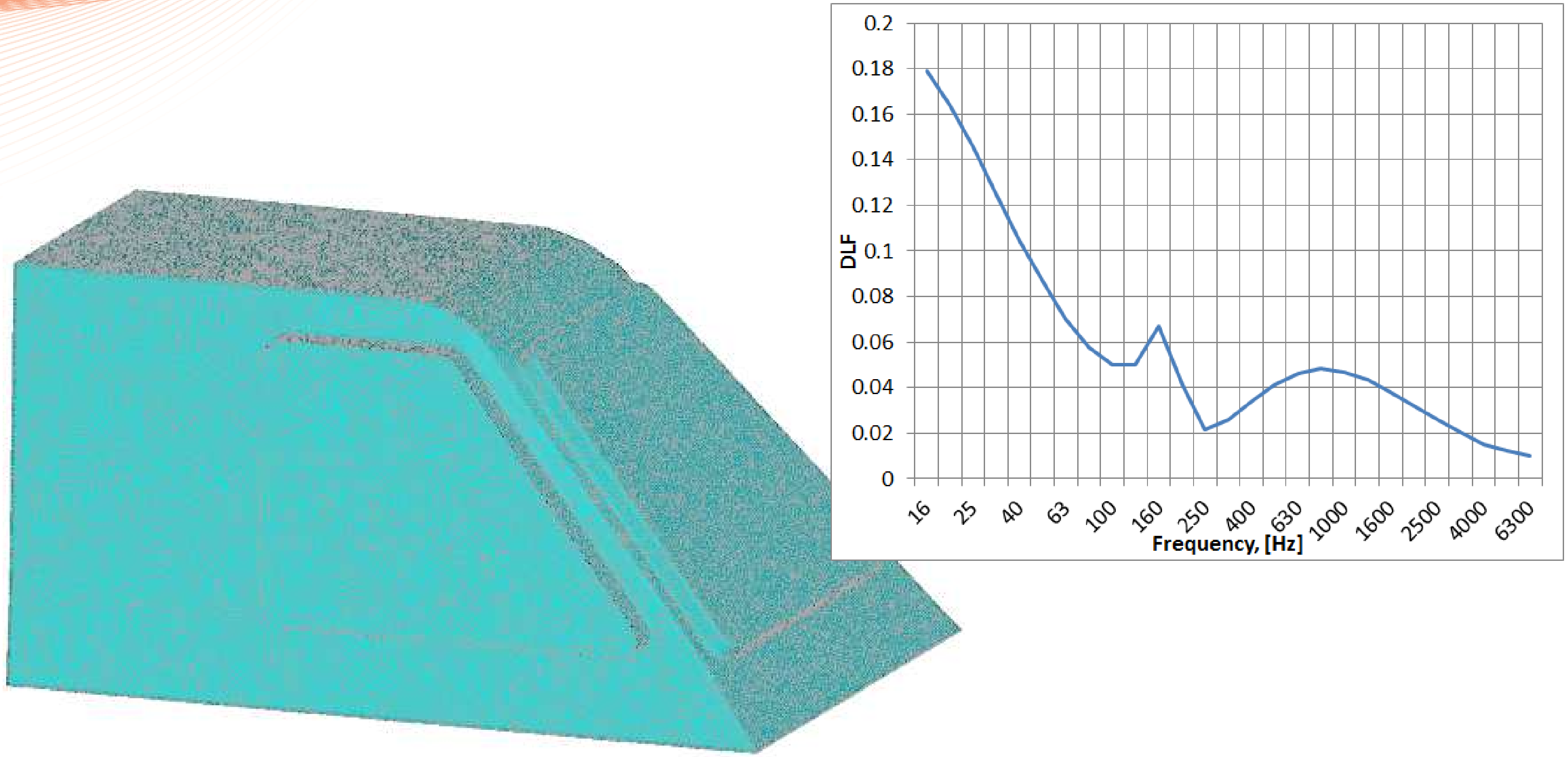


Lay-up Noise Control Treatment

Name: HSV NCT

Layer	Type	Solid Material	Fluid Material	Thickness (m)	Loss Factor
Structure side					
1	Gap	None	Air	0.001	0
2	Foam	PU Foam(ESI)	Air	0.01	0.98
3	Gap	None	Air	0.001	0
4	Panel	Heavy Layer(ESI)	None	0.004	0
5	Gap	None	Air	0.001	0
6	Foam	PU Foam(ESI)	Air	0.02	0.98
Fluid side					

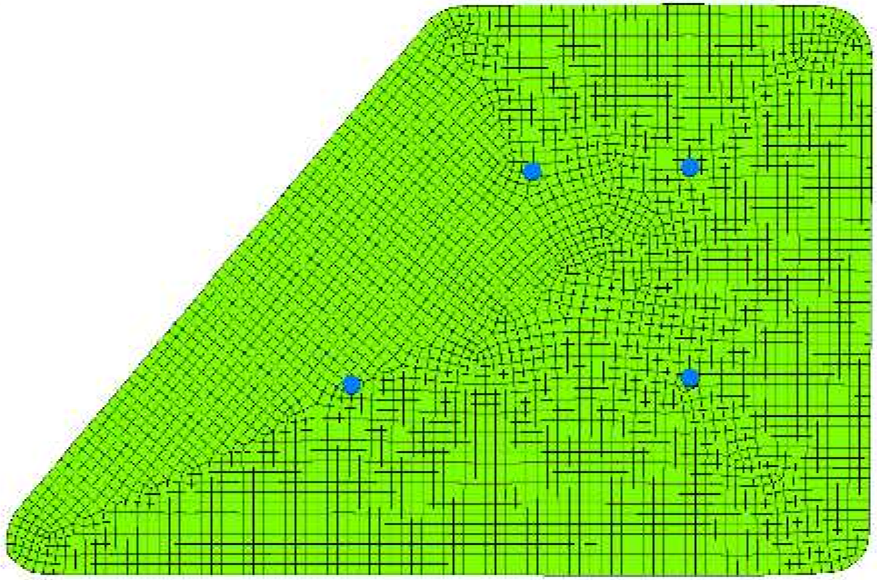
BEM cavity model

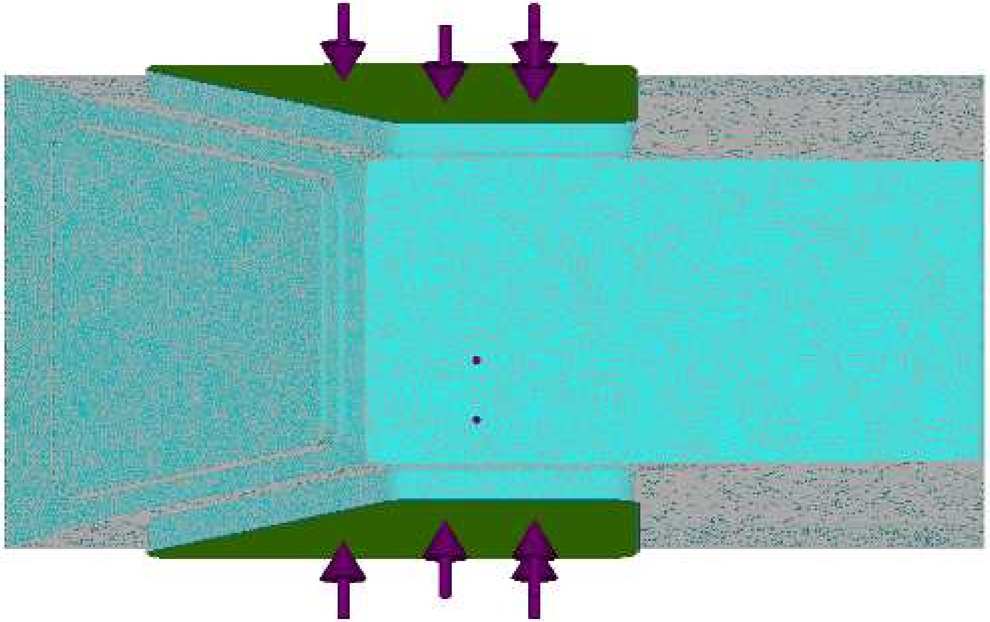


- TRIA mesh for interior surface mesh of cavity
- Element size is 10.4 mm

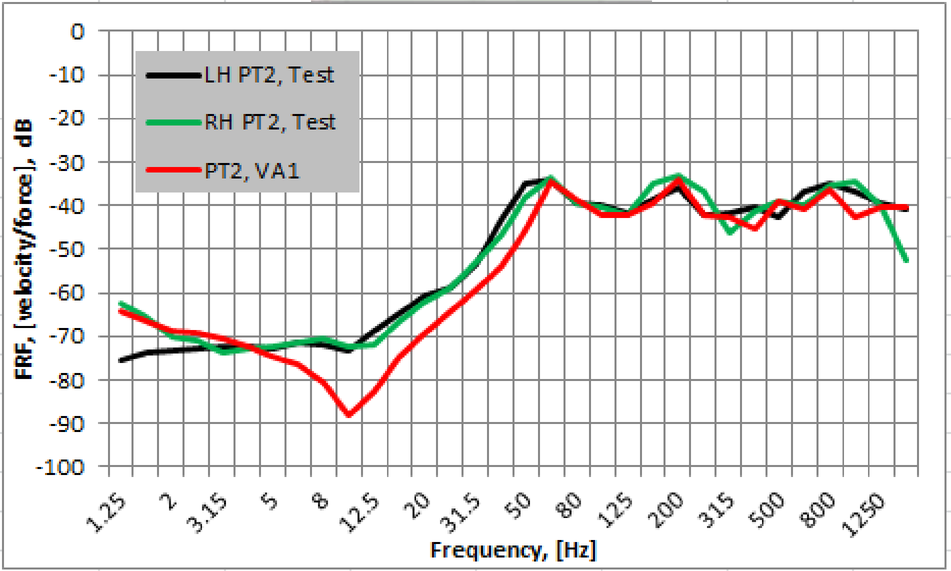
Validation of the model

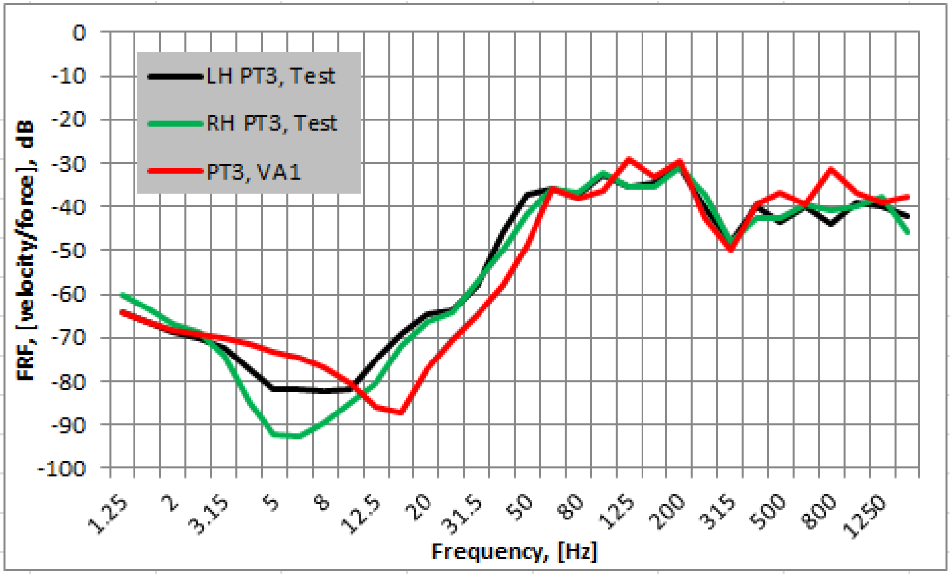
Location of the sensors and excitation points

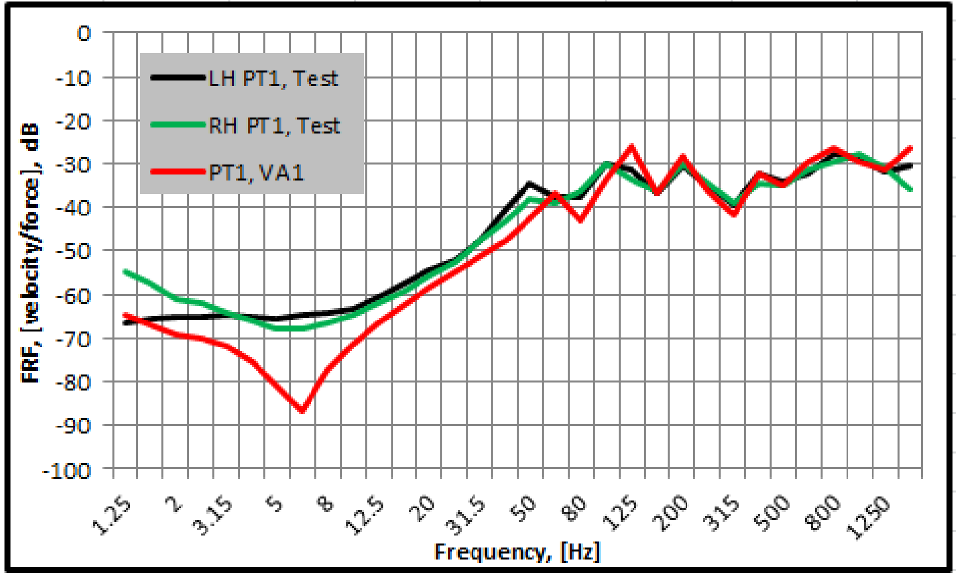


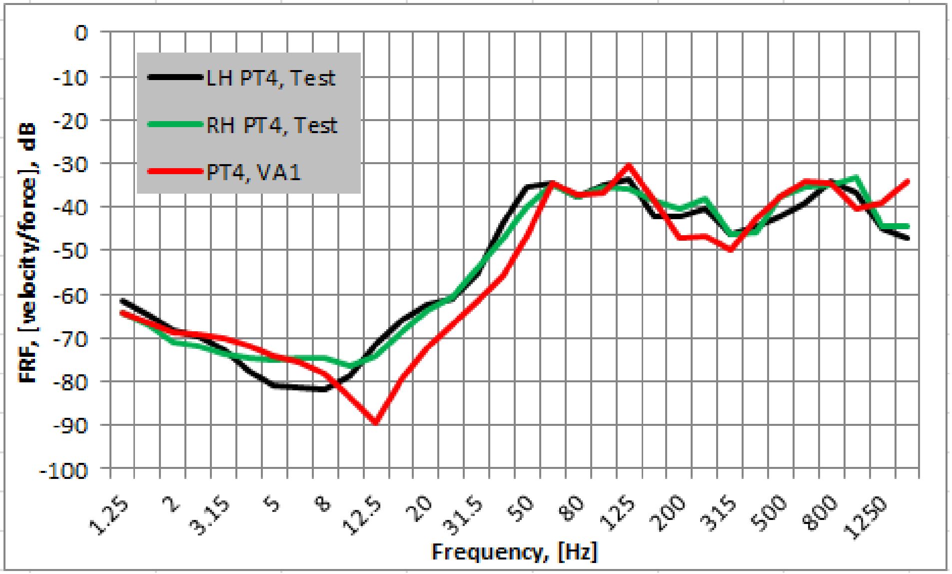


Comparison of FRF on the side glass (1/3rd octave band)









