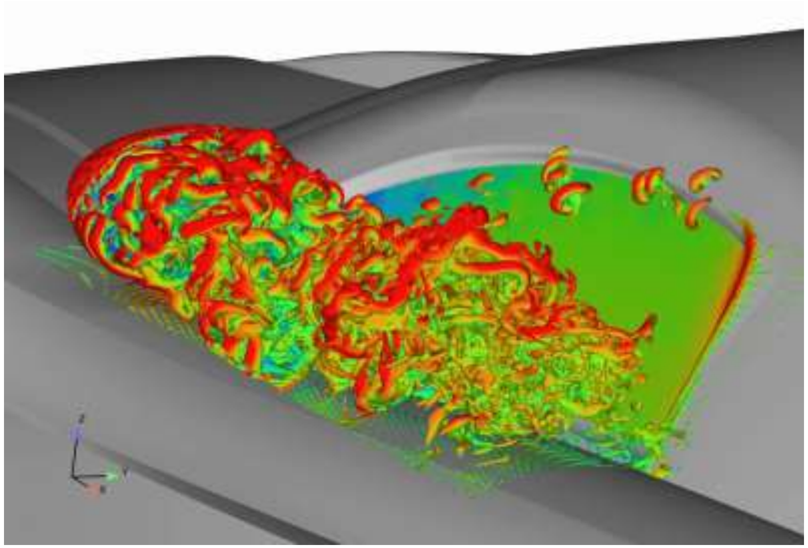
On the use of Full-Frequency Vibro-Acoustic models for windnoise predictions

Denis Blanchet
Anton Golota
Nov 16 2013

www.esi-group.com

The challenge

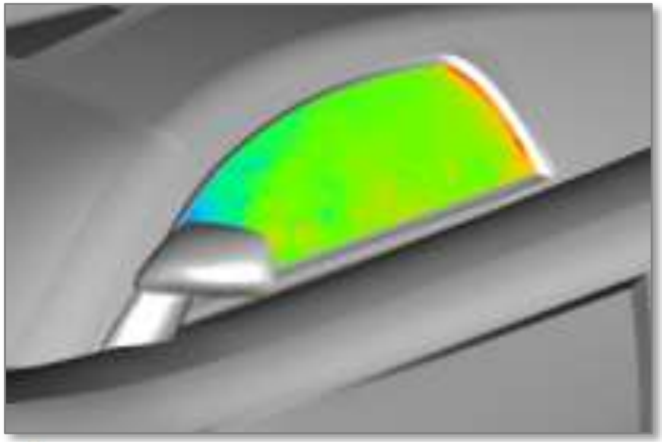
- Turbulent flow generates convective and acoustic pressure fluctuations on side glass.
- This energy can potentially be transfered inside vehicle

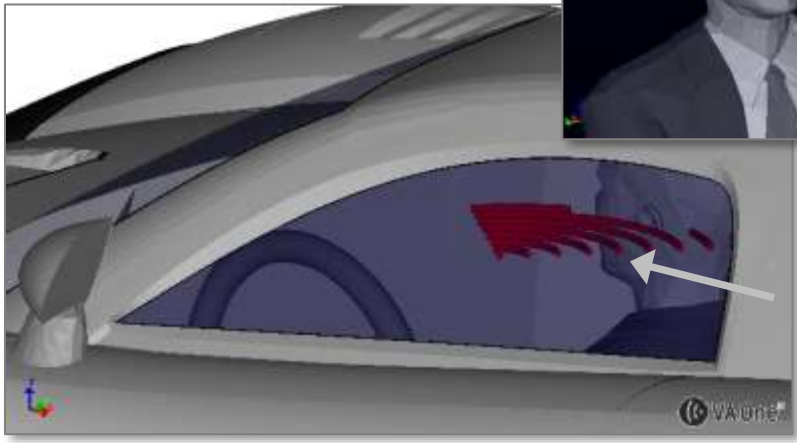


Physical mechanisms

1 Pressure fluctuation on side glass

- Pressure field includes convective and acoustic component
- Acoustic comp. ~70 dB smaller in amplitude than convective
- Acoustic comp. highly directional
- Both components contribute to SPL at driver‘s ear



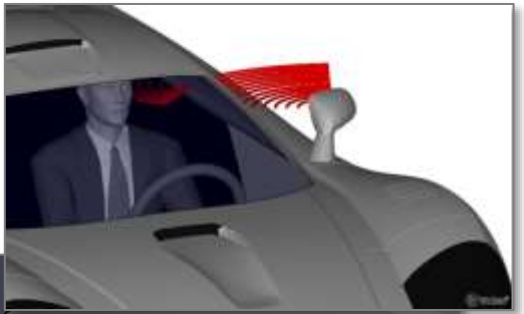


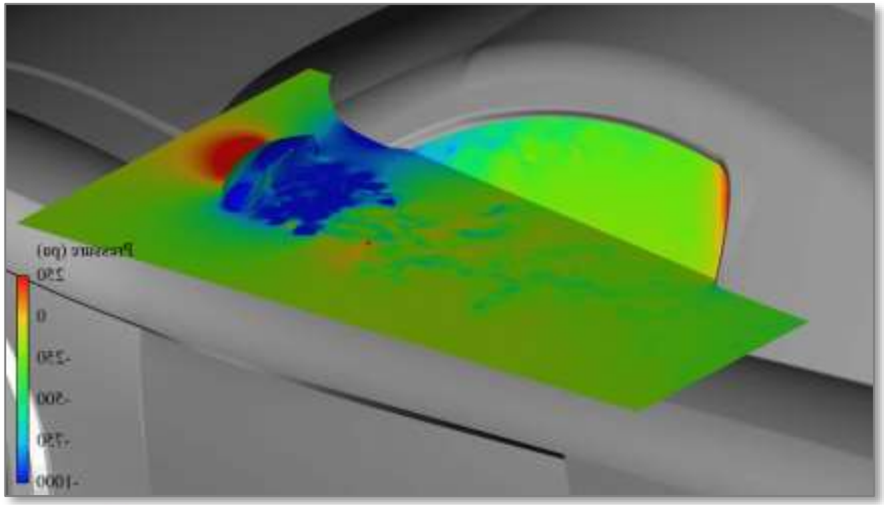
Acoustic waves travelling from side glass to driver’s ear

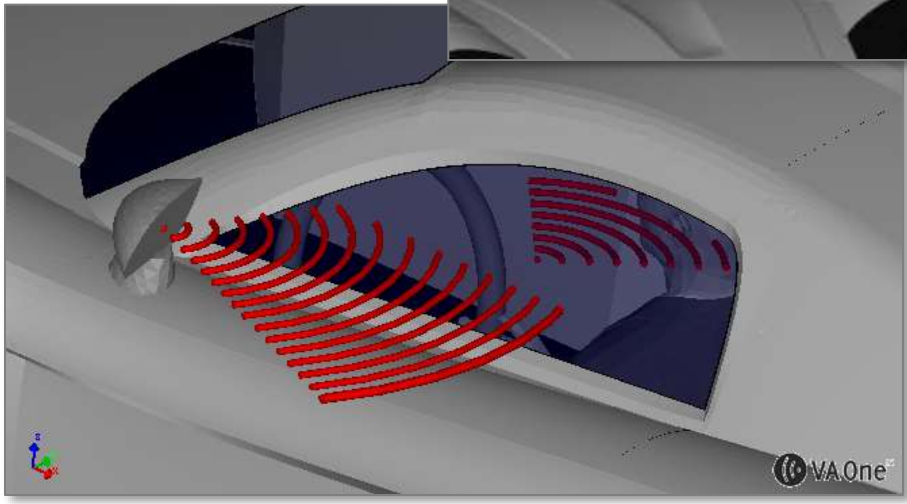
Physical mechanisms

2 Pressure fluctuation on mirror

- Pressure fluctuations on mirror rear face 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

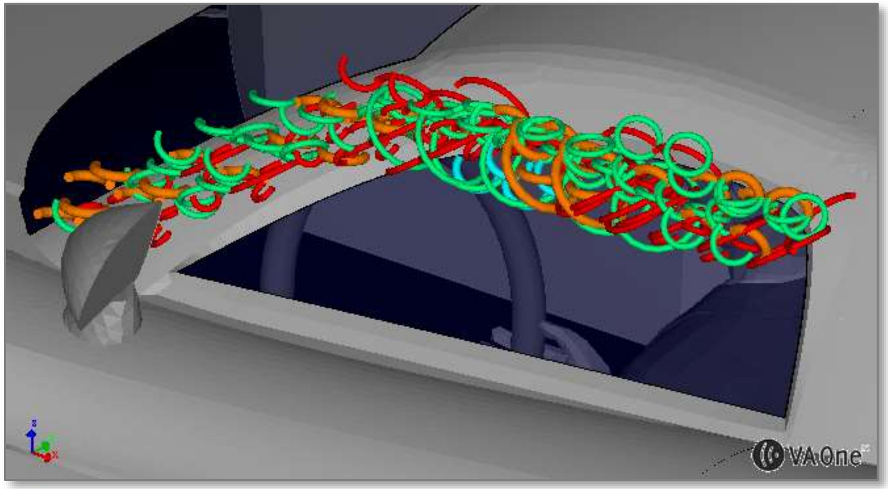


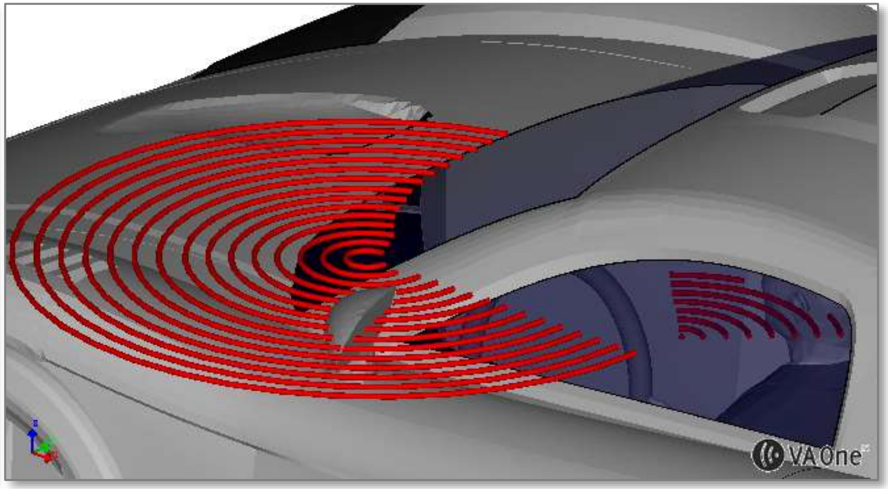




Physical mechanisms

- 3 Pressure fluctuation on A-Pillar
  - Pressure fluctuations on A_Pillar generate acoustic waves that propagate away from A-Pillar
  - Acoustic waves travel with specific heading
  - Associated to a dipole source (surface terms)
  - Waves travel through side glass to driver‘s ear

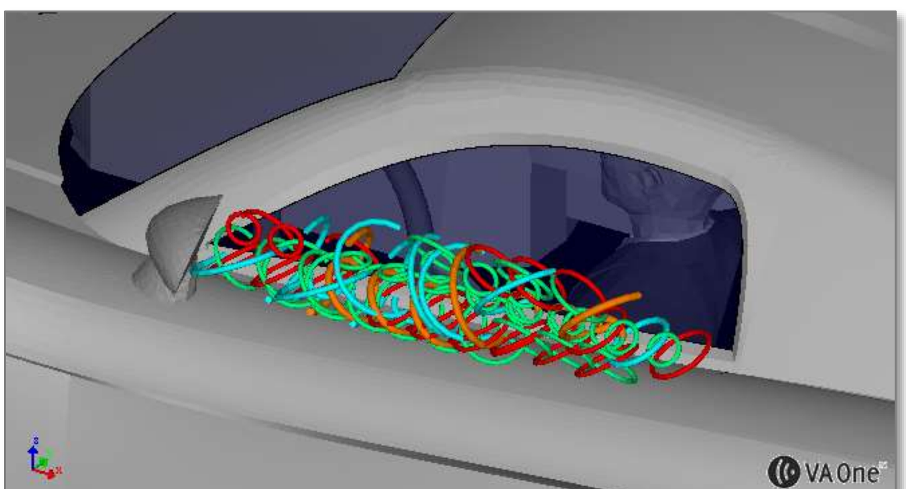


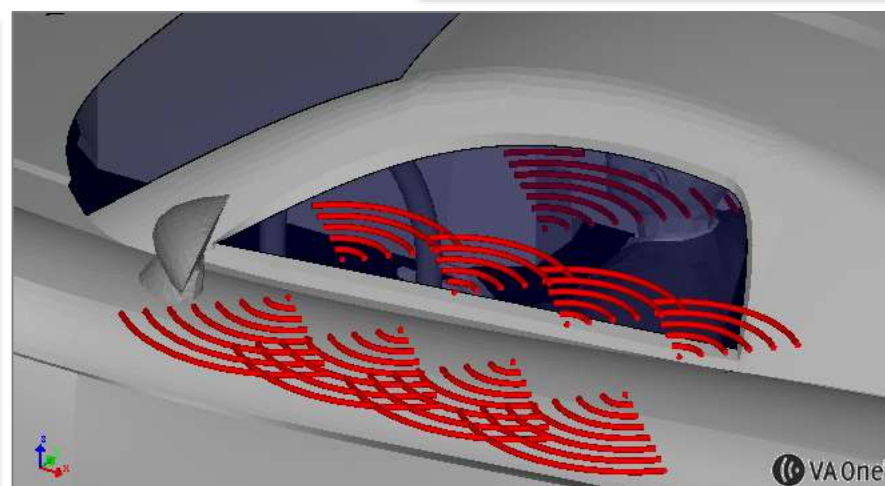


Physical mechanisms

4 Acoustic sources within eddies

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

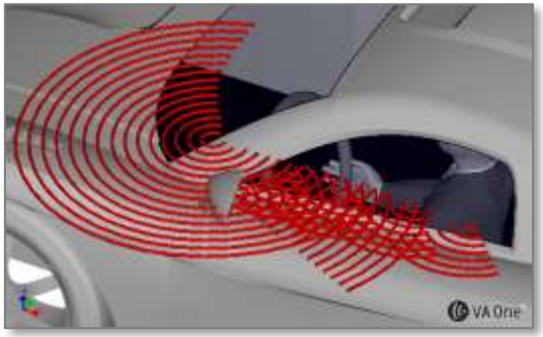


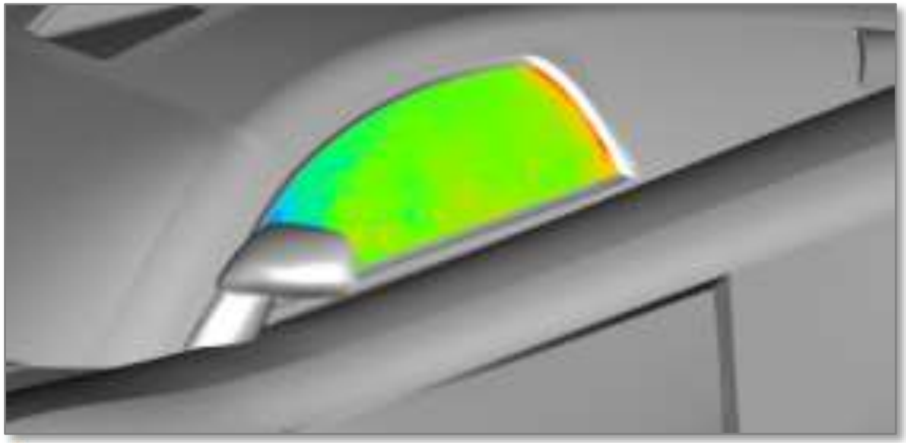


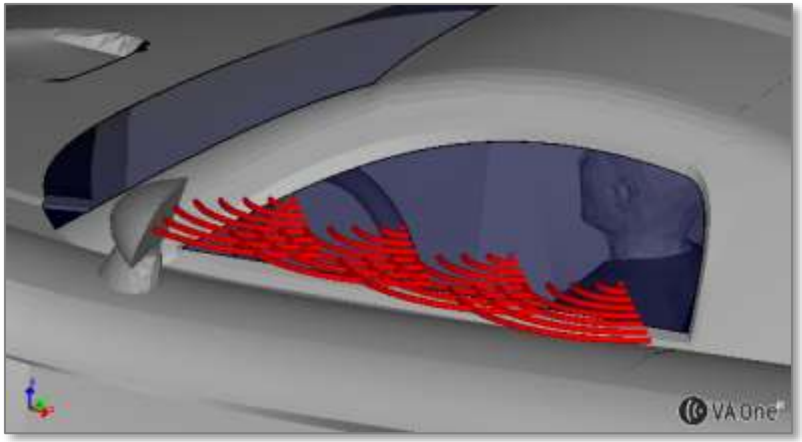
Physical mechanisms

5 Pressure fluctuation on side glass

- Pressure fluctuations on side glass generate acoustic waves that propagate away from side glass
- Can interfere with incoming acoustic waves from A-Pillar and mirror
- Has negligeable impact on driver‘s ear SPL