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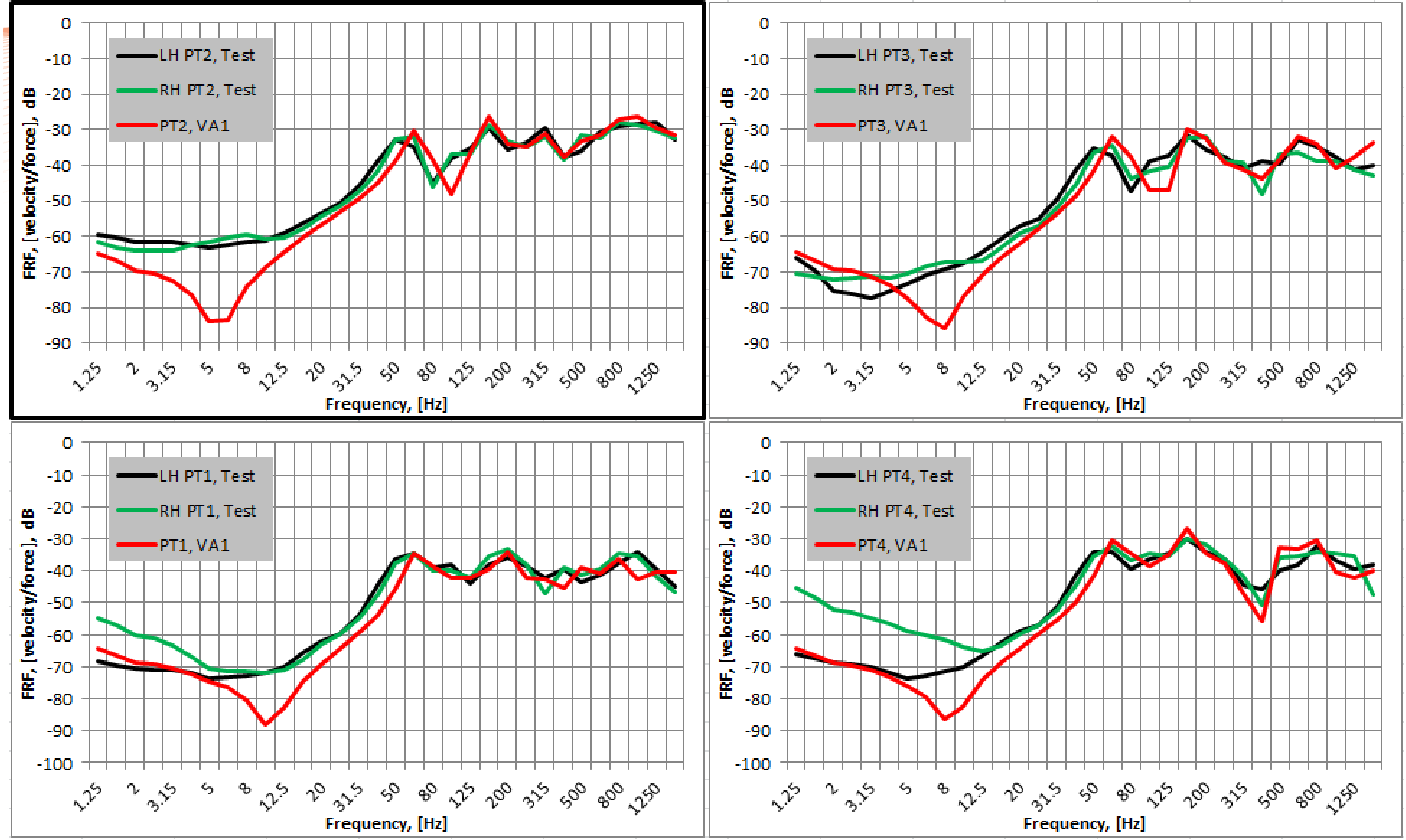

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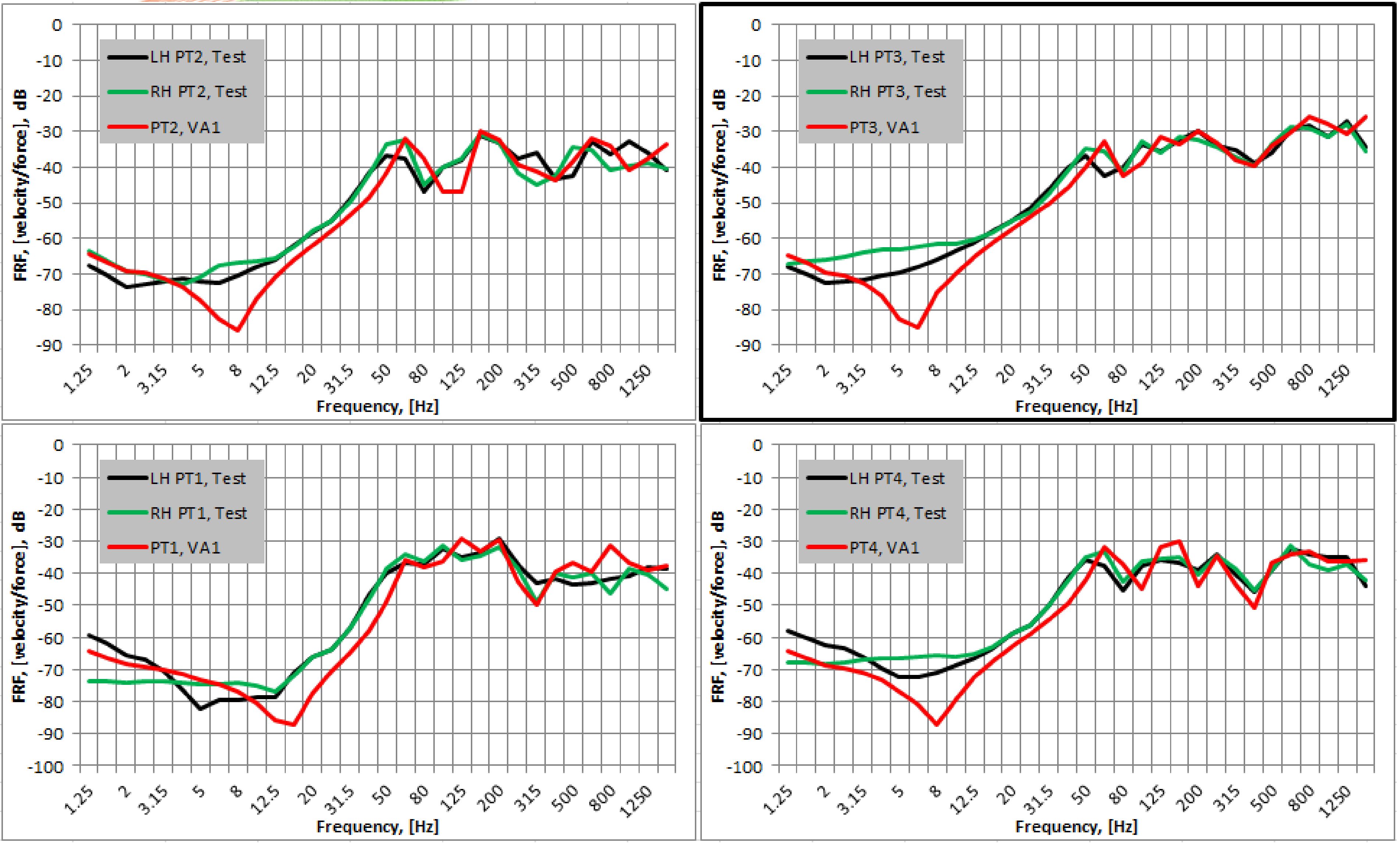

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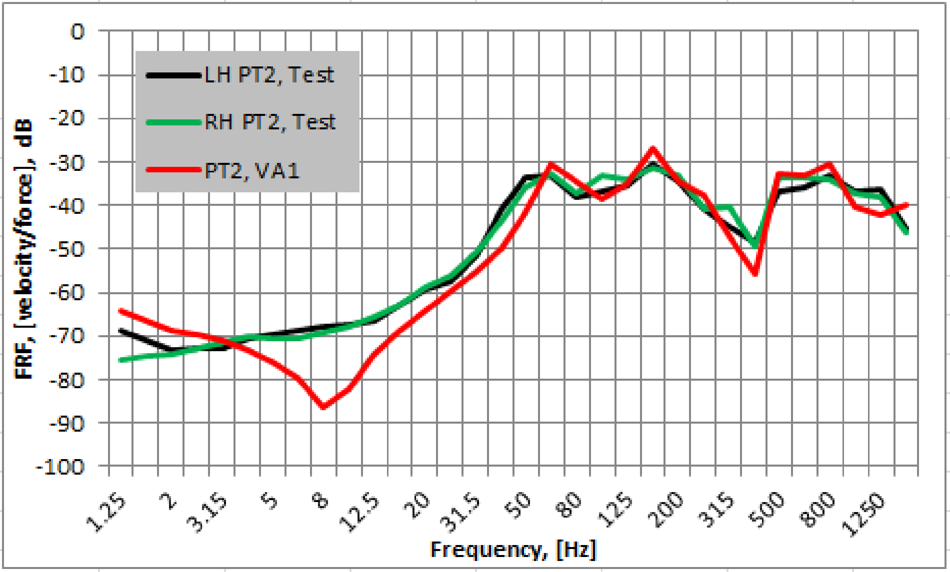
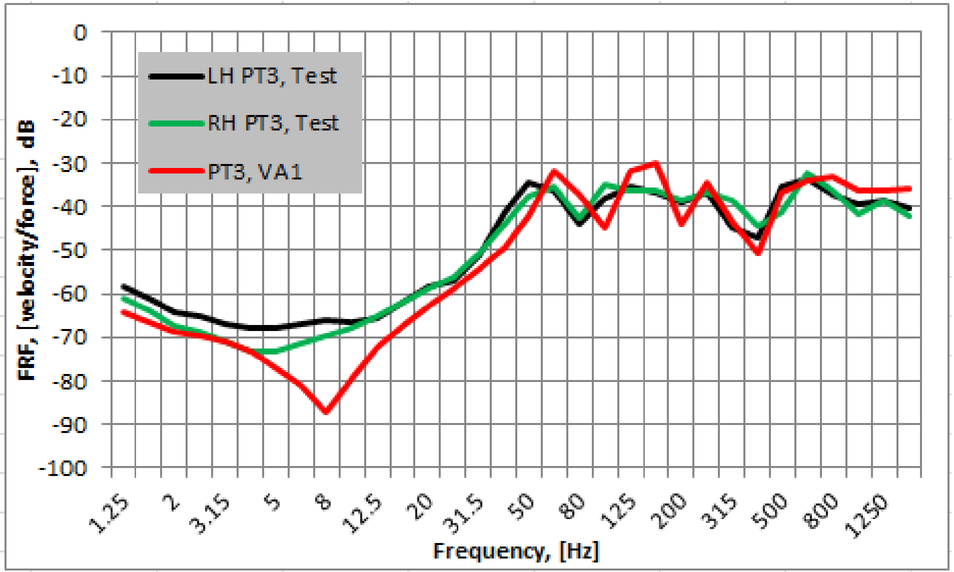
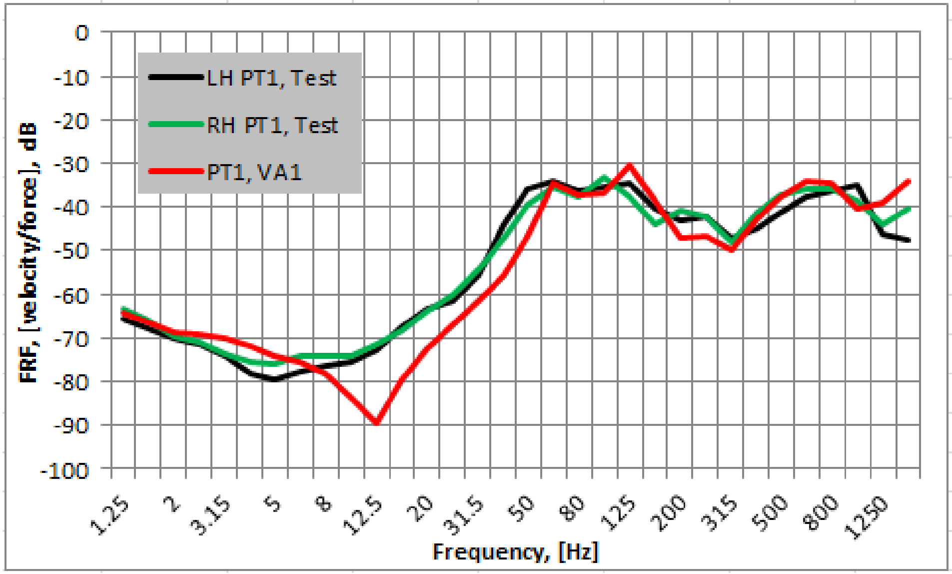
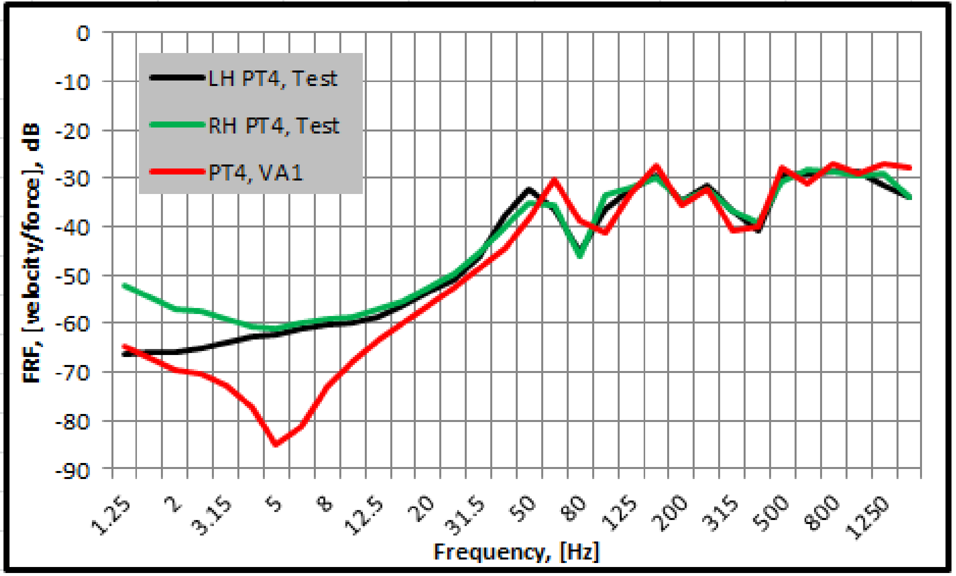
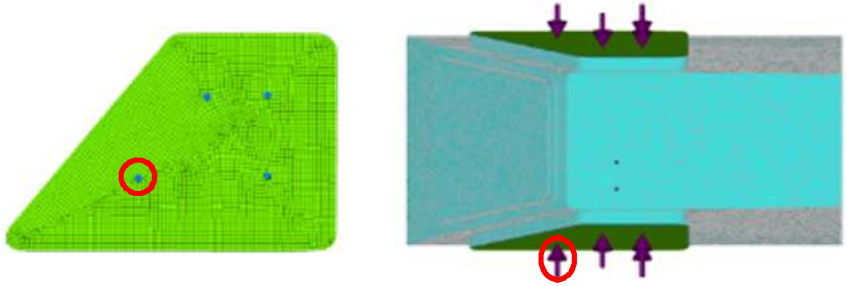




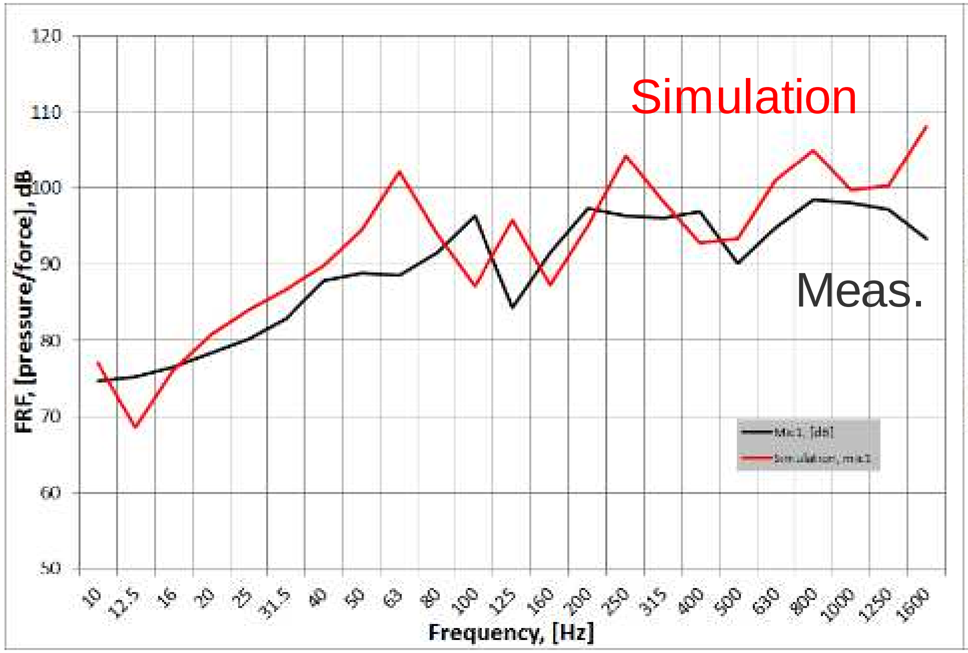




FRF from glass to microphones (1/3rd octave band)



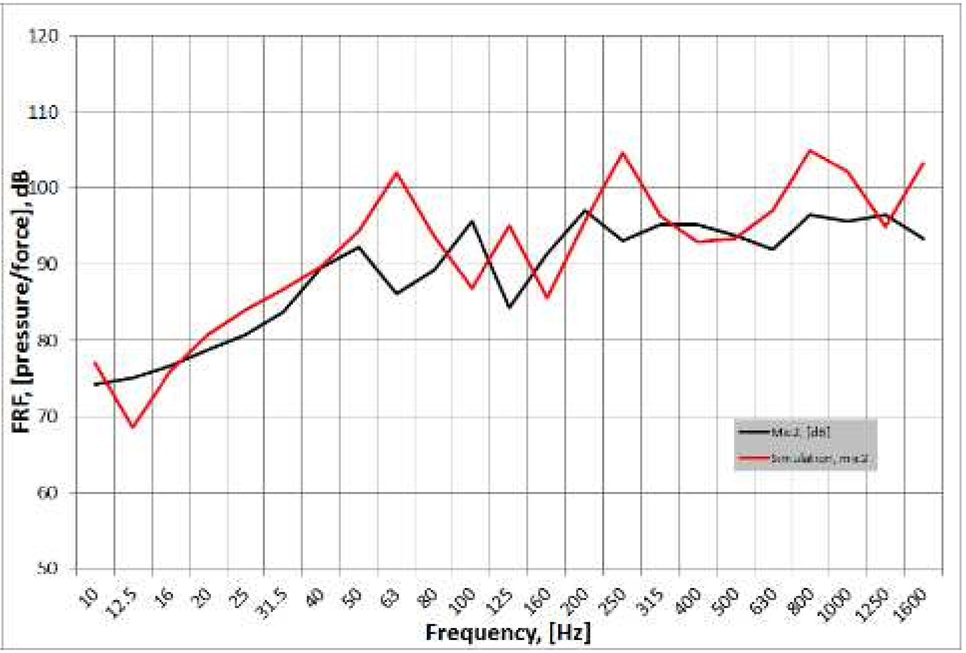
Mic 1



Simulation

Meas.

Mic 2



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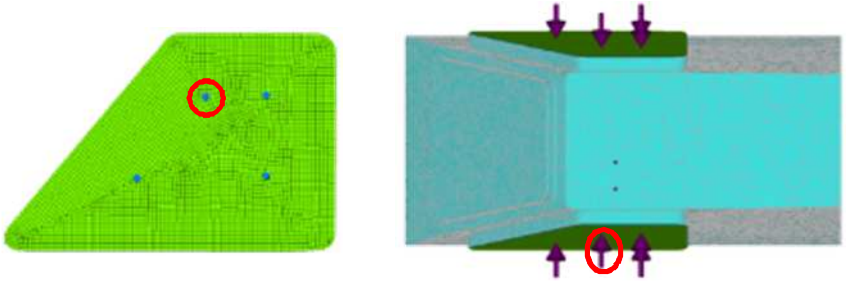

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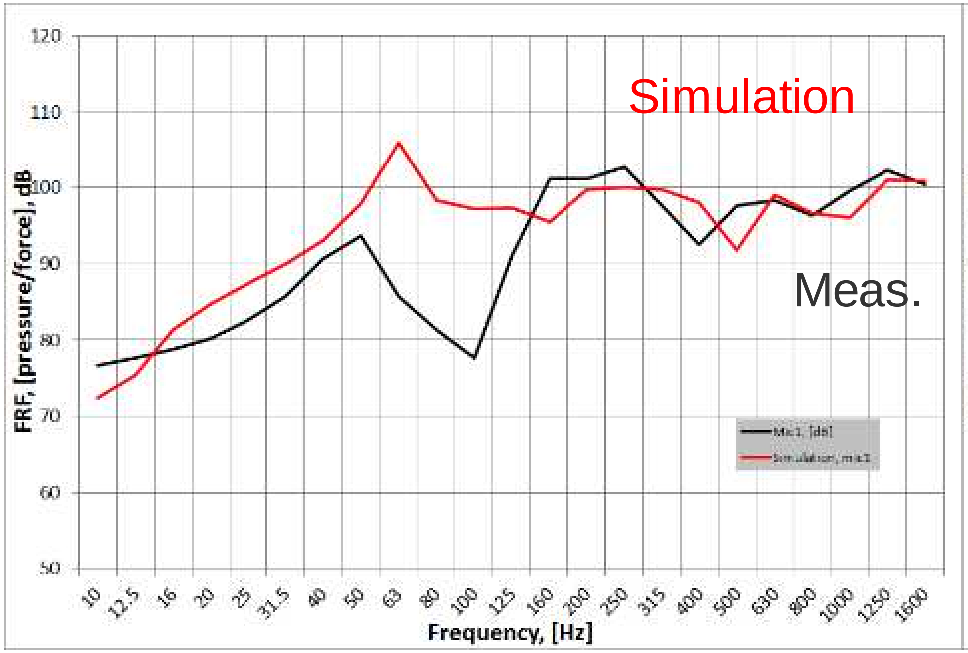
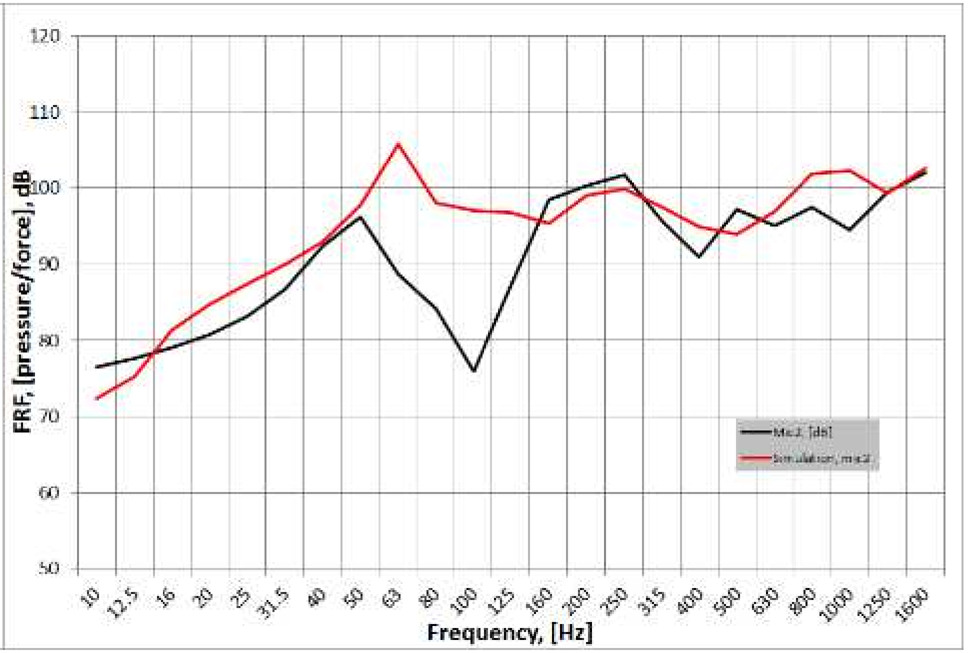


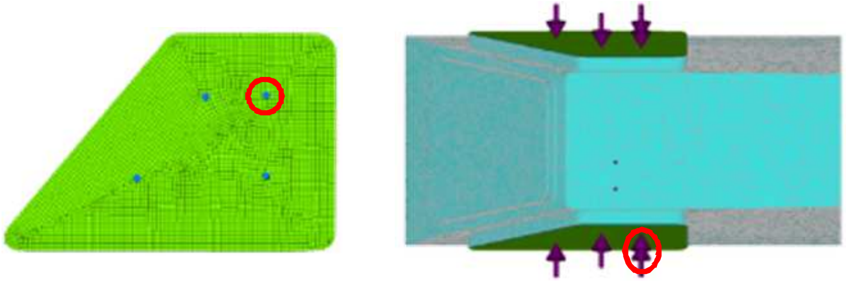
Simulation

Meas.

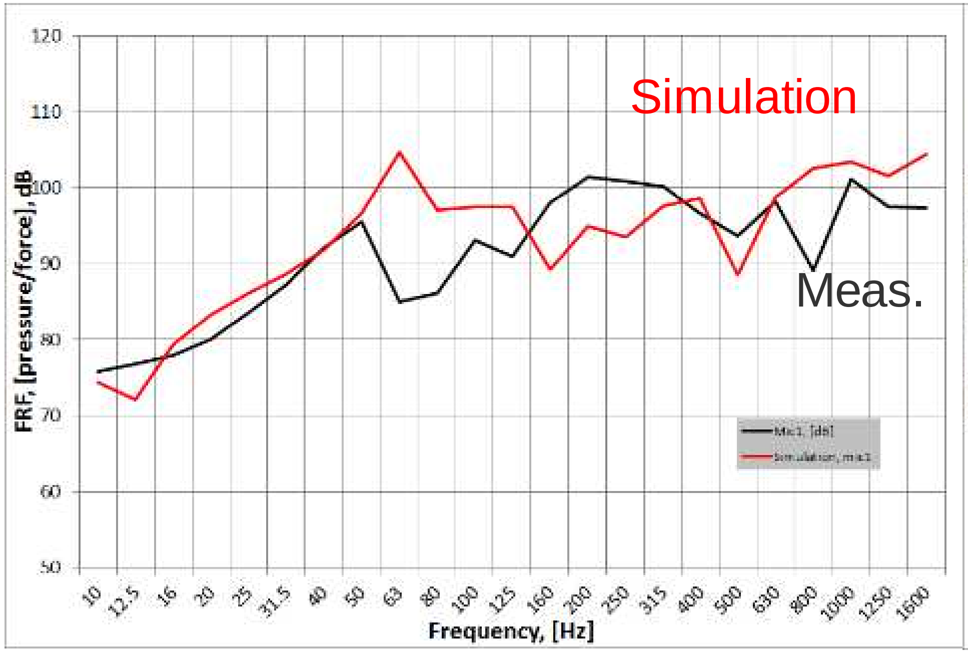
Mic 2



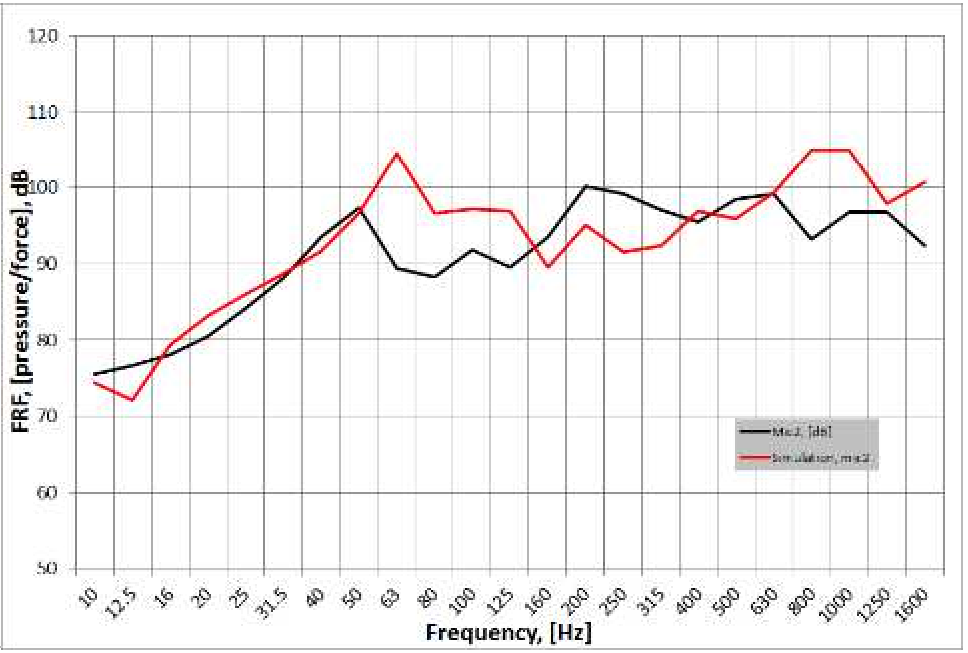
FRF from glass to microphones (1/3rd octave band)