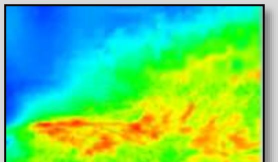




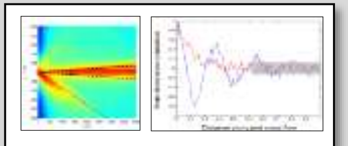


From Turbulent Flow to Interior Noise

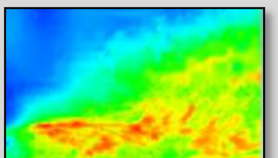
Source characterization



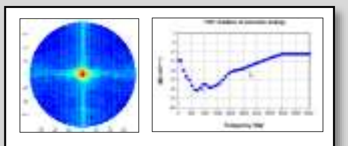
Experimental



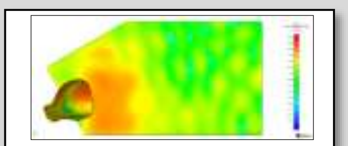
Extract Convective component



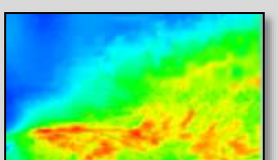
CFD Incompressible



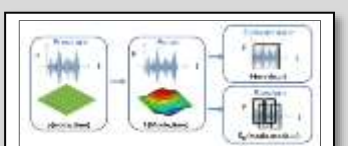
Extract Acoustic component



BEM



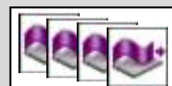
CFD Compressible



Modal Forces (F,Sff)

Source

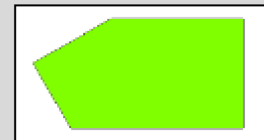
Corcos



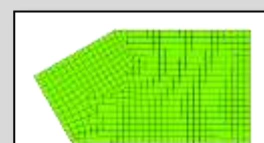
PWF

F, Sff

Glass

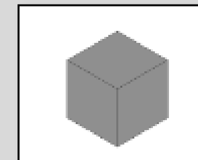


SEA

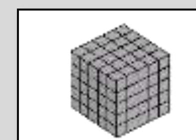


FEM

Interior



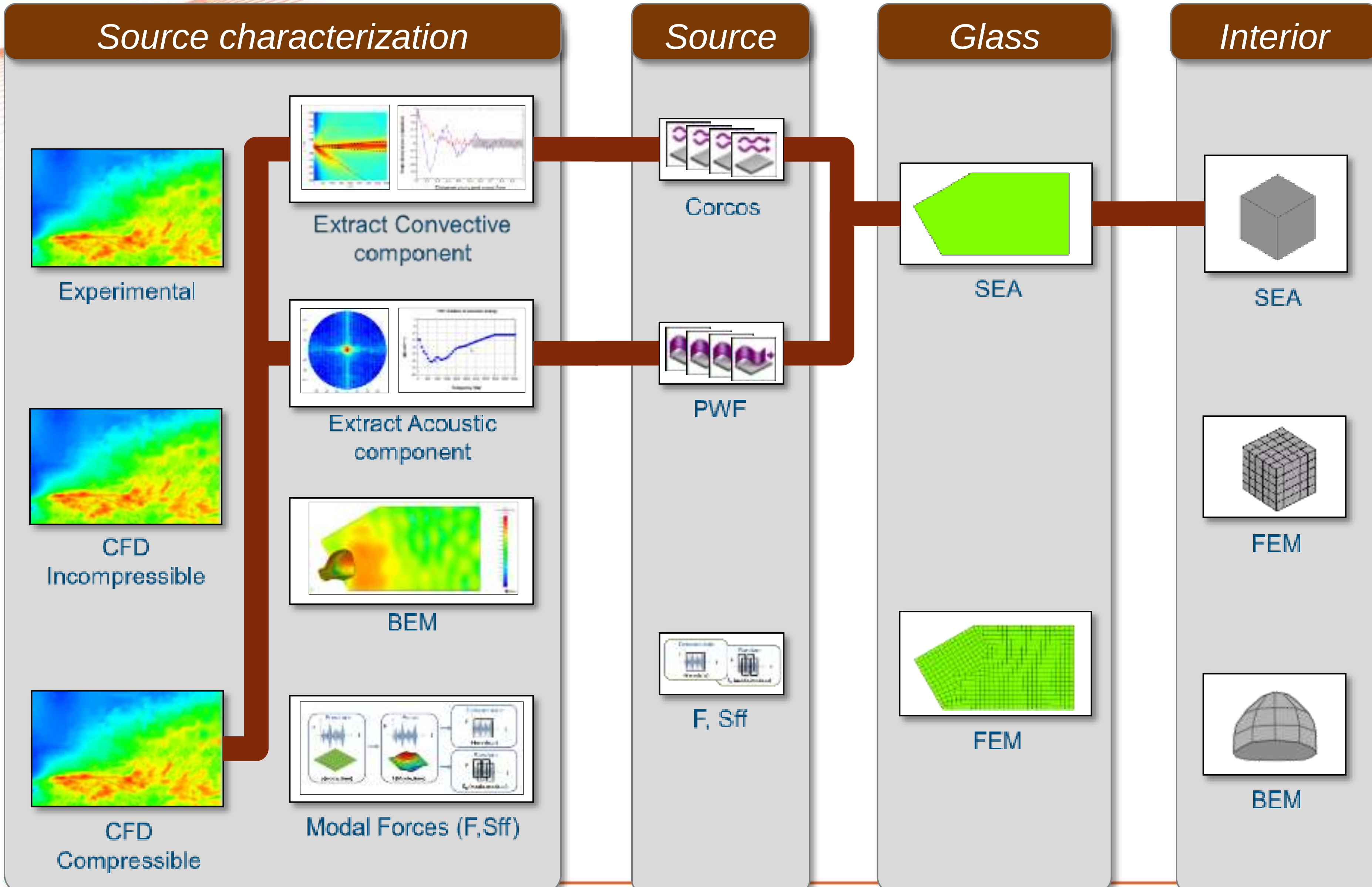
SEA



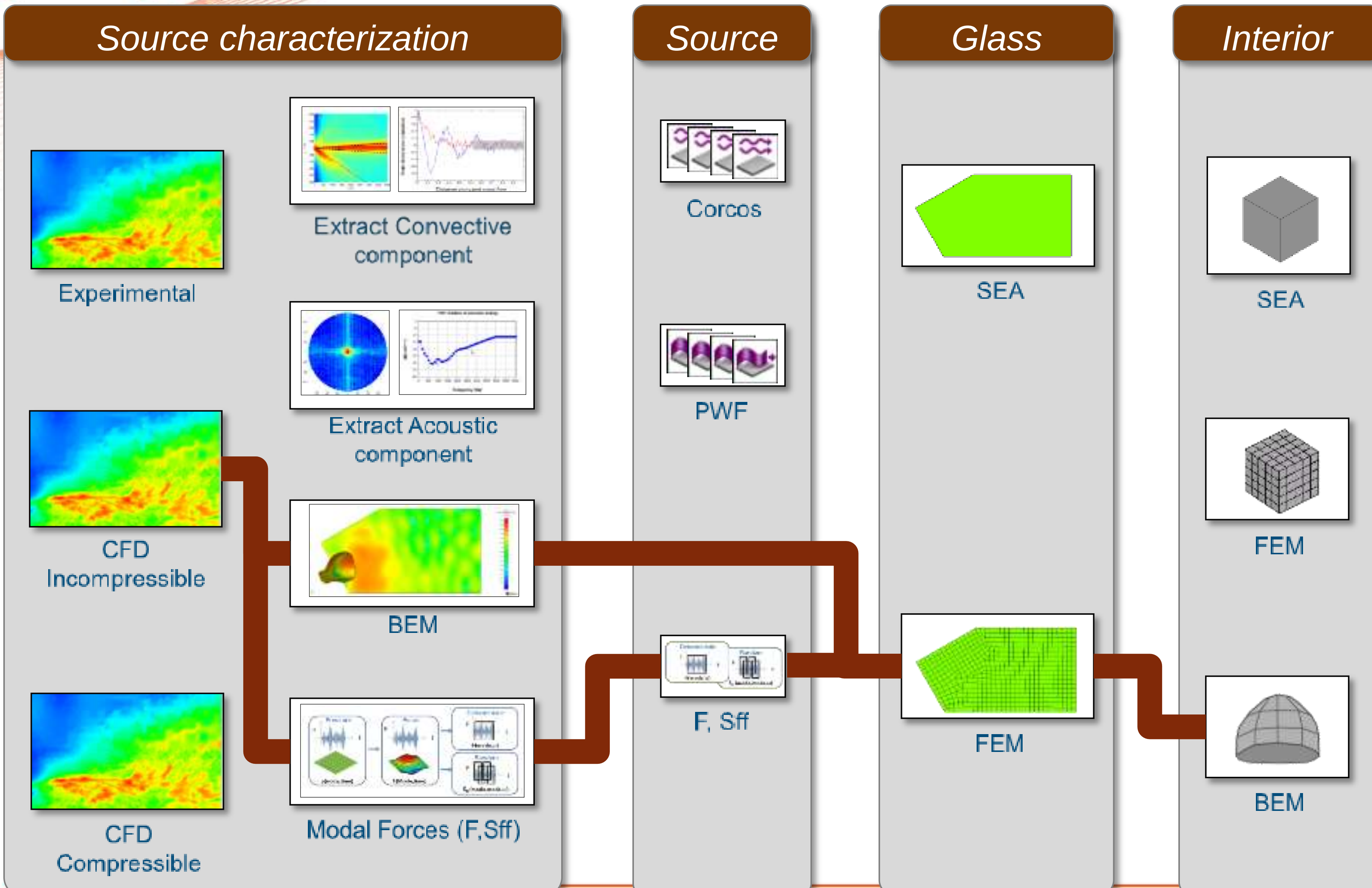
FEM

BEM

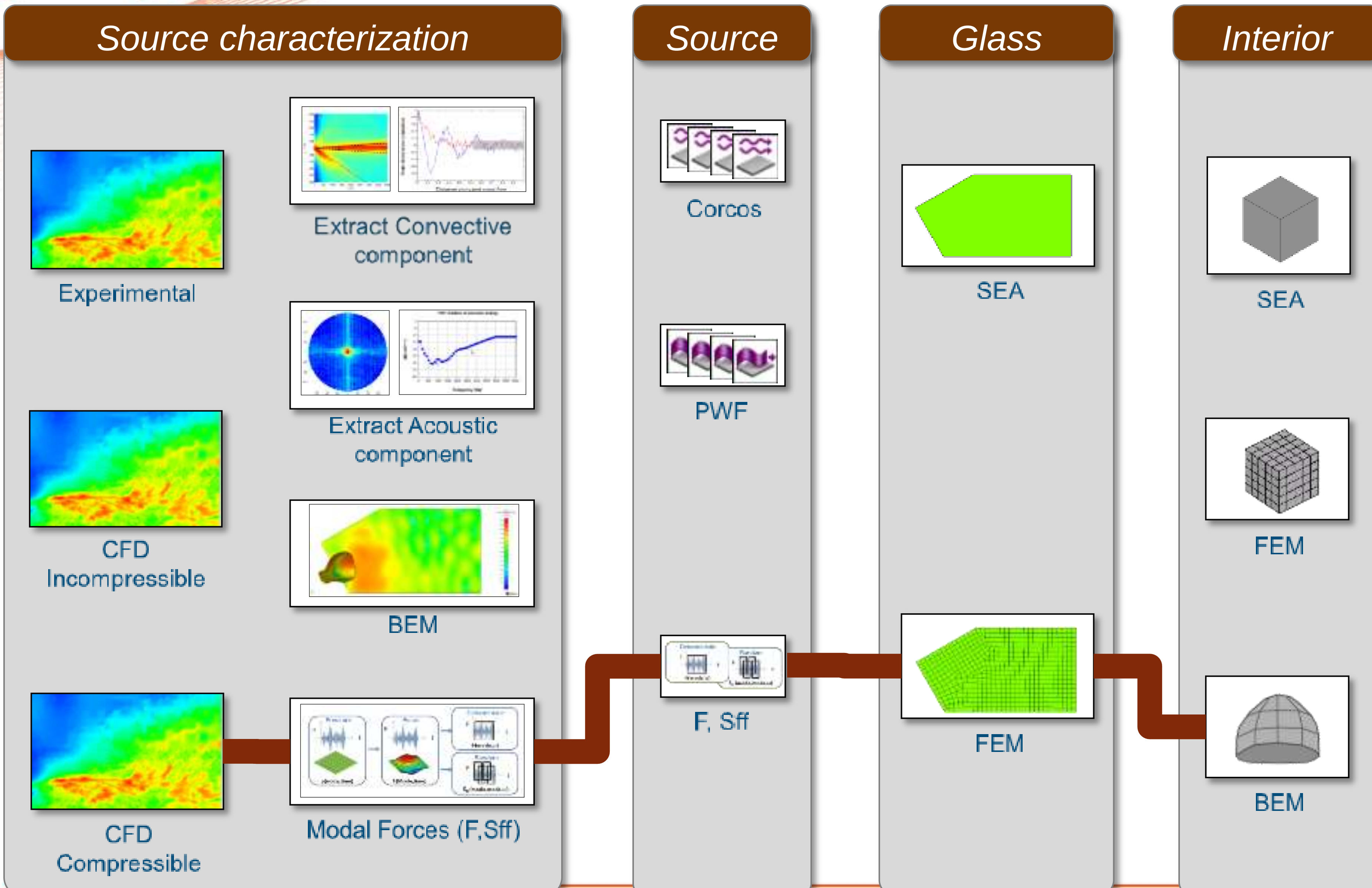
One could imagine …



One could imagine …



One could imagine …



Global Objectives

Vibro-Acoustic session - Morning

- Create an accurate vibro-acoustic model that represents the SAE body so it can be used for windnoise prediction
- Validate the vibro-acoustic model against semi-anechoic room Measurements
- Create predictive windnoise model to predict SPL inside vehicle using the vibro-acoustic model coupled to CFD source model
- Validate windnoise predictions against wind tunnel measurements

Aero-Vibro-Acoustic session - Afternoon

Global Objectives

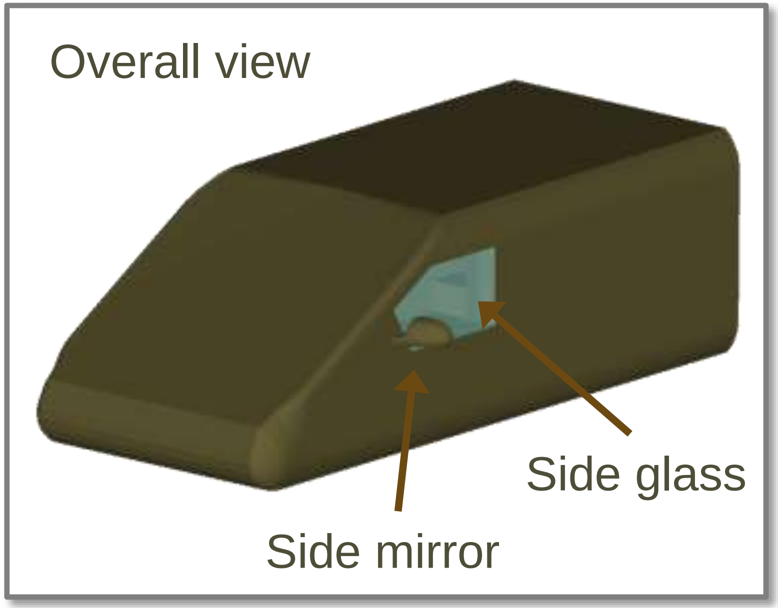
Vibro-Acoustic session - Morning

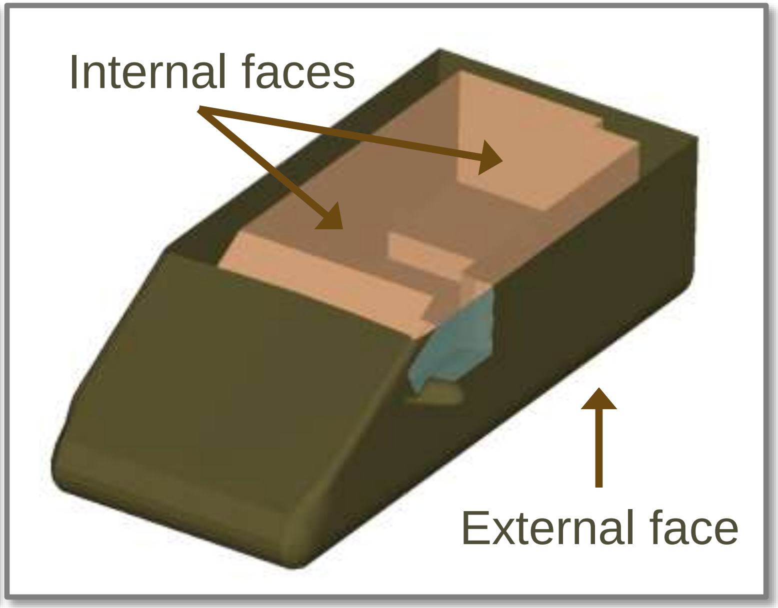
- Create an accurate vibro-acoustic model that represents the SAE body so it can be used for windnoise prediction
- Validate the vibro-acoustic model against semi-anechoic room Measurements
- Create predictive windnoise model to predict SPL inside SAE body using the vibro-acoustic model coupled to CFD source model
- Validate windnoise predictions against wind tunnel measurements