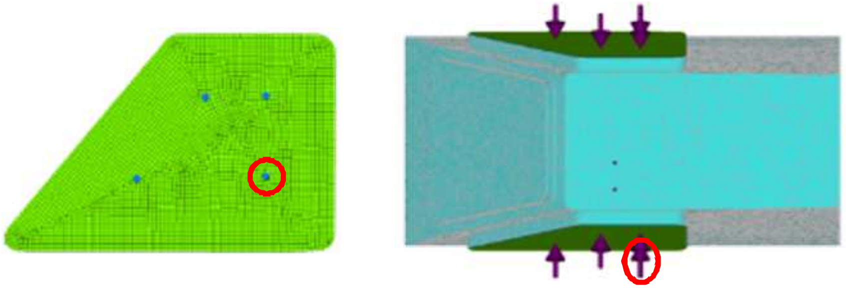
Mic 1



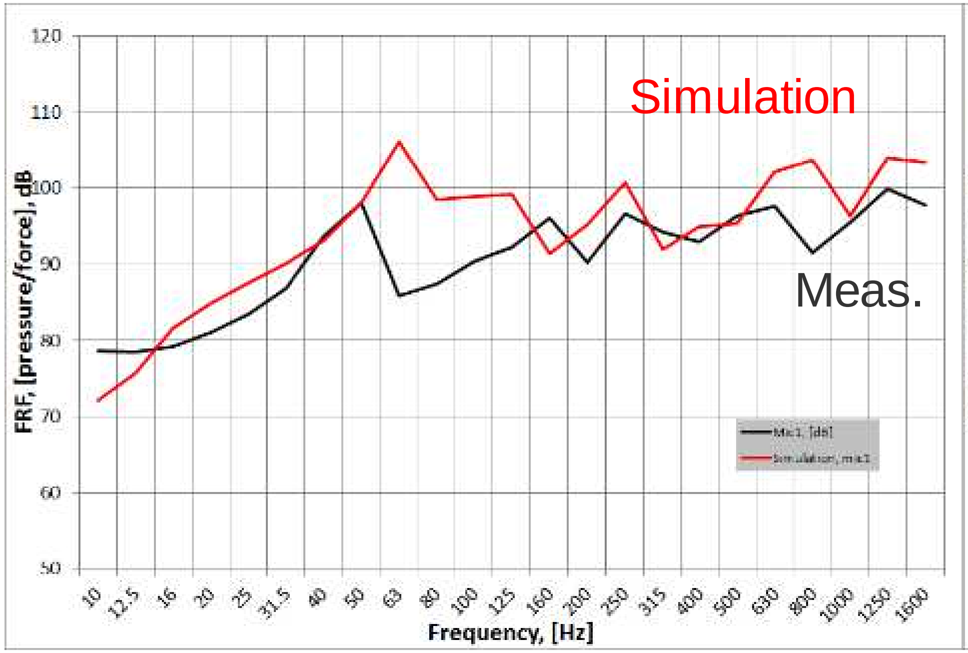
Mic 2



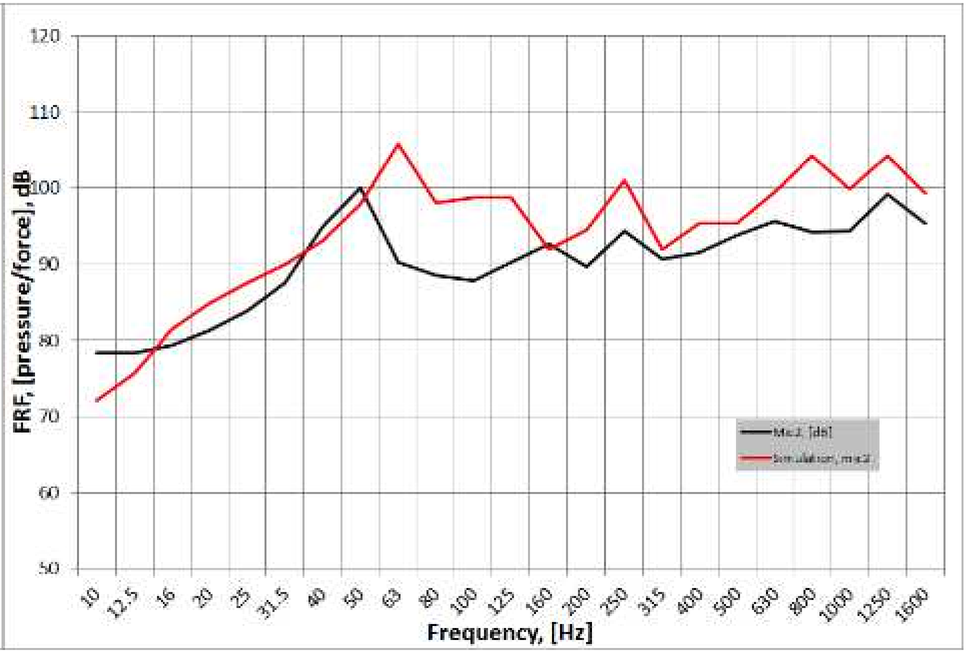
FRF from glass to microphones (1/3rd octave band)



Mic 1



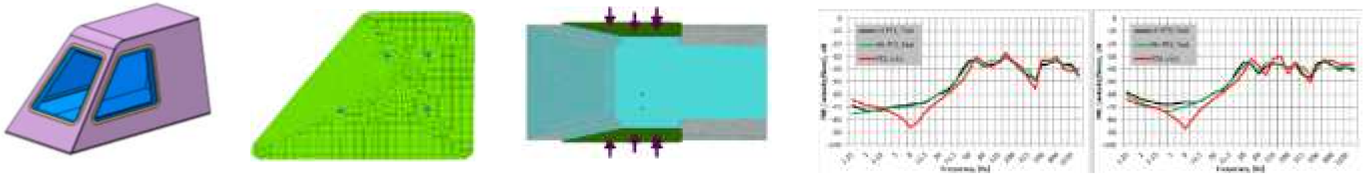
Mic 2



Outline

Overview of available approaches

Validation of Vibro-Acoustic models

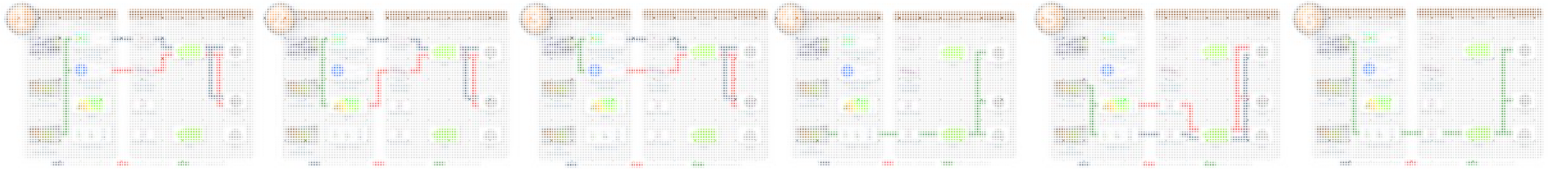


Validation of aero-vibro-acoustic (AVA) models

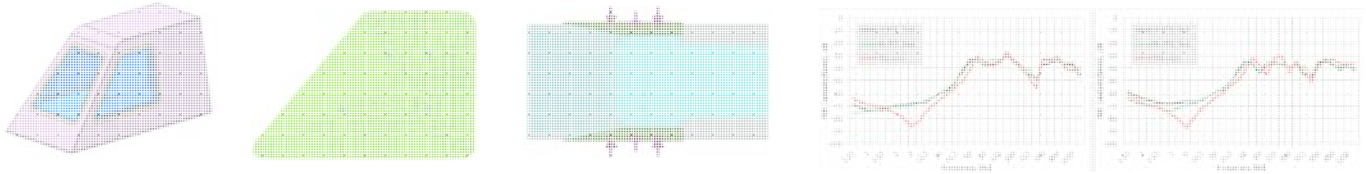
Conclusions

Outline

Overview of available approaches



Validation of Vibro-Acoustic models



Validation of aero-vibro-acoustic (AVA) models

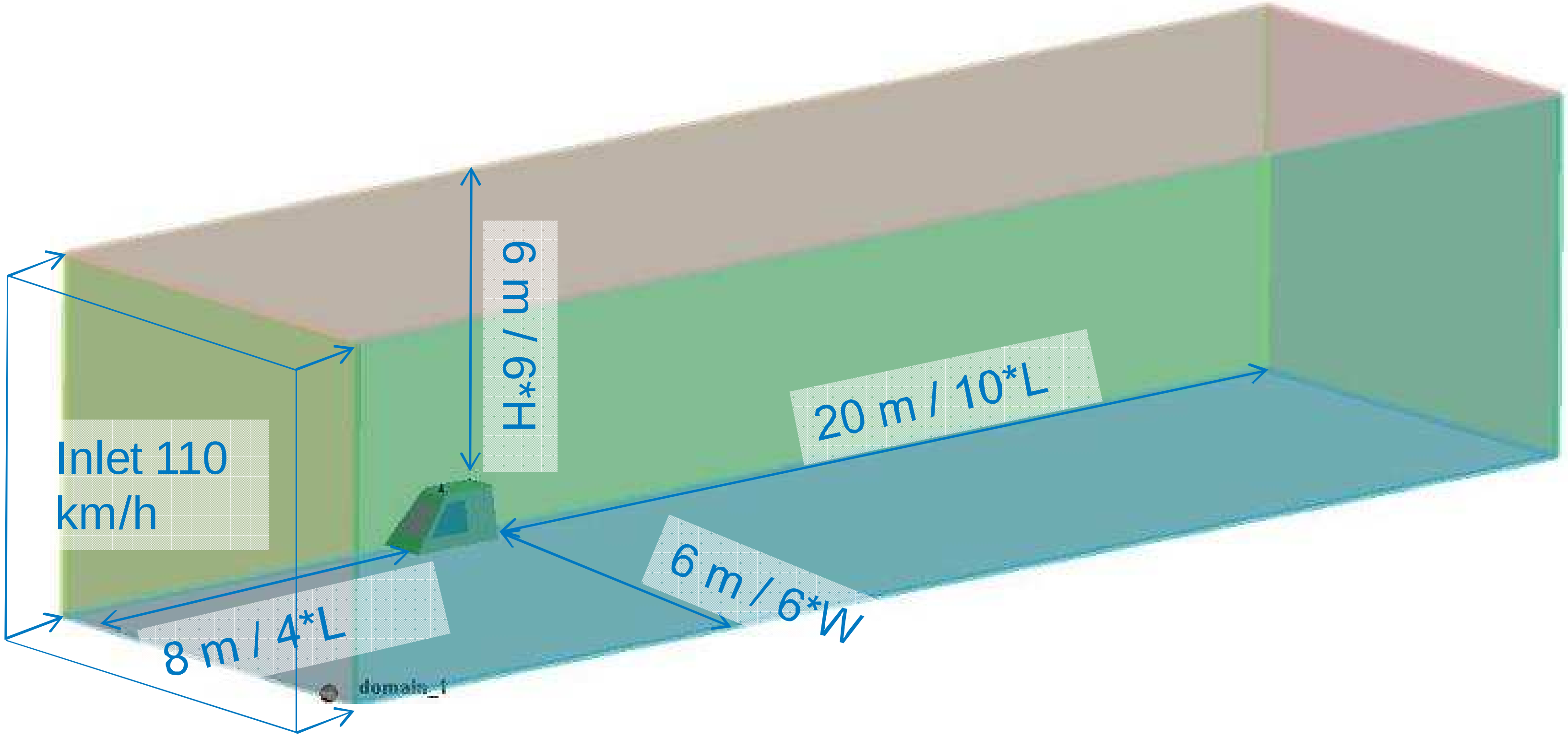
Conclusions

Steps for CFD simulation

- Meshing (snappyHexMesh)
  - Few design iterations are required to ensure flow will be captured in all relevant areas.
- Steady state incompressible simulation (simpleFoam), to have meaningful flow conditions at the start of the transient, and reduce the ramp-up effects.
- Transient incompressible simulation (pimpleFoam, IDDES):
  - Max courant number of around 1.5 .
  - Initially, the wall pressure data is not saved as the turbulent flow needs stabilising.
  - After some time, wall pressure data on side window and Apillar is saved and exported to VAOne.
  - This is the most time consuming part as requires a few days to run.
- Simulation done in Rescale (www.rescale.com), with 128 CPUs.