Aero-Vibro-Acoustic session - Afternoon

Description of SAE body

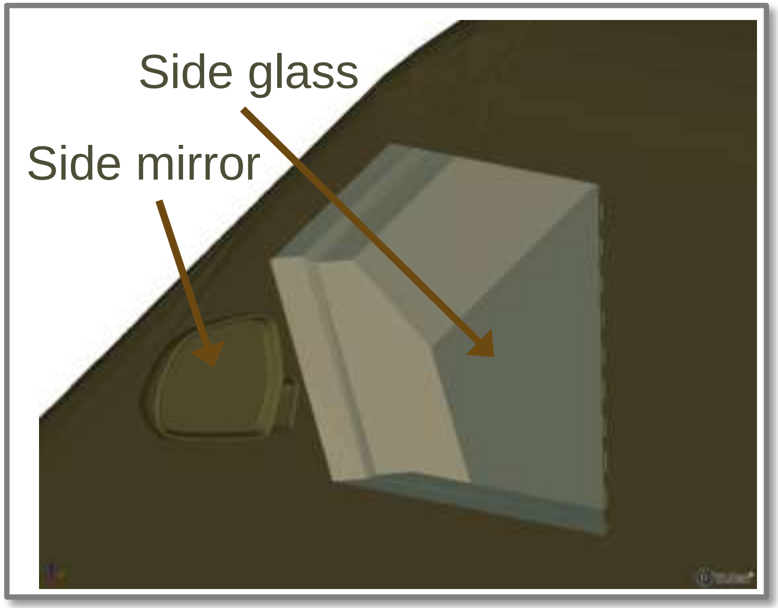
- The SAE body is a generic automotive geometry structure built out of stiff foam
- It allows competing automotive manufacturers to study physical phenomena without disclosing any confidential information related to a particular vehicle design
  - Ref: “Wind Noise caused by the A-pillar and the Side Mirror flow of a Generic Vehicle Model”, AIAA2012, M. Hartmann, J. Ocker,T. Lemke, A. Mutzke, V. Schwarz, H. Tokuno, R. Toppinga, P. Unterlechner, G. Wickern



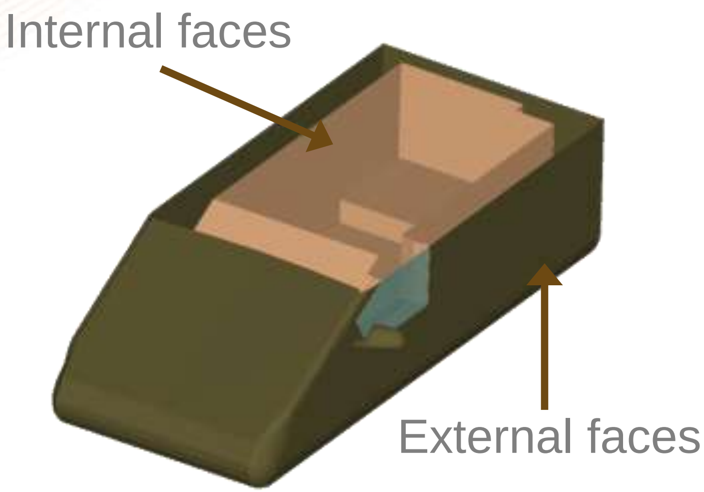


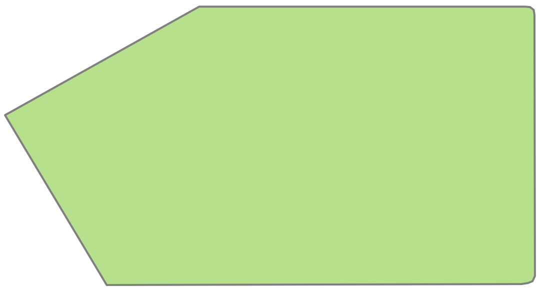
Details of side glass location

- An automotive type side glass fitted into the SAE body wall
- Location reflects similar geometry conditions as in real vehicle, with the presence of a slope in the front (windshield), presence of A-Pillar and side mirror.



Structural properties



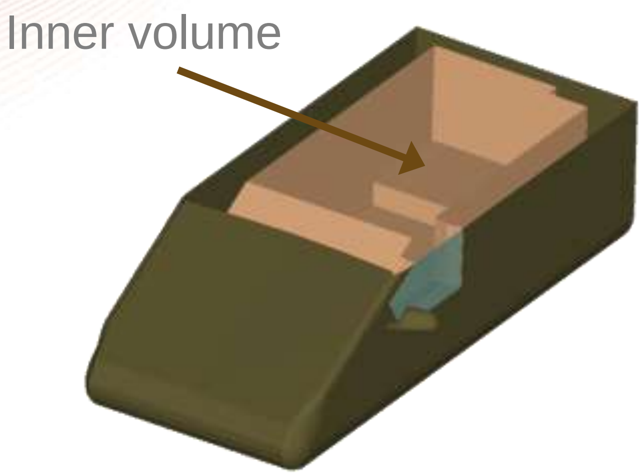


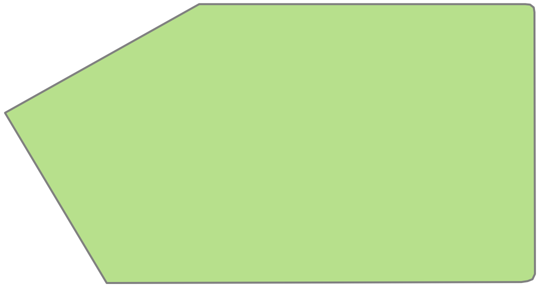
Assumtions:

External face: Rigid
Internal face: Rigid
NR walls >> NR Side Glass

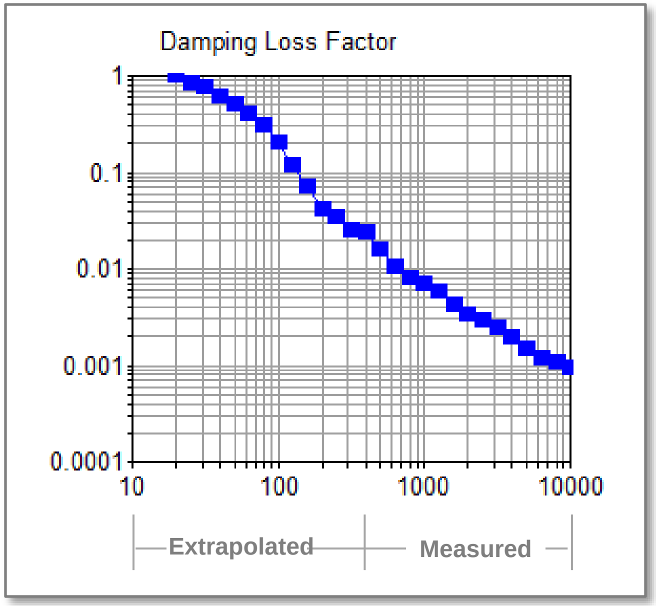
Glass type: Tempered glass
Young's Modulus (E): 70 GPa
Density (Rho): 2700 Kg/m3
Poisson's Ratio (nu): 0.33
FEM BC: Simply supported