Model definition
Windtunnel

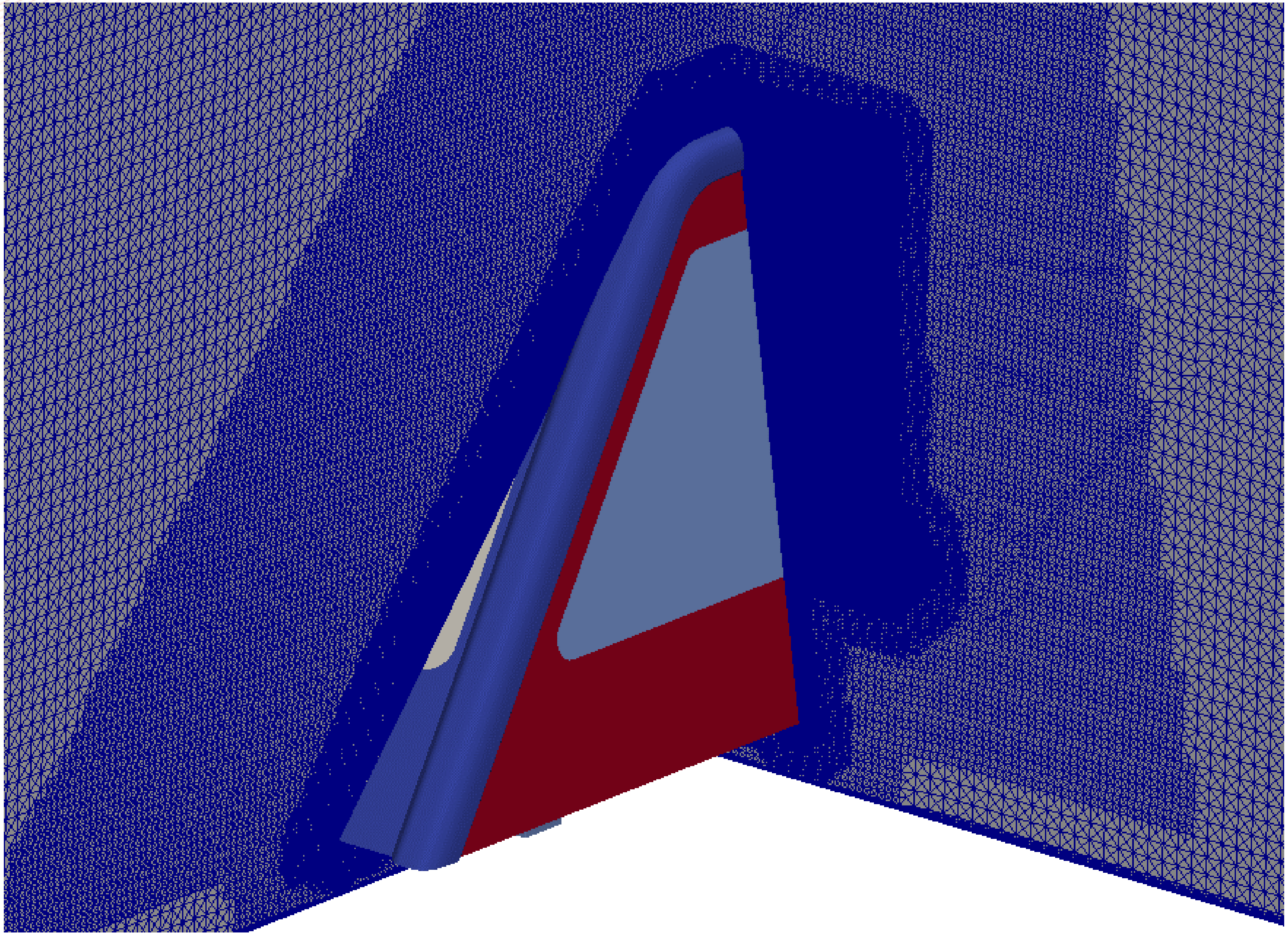
All the boundary conditions were set far away from the car, so that they did not conditioned the results in the areas of interest.



Model definition
Mesh

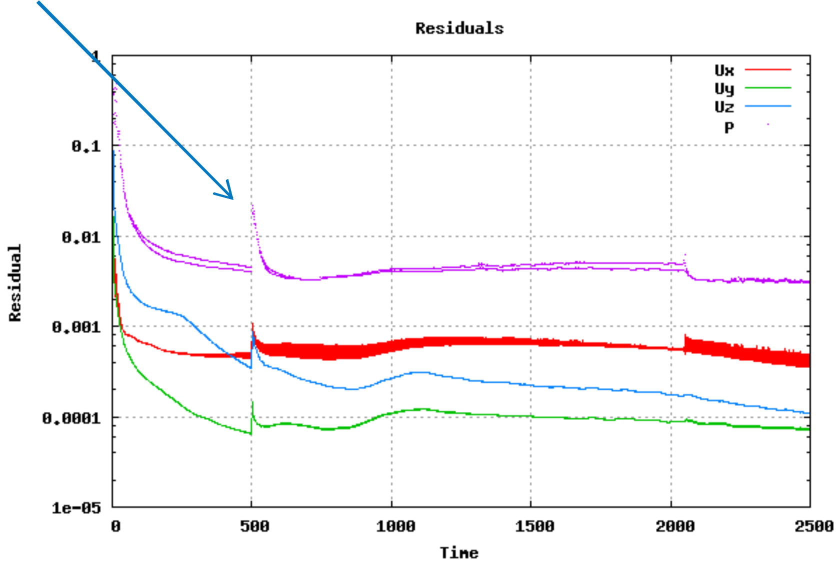
- Only the –Y (LH) portion of the model was simulated in the CFD process.
  - Plane at Y=0 m defined as symmetry Plane for all cases.
- Mesh size around A-Pillar, side window is 2 mm.
  - Refinements restricted to areas of interest.
  - 7 prism layers to improve the flow prediction in the boundary layer.
  - Final cell count 58 Million cells, mostly hexaedral.
- Meshed using blockMesh+snappyHexMesh approach.
  - Maximum non-orthogonality below 65 deg.

Model definition
Mesh



Model definition simpleFoam

- Steady state incompressible simulation done with simpleFoam in 2 steps:
  - First few hundred iterations done in first oder, for better numerical stability (20% of the simulation length).
  - Switch to second order in all equations to complete the remaining 80% of simulation length.



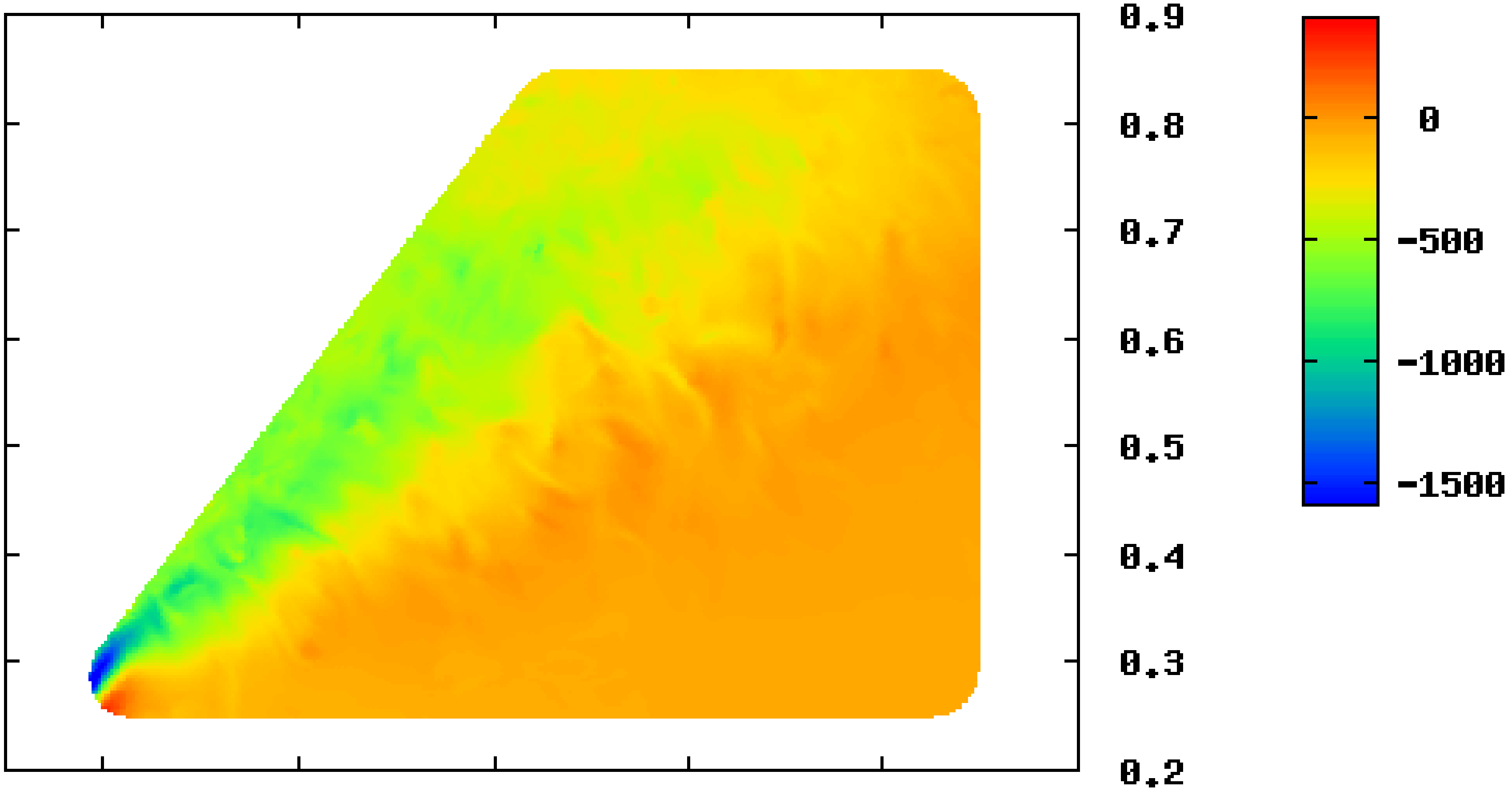
  - OpenFOAM v2.3.0 was used.

Model definition
pimpleFoam

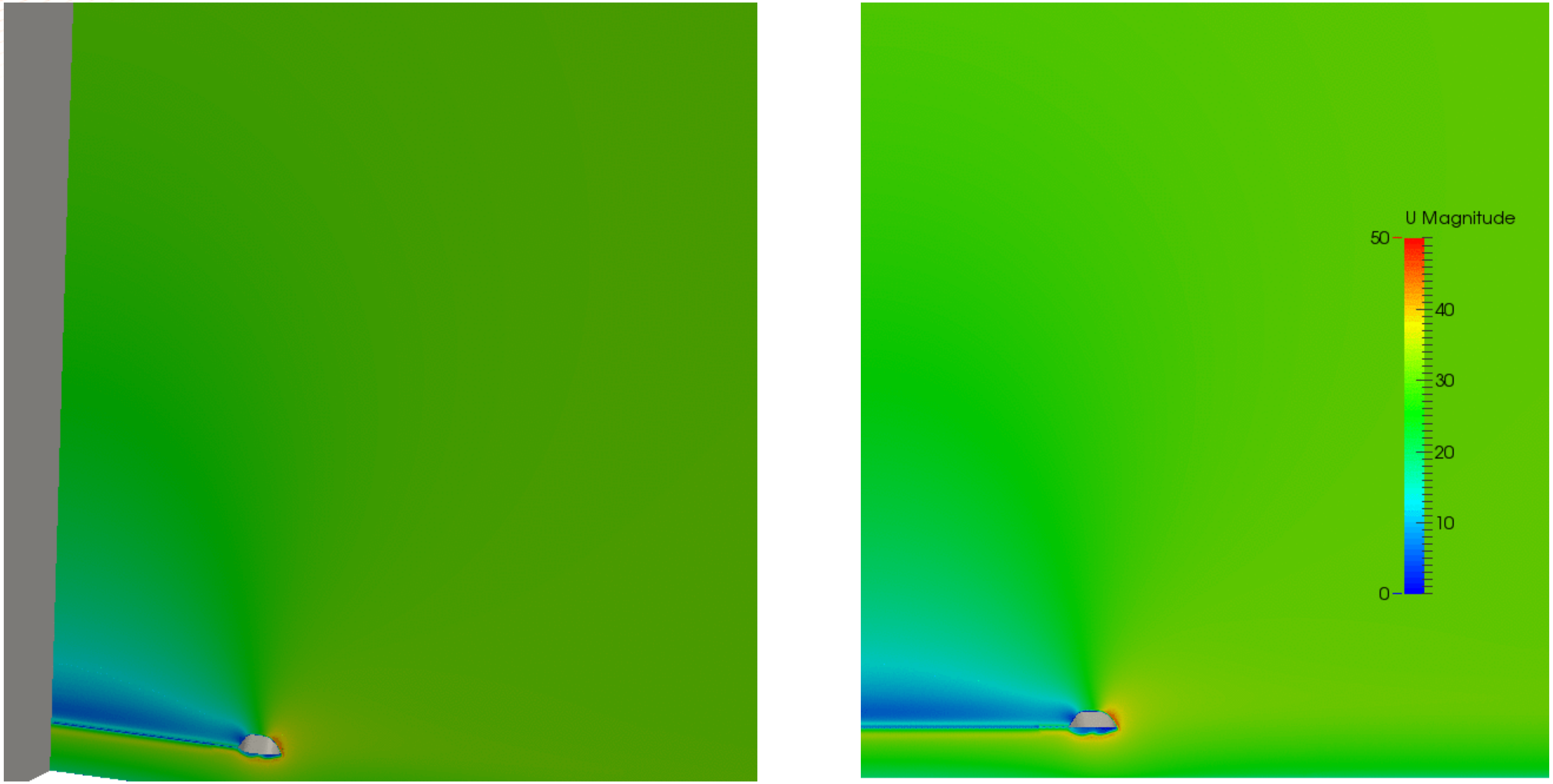
- Transient incompressible simulation done with pimpleFoam:
  - Simulation done in Rescale (www.rescale.com), with 128 CPUs.
  - Turbulence model Spalart-Allmaras IDDES.
  - Timestep in the range of 1e-5 s, producing a maximum CFL (Courant) number of around 1.5.
  - All variables calculated as second order.
  - First few hundreths of second were ignored for wall pressure result, to allow the eddies to generate and travel downstream
  - Once the flow conditions stabilised (approx 0.1s), wall pressure data was recorded.

  - OpenFOAM v2.3.0 was used.