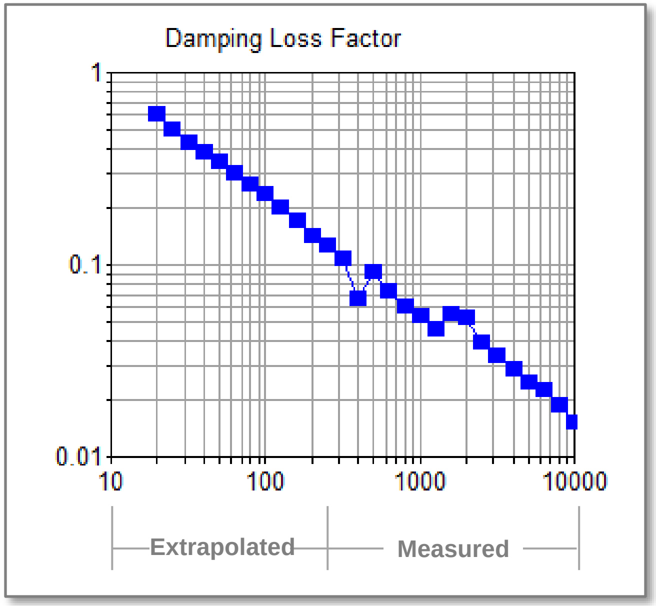
Damping spectra





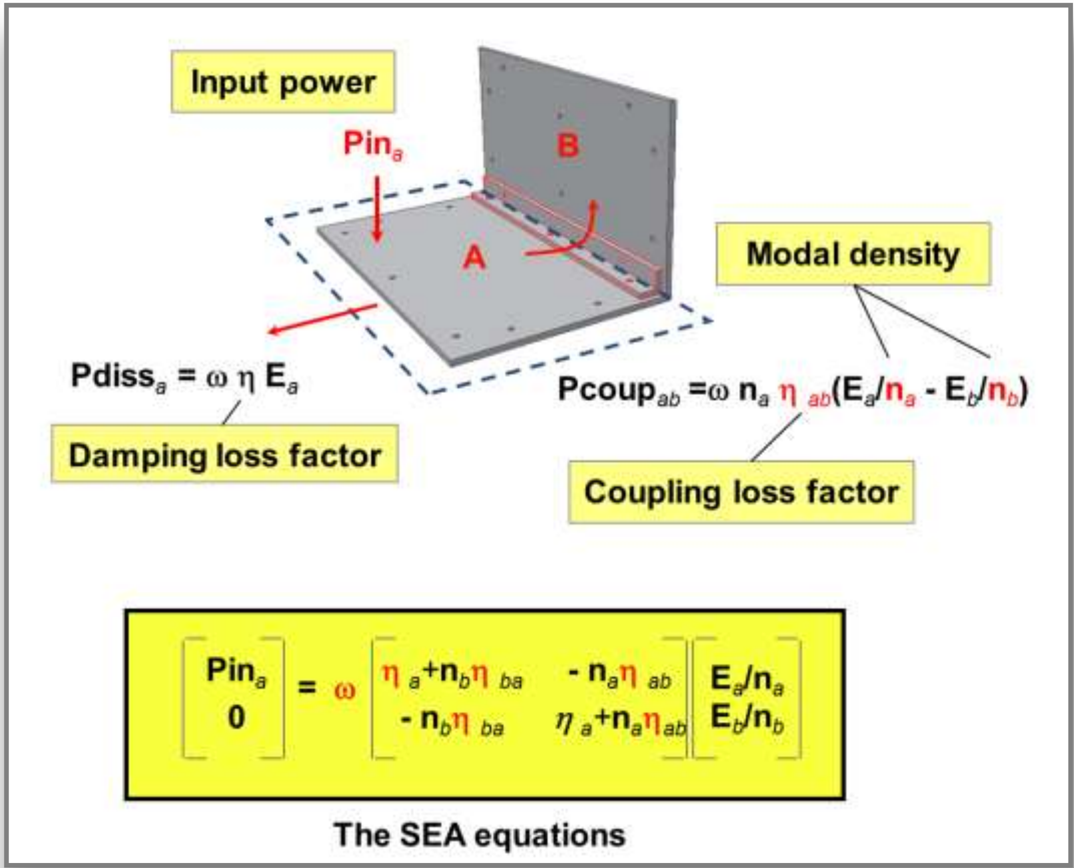
Side Glass

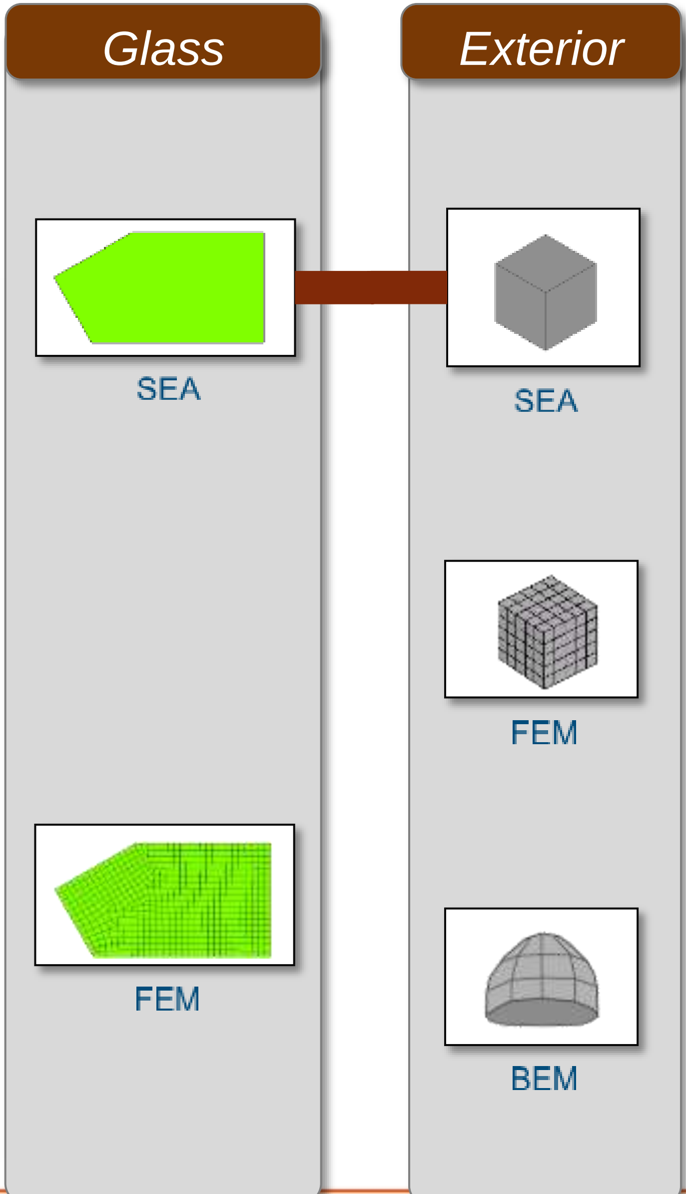




Modelling methods used

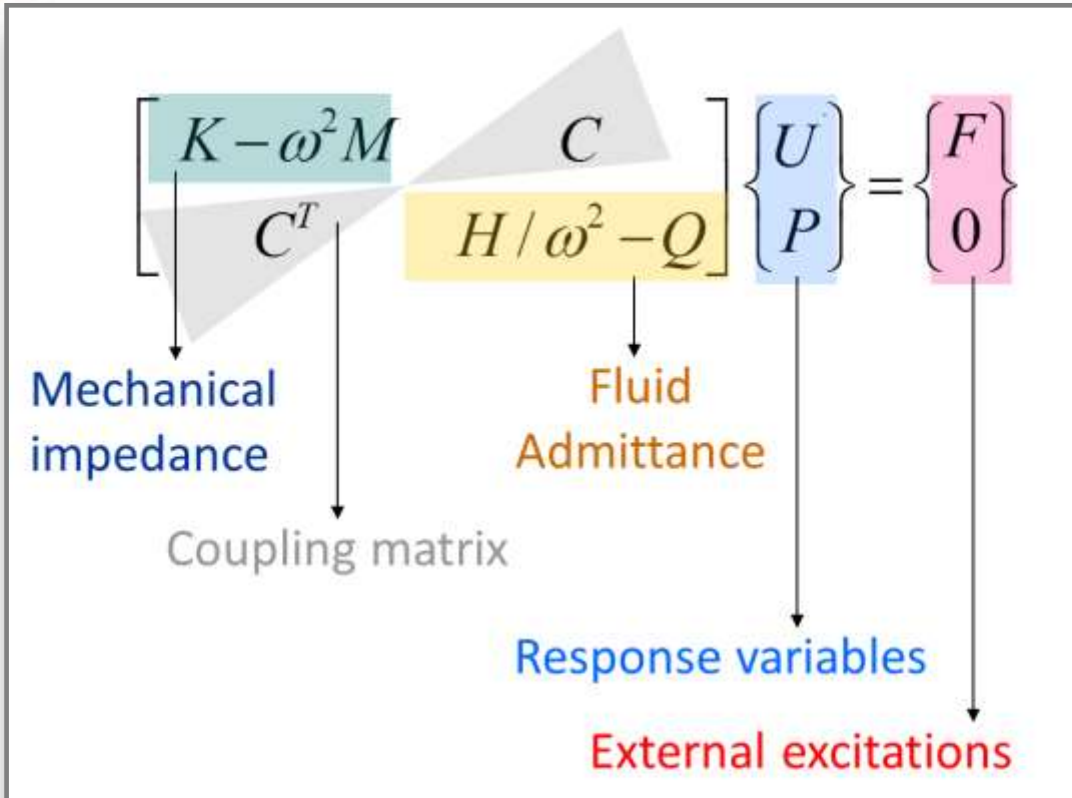
SEA: Statistical Energy Analysis

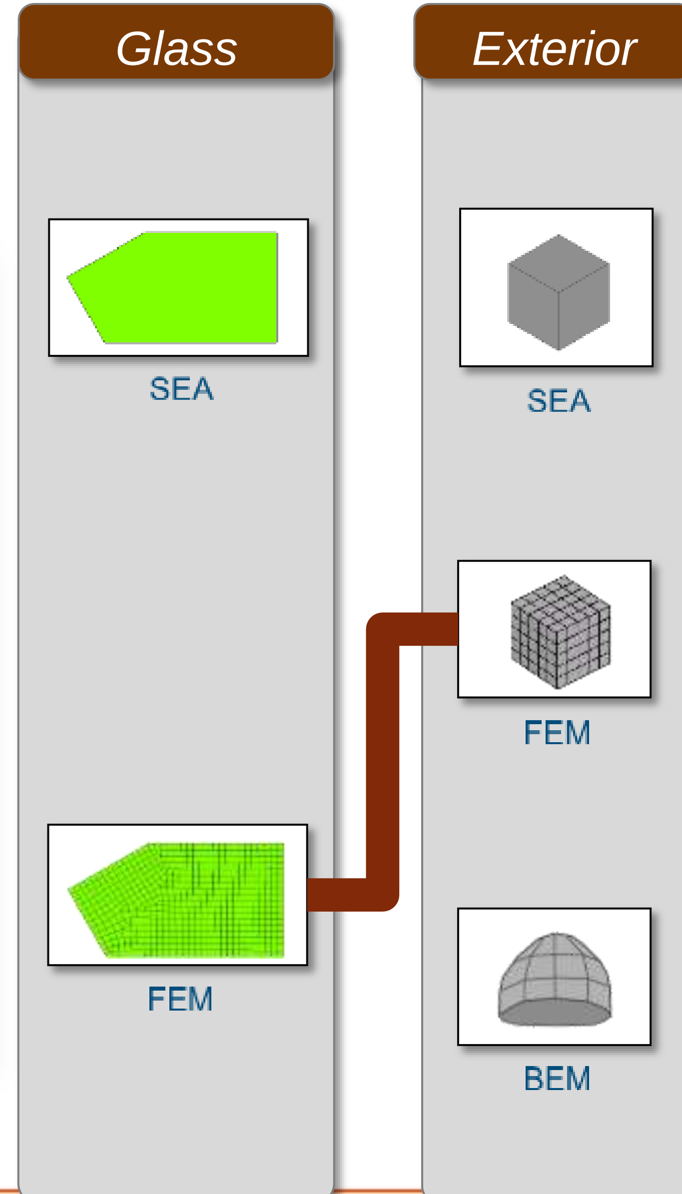




Modelling methods used

FEM: Finite Element Method

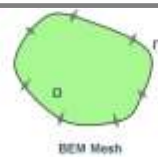




Modelling methods used

BEM: Boundary Element Method

$$c(P)u(P)+\sum_{j=1}^{N}\int_{\Gamma_j} u.\frac{\partial\omega}{\partial n}d\Gamma=\sum_{j=1}^{N}\int\frac{\partial u}{\partial n}.\omega d\Gamma$$



Use BIE to find the surface distributions of u and ∂u/∂n and then find the solution at any point P Ω. Over each element Γj , use standard FE basis functions

$$u_j=\sum_n\varphi_j.u_{j\alpha}\qquad q_j=\frac{\partial u_j}{\partial n}=\sum_n\varphi_\alpha.q_{j\alpha}$$

where uj, qj are values of u and q on element Γ j, and ujα ,qjα are values of u and q at node on element Γj. The BIE for node i becomes

$$c_i.u_i+\sum_{j=1}^{N}\sum_\alpha u_{j\alpha}.a_{ij}^{\alpha}=\sum_{j=1}^{N}\sum_\alpha q_{j\alpha}.b_{ij}^{\alpha}$$

where

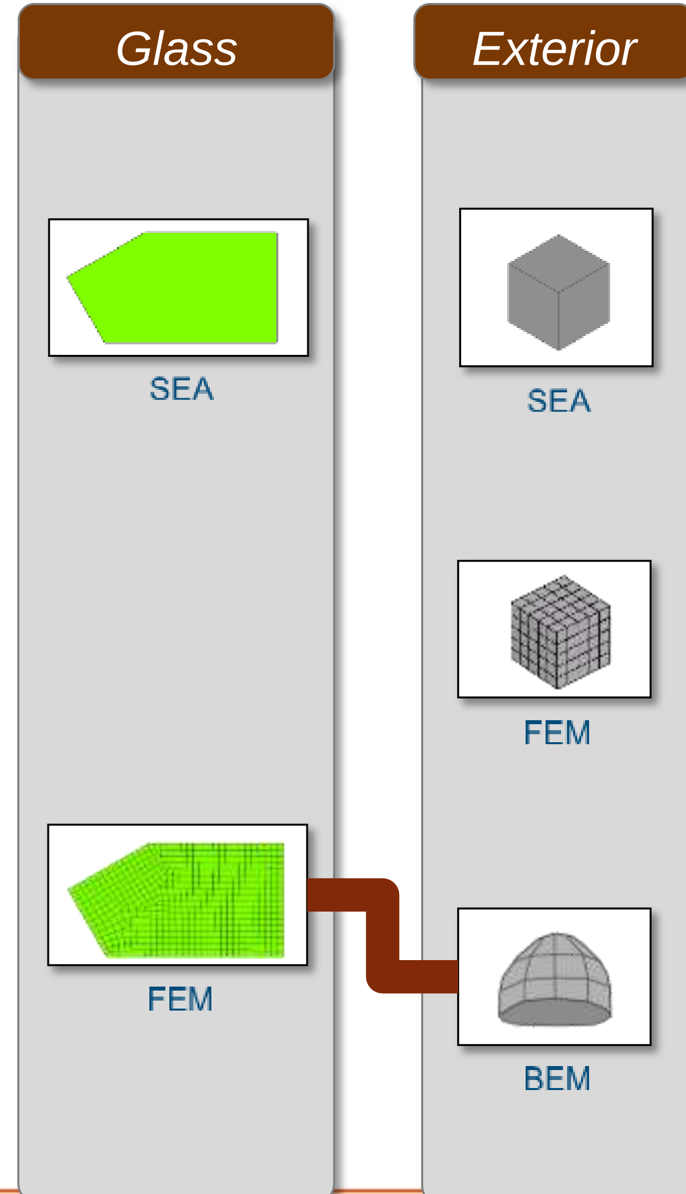