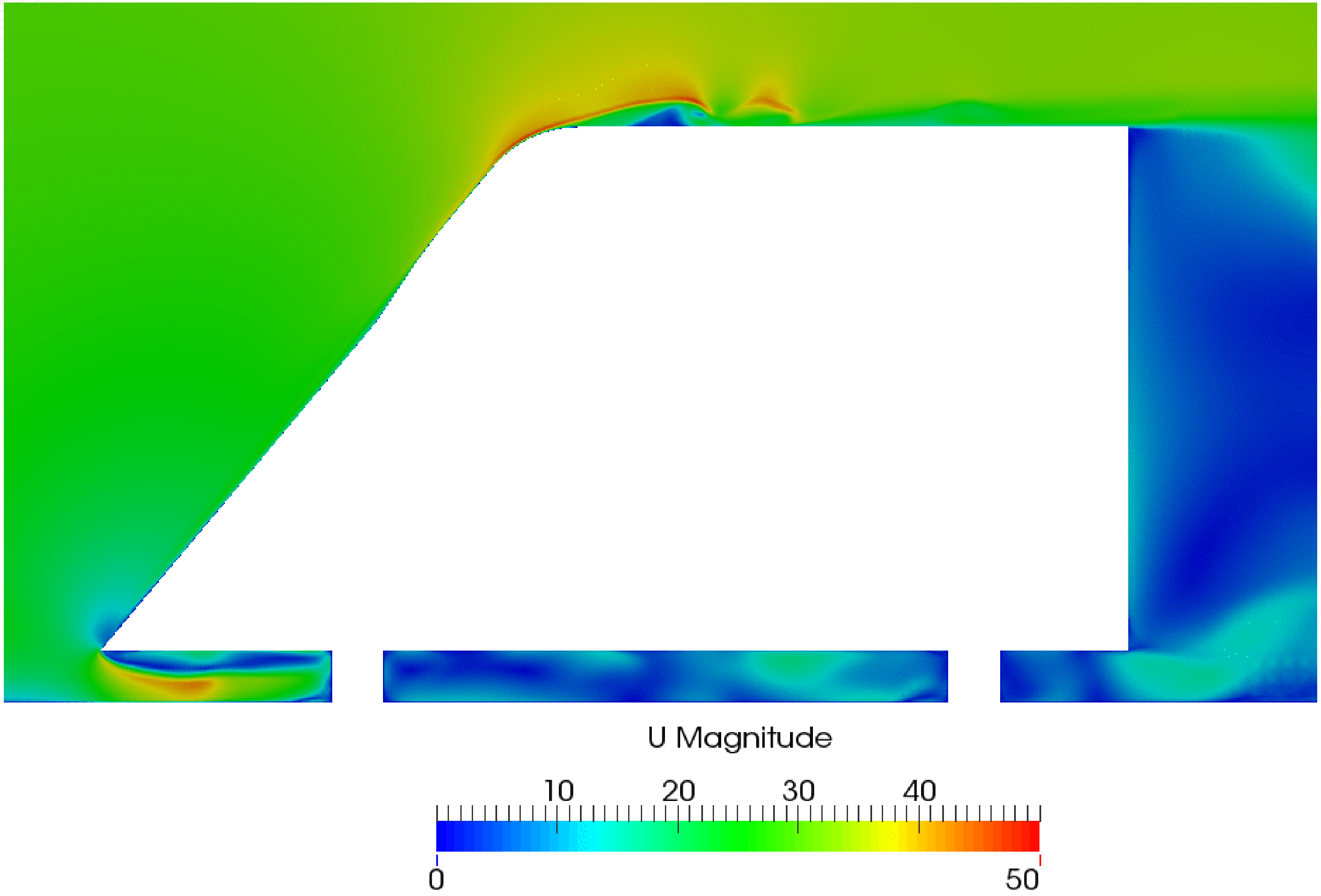
Results
Pressure on side window



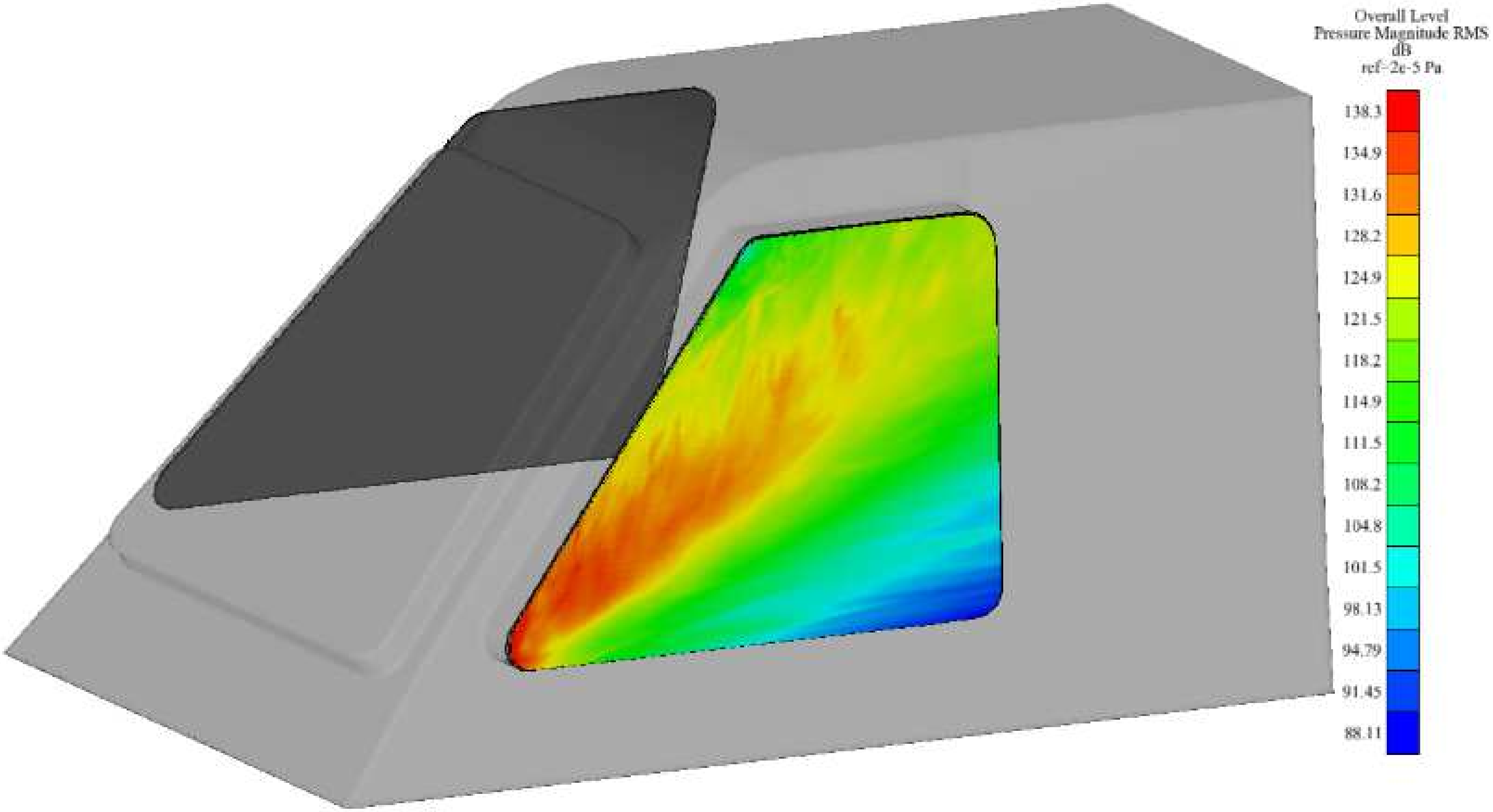
Results
pimpleFoam, flow at time 0.2 s



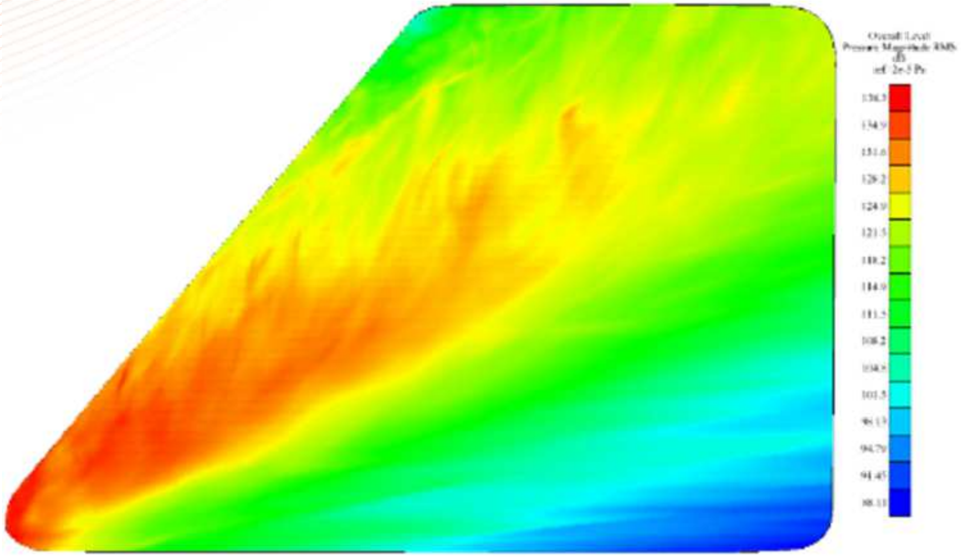
Results
pimpleFoam, velocity at Y=-0.30 m

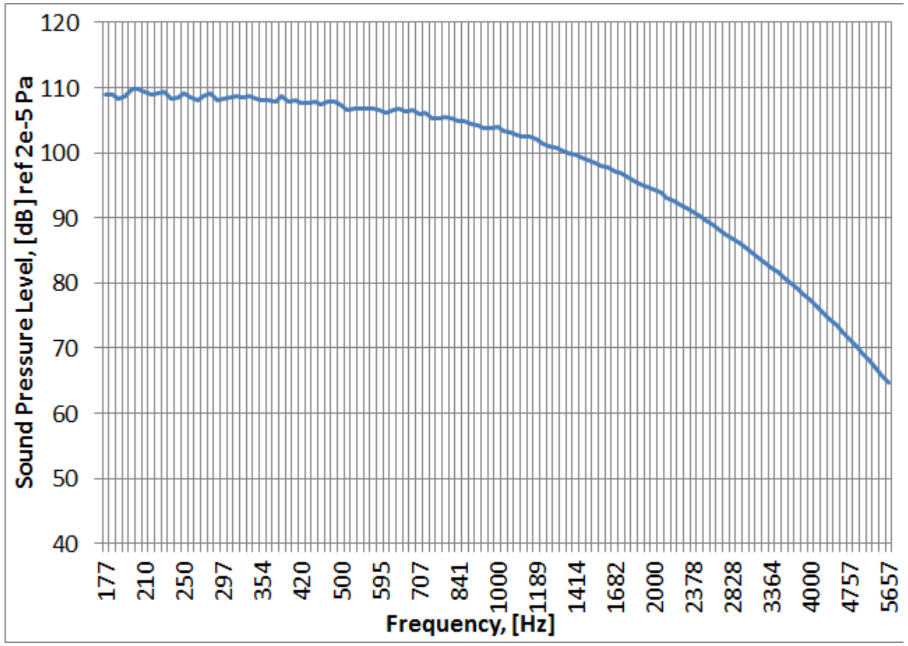


Aero-Vibro-Acoustic model



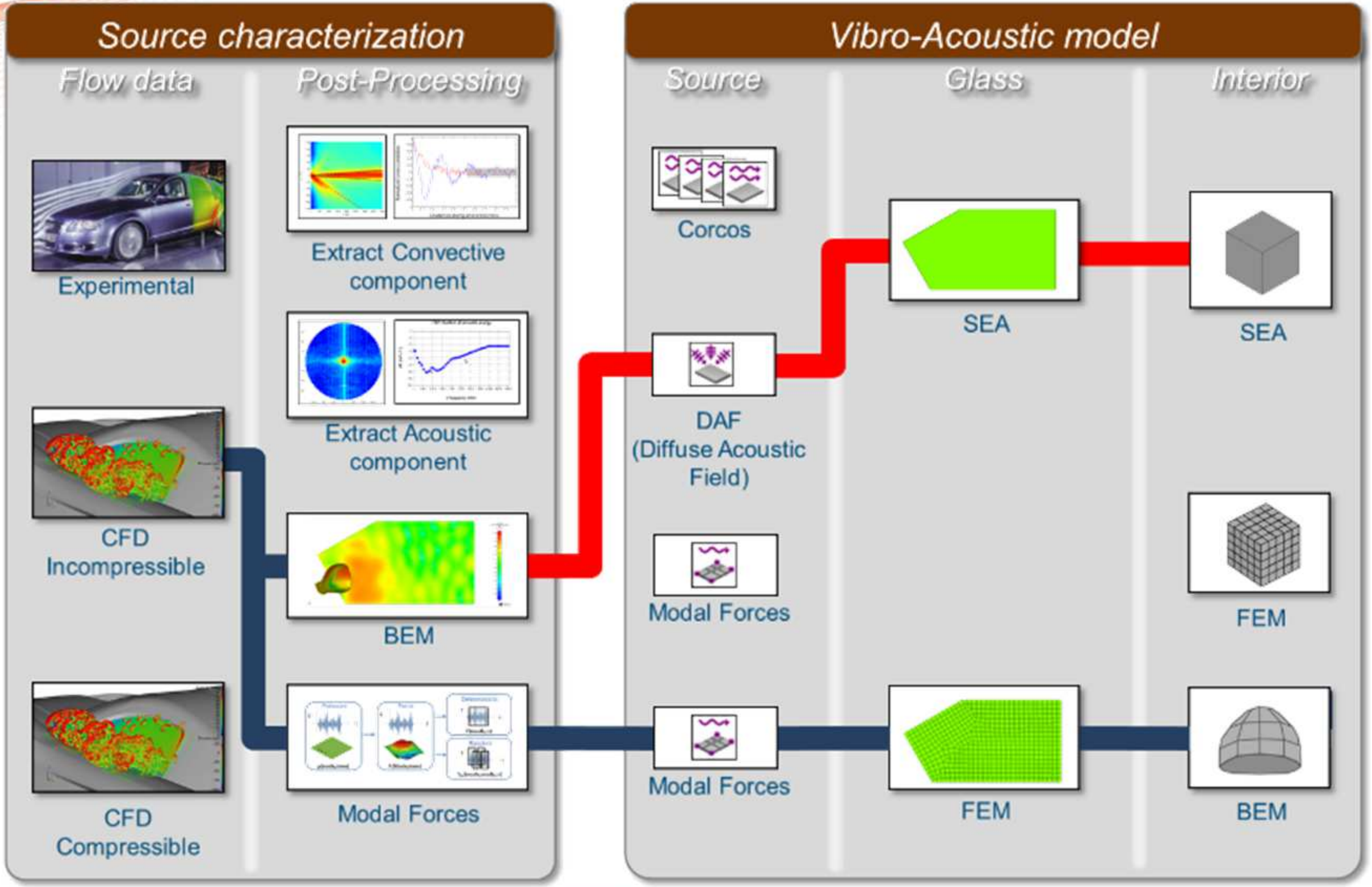
Aero-Vibro-Acoustic model





- Surface pressure from CFD simulation is mapped to the FE mesh with element size 2.11 mm.
- Mean pressure removed to keep only fluctuating surface pressure
- Hann window is applied for FFT

Methods used



Source characterization

Flow data

- Experimental
- CFD Incompressible
- CFD Compressible

Post-Processing

- Extract Convective component
- Extract Acoustic component
- BEM
- Modal Forces

Vibro-Acoustic model

Source

- Corcos
- DAF (Diffuse Acoustic Field)
- Modal Forces
- Modal Forces

Glass

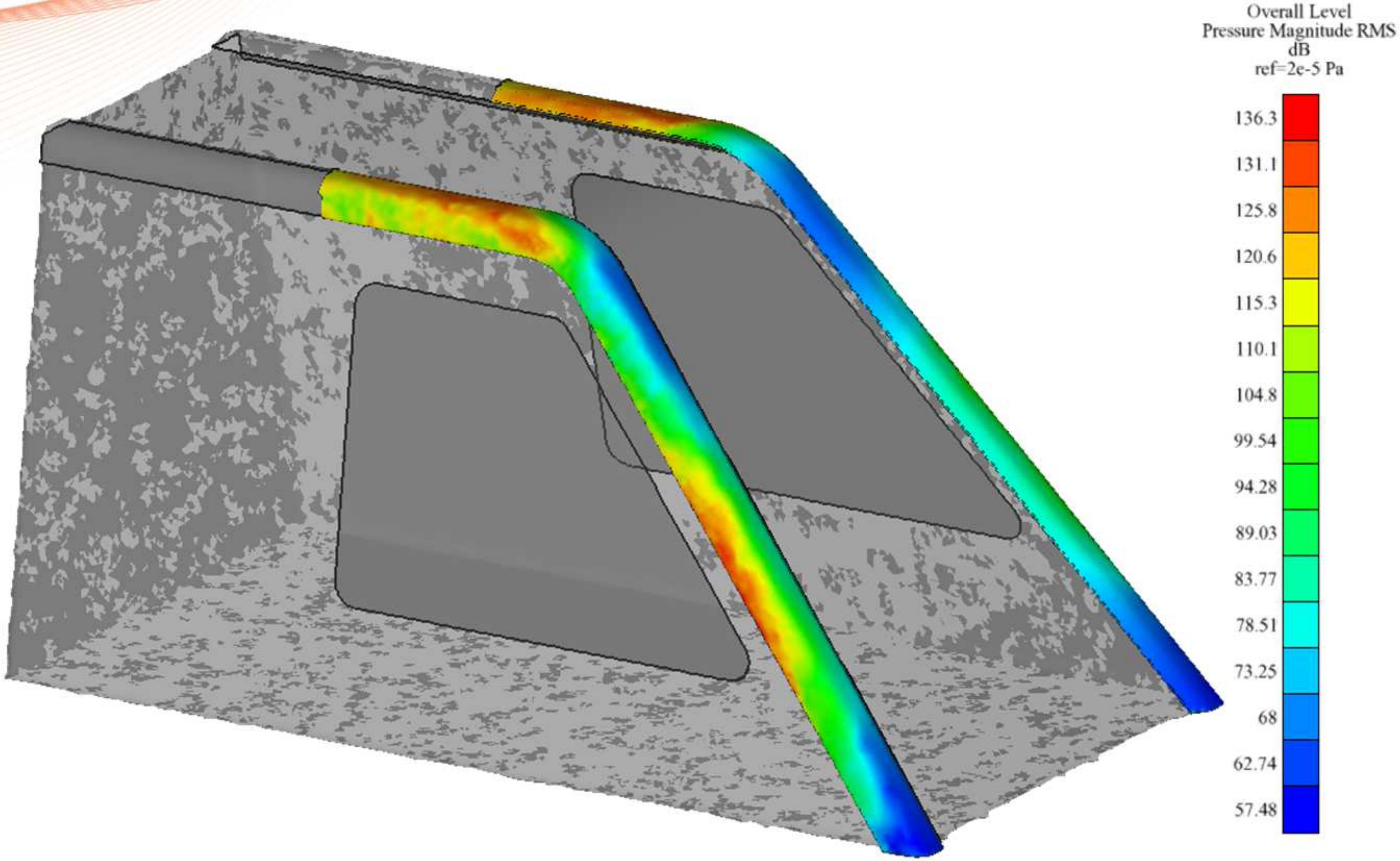
- SEA
- FEM

Interior

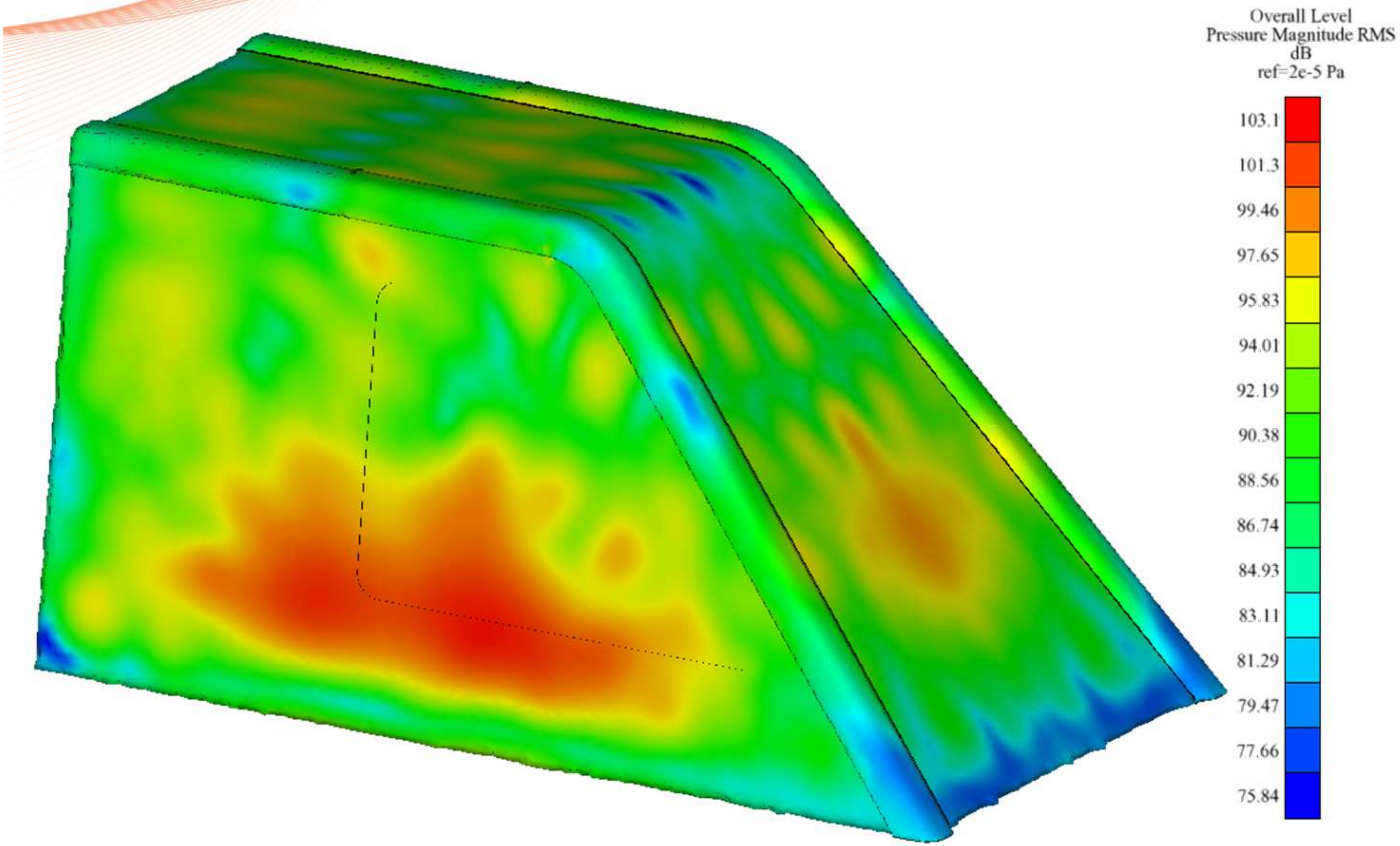
- SEA
- FEM
- BEM

🟦 Convective component 🟥 Acoustic component 🟩 Both components

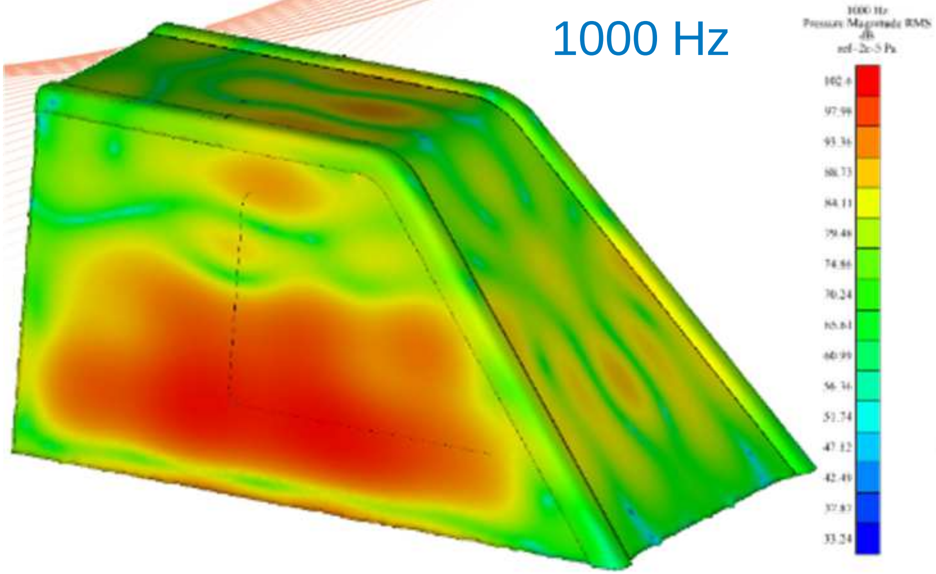
CFD Surface pressure imported on Apillar