$$a_{ij}^{\alpha}=\int_{\Gamma_j}\varphi_\alpha.\frac{\partial\omega_i}{\partial n}d\Gamma\qquad b_{ij}^{\alpha}=\int_{\Gamma_j}\varphi_\alpha.\omega_i d\Gamma$$

Since we have L nodes, then we can generate L equations and assemble these into a matrix system. Replacing variable u with sound pressure p and variable q with normal velocity v_n on the surface.

$$[A]_{NxN}\{p\}_{Nx1}=[B]_{NxN}\{v_n\}_{Nx1}$$

Use BC to eliminate one of the variable

$$[A]_{NxN}\{p\}_{Nx1}=\{b\}_{Nx1}\quad or\quad \{p\}_{Nx1}=[B]_{NxN}\{vn\}_{Nx1}$$



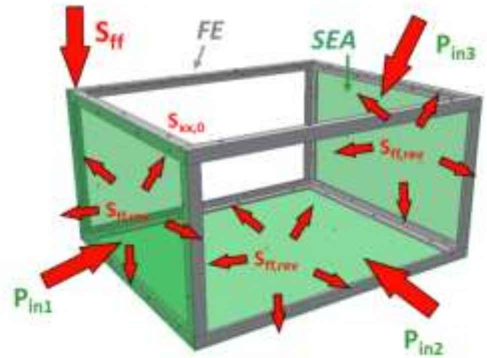
Modelling methods used

FE/SEA Coupled

Response due to FE external excitation

$$\left[\mathbf{D}_0 + \sum_i \mathbf{D}_{i,dir}\right]\{\mathbf{x}\} = \{\mathbf{f}\}$$

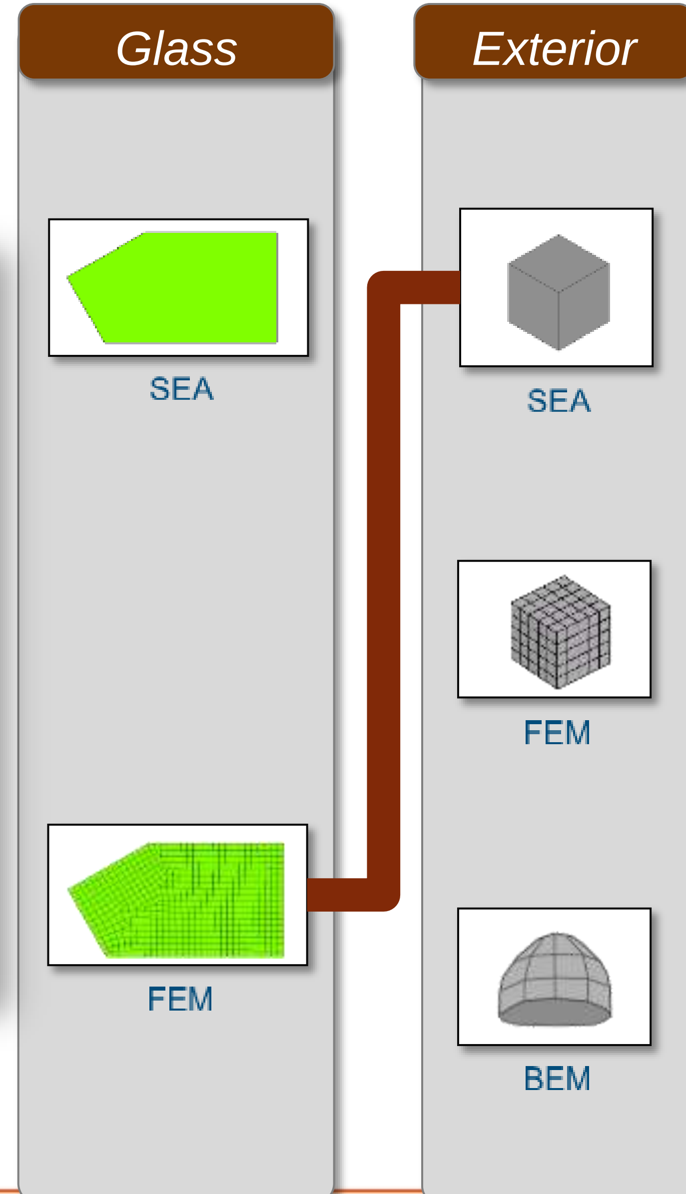
Dynamic stiffness of SEA subsystem



Total response is sum of response to FE external excitation AND reverberant loading from each SEA subsystem

$$\mathbf{S}_{xx} = \mathbf{S}_{xx,0} + \sum_i \mathbf{S}_{xx,rev,i} = \mathbf{R}\left[\mathbf{S}_{ff,0} + \sum_i \mathbf{S}_{ff,rev,i}\right]\mathbf{R}^H$$

where $\mathbf{R} = \left[\mathbf{D}_0 + \sum_i \mathbf{D}_{i,dir}\right]^{-1}$



Global Objectives

Vibro-Acoustic session - Morning

Create an accurate vibro-acoustic model that represents the SAE body so it can be used for windnoise prediction