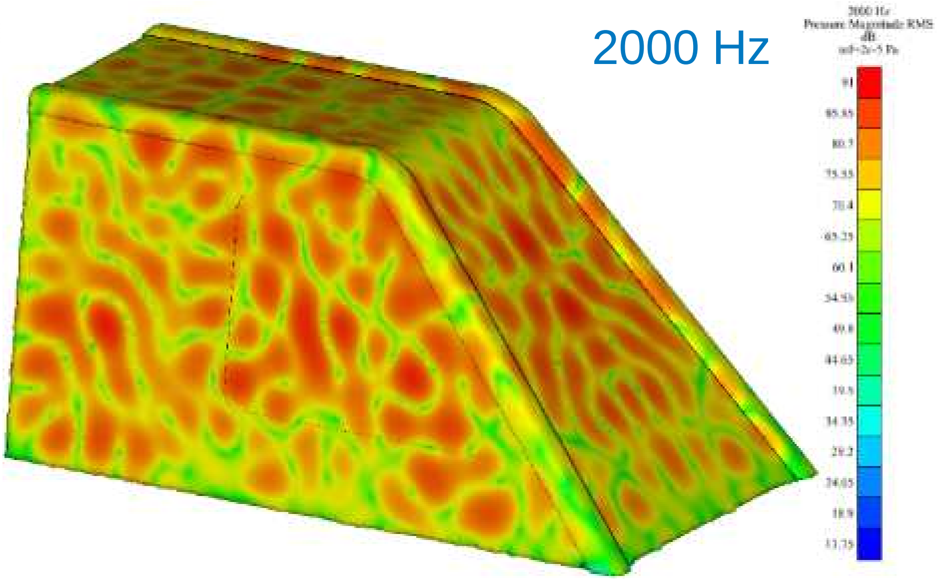


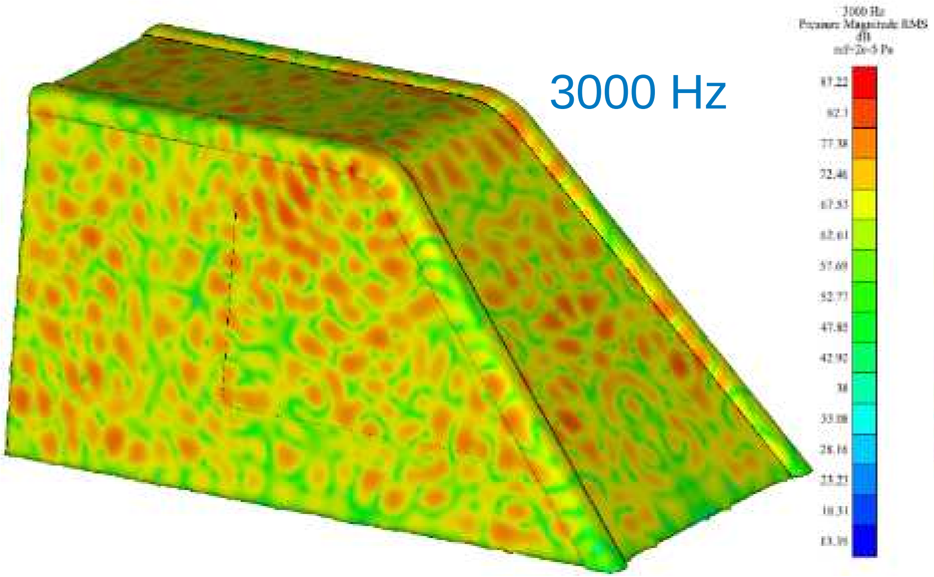
Acoustic pressure

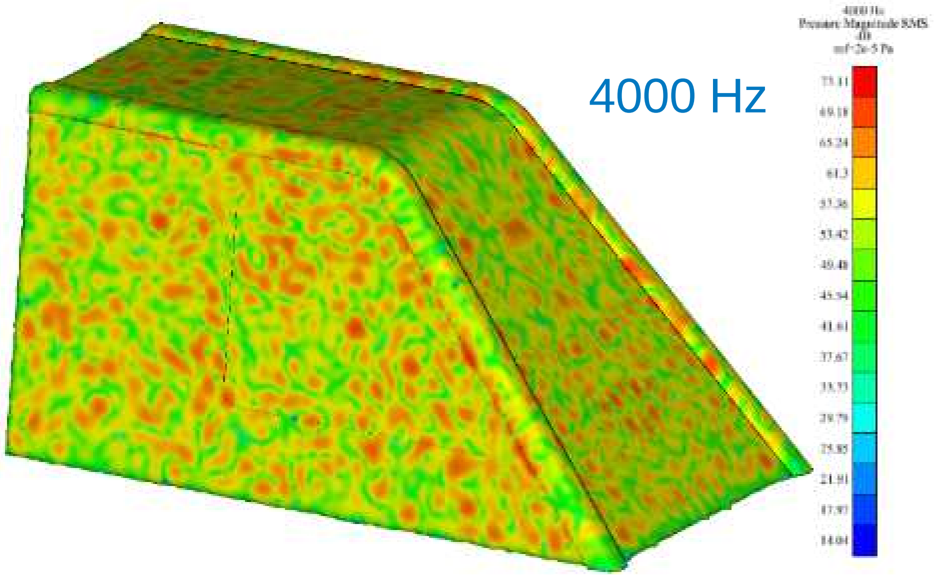


Acoustic pressure

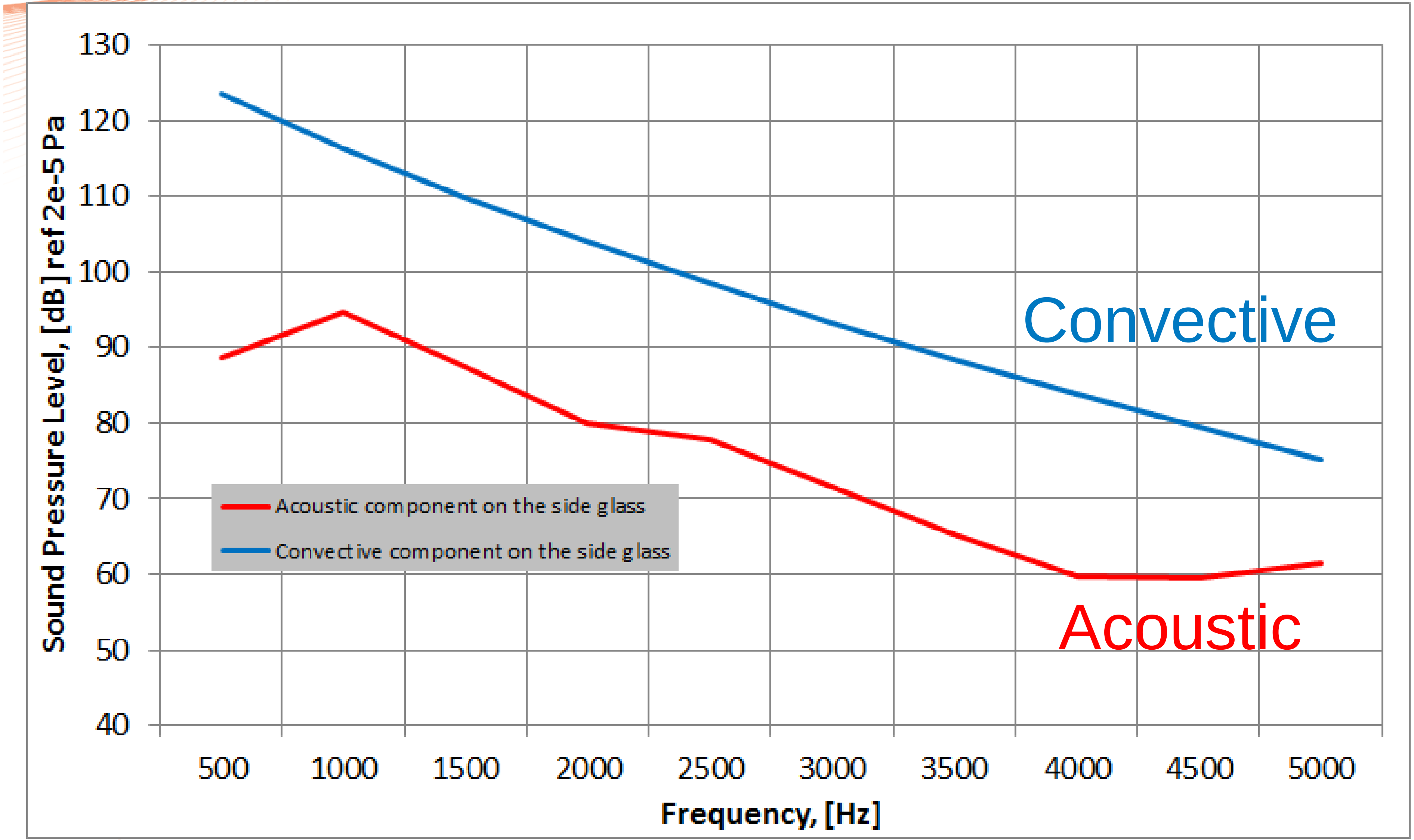

1000 Hz


2000 Hz


3000 Hz


4000 Hz

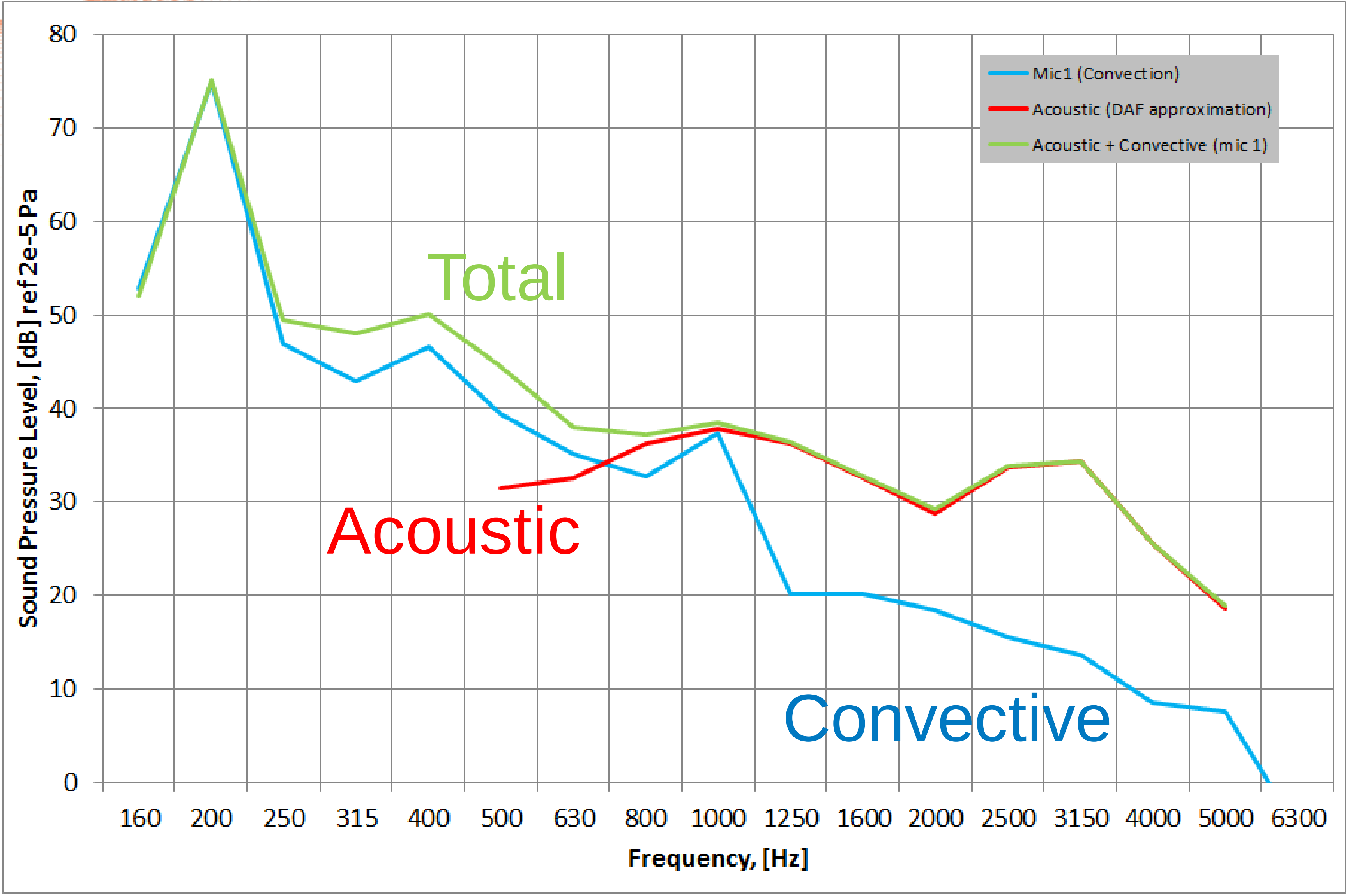
Acoustic and convective components on the side glass



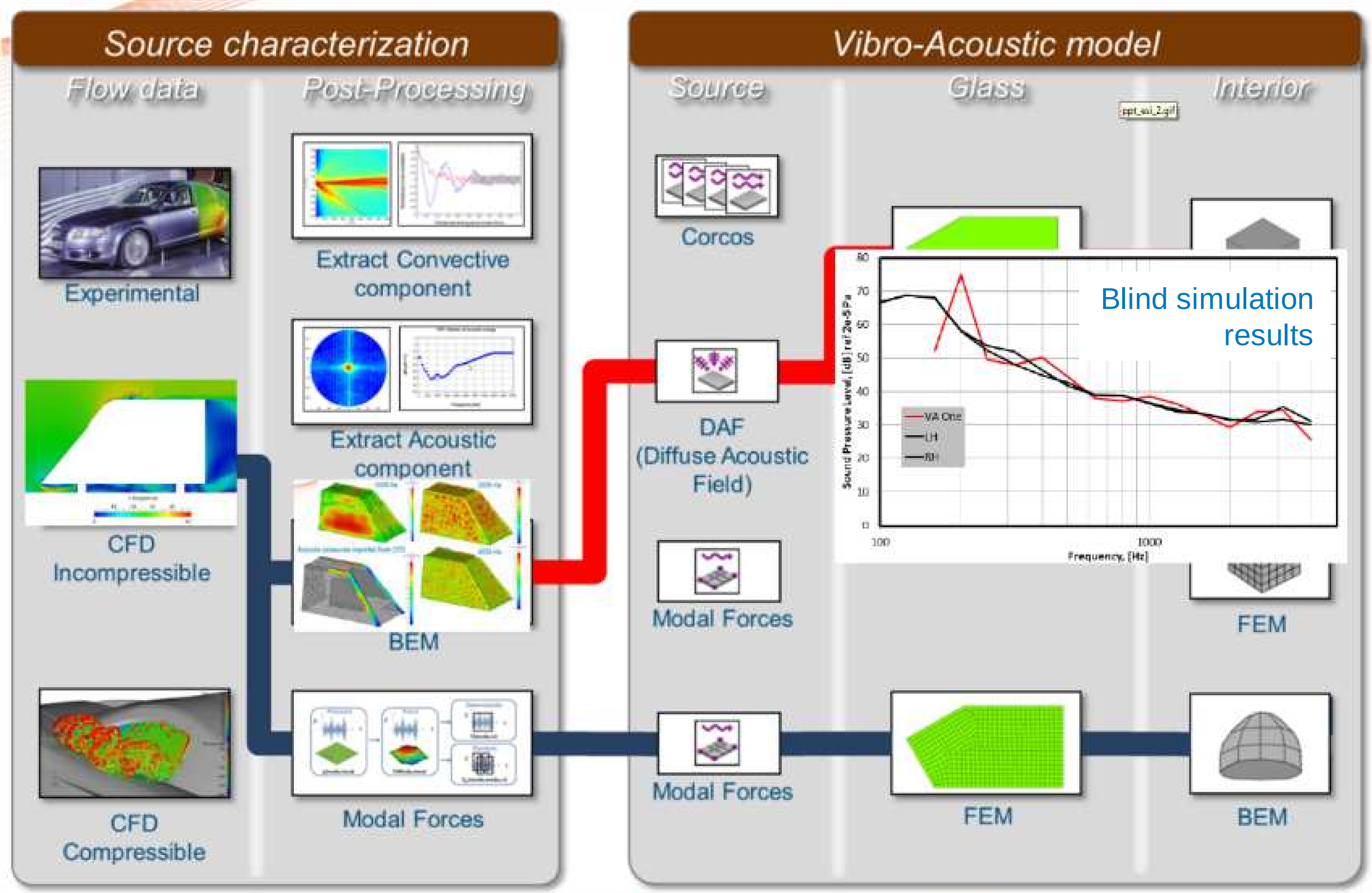
SEA Model for acoustic contribution

- The average pressure on side glass obtained from exterior BEM is used in DAF
- SIF (Semi-Infinite Fluid) is located at LH mic
- Side Glass is represented with SEA

Interior SPL
Convective and acoustic contribution



AVA Methodologies



Source characterization

Flow data

Experimental

CFD
Incompressible

CFD
Compressible

Post-Processing

Extract Convective
component

Extract Acoustic
component

BEM

Modal Forces

Vibro-Acoustic model

Source

Corcos

DAF
(Diffuse Acoustic
Field)

Modal Forces

Modal Forces

Glass

FEM

Interior

FEM

BEM

Blind simulation
results

🟦 Convective component 🟥 Acoustic component 🟩 Both components

Notes on results

- Very preliminary results
- CFD
  - Computation should be ran for a longer period, idealy 0.5 seconds to ensure convergence
  - Final results should be lower for both convective and acoustic component
- VA
  - Model should be fully computed with BEM for best accuracy
  - SEA could be used to represent interior cavity in combination with FE glass

Outline

Overview of available approaches

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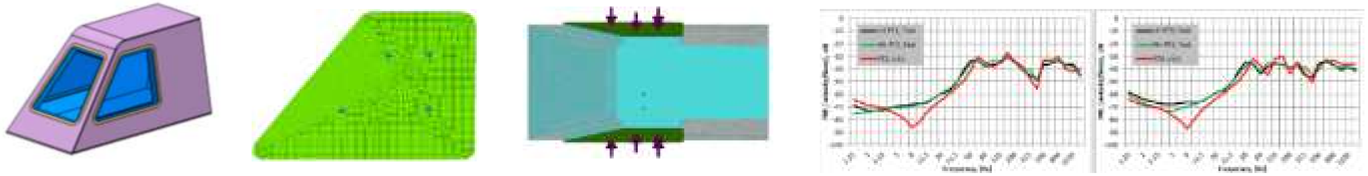

Validation of aero-vibro-acoustic (AVA) models

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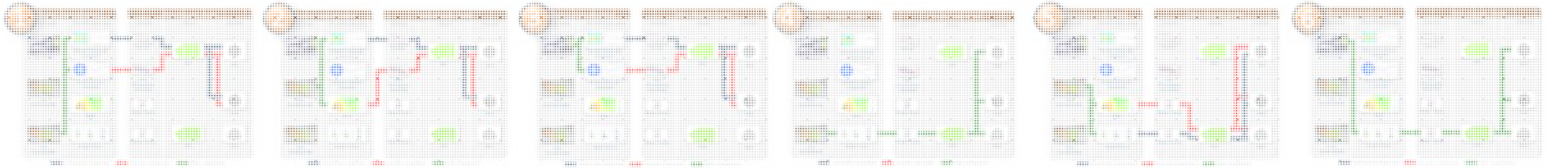
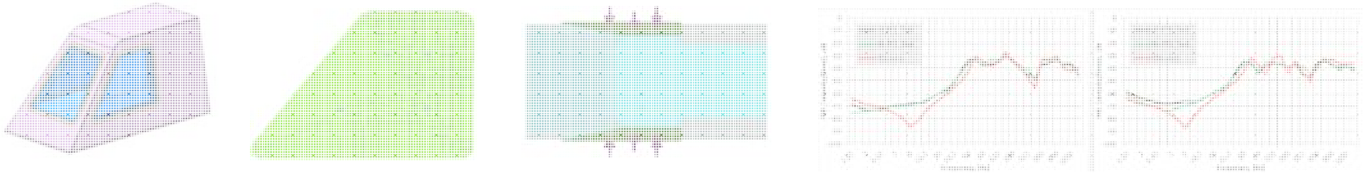


Validation of Vibro-Acoustic models



Validation of aero-vibro-acoustic (AVA) models

Conclusions

Conclusion

- The BMT4 benchmark baseline has been studied
- Due to computer ressources and engineering time availability, a CFD compressible simulation was performed instead of the planned compressible run
- A vibro-acoustic model has been coarsely validated and a combination of BEM, FEM and SEA were used to generate results in time for this conference
- Initial results show typical trend but are overestimated
- On-going activity should yield highly accurate results in the near futur based on other project success

Thank you