Validate the vibro-acoustic model against semi-anechoic room Measurements

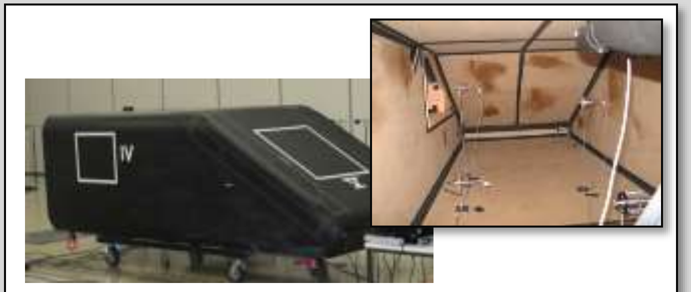
Create predictive windnoise model to predict SPL inside SAE body using the vibro-acoustic model coupled to CFD source model

Validate windnoise predictions against wind tunnel measurements

Aero-Vibro-Acoustic session - Afternoon

VA models used

Source characterization

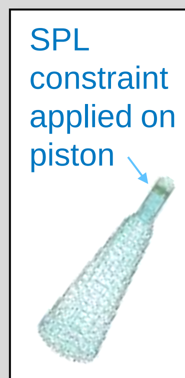


Measurement of SPL inside SAE body for Omnisource excitation

Omnidirectional Volume Velocity Source with OmniSource Sound Source – Type 4295 and Volume Velocity Adaptor – Type 4299

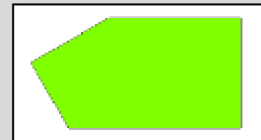
Source

Average interior SPL

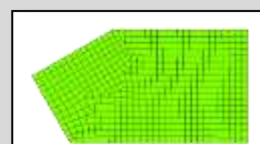


BEM model of Omnisource

Glass

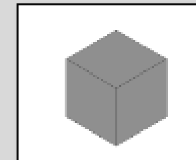


SEA

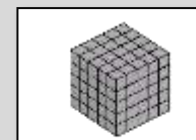


FEM

Exterior



SEA

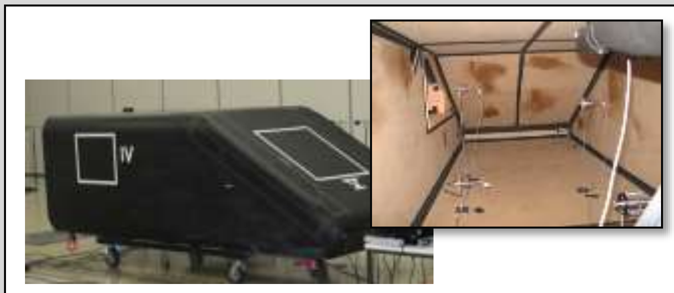


FEM

BEM

VA models: Test-SEA-SEA

Source characterization

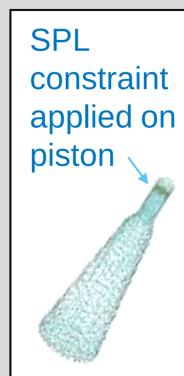


Measurement of SPL inside SAE body for Omnisource excitation

Omnidirectional Volume Velocity Source with OmniSource Sound Source – Type 4295 and Volume Velocity Adaptor – Type 4299

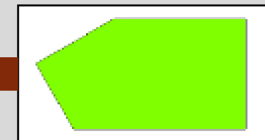
Source

Average interior SPL

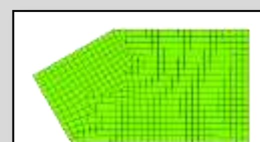


BEM model of Omnisource

Glass

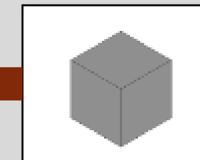


SEA

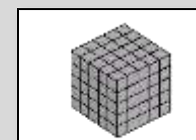


FEM

Exterior



SEA

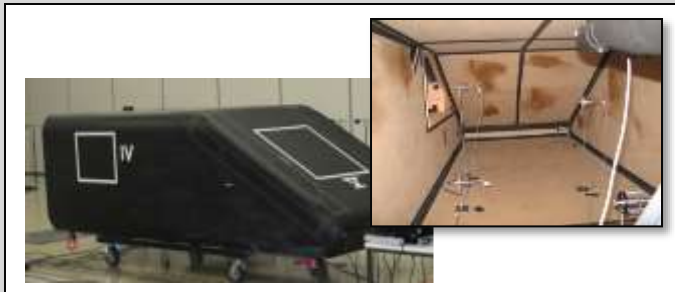


FEM

BEM

VA models: Test-FEM-SEA

Source characterization



Measurement of SPL inside SAE body for Omnisource excitation

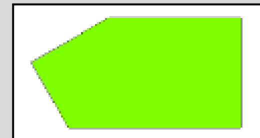
Omnidirectional Volume Velocity Source with OmniSource Sound Source – Type 4295 and Volume Velocity Adaptor – Type 4299

Source

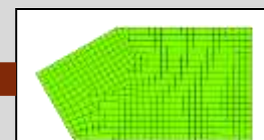
Average interior SPL

BEM model of Omnisource

Glass

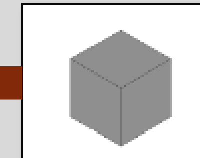


SEA

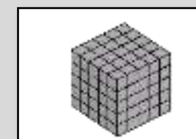


FEM

Exterior



SEA



FEM

BEM

VA models: Test-FEM-BEM

Source characterization

Measurement of SPL inside SAE body for Omnisource excitation

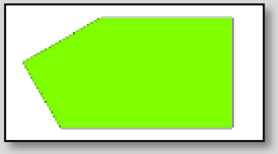
Omnidirectional Volume Velocity Source with OmniSource Sound Source – Type 4295 and Volume Velocity Adaptor – Type 4299

Source

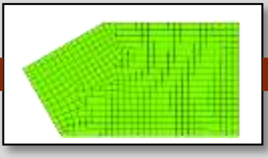
Average interior SPL

BEM model of Omnisource

Glass

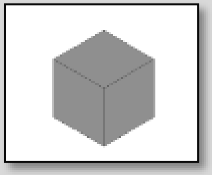


SEA

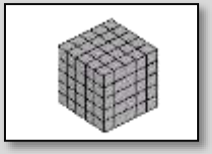


FEM

Exterior



SEA



FEM

BEM

VA models: BEM-FEM-BEM

Source characterization

Measurement of SPL inside SAE body for Omnisource excitation

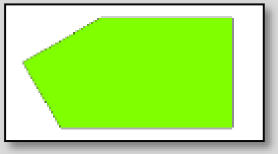
Omnidirectional Volume Velocity Source with OmniSource Sound Source – Type 4295 and Volume Velocity Adaptor – Type 4299

Source

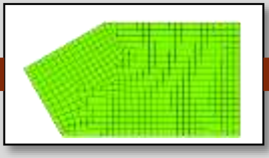
Average interior SPL

BEM model of Omnisource

Glass

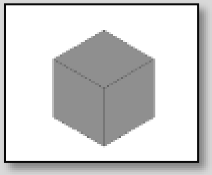


SEA

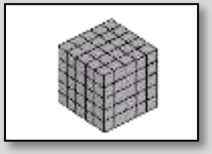


FEM

Exterior



SEA



FEM

BEM

Validate VA model against test

Objectives:

Validate assumptions concerning SAE body walls

- Rigid surfaces
- NR larger than side glass

Validate that for an acoustic source inside SAE body, the VA model accuratly predicts:

- SPL at interior microphones
- Average SPL inside SAE body
- Radiated acoustic power by side glass
- SPL at exterior microphones for specific angles

Validate that for an acoustic source outside SAE body, the VA model accuratly predicts:

- SPL at interior microphones
- Average SPL inside SAE body

Validate VA model against test
Objectives:

Validate assumptions concerning SAE body walls

- Rigid surfaces
- NR larger than side glass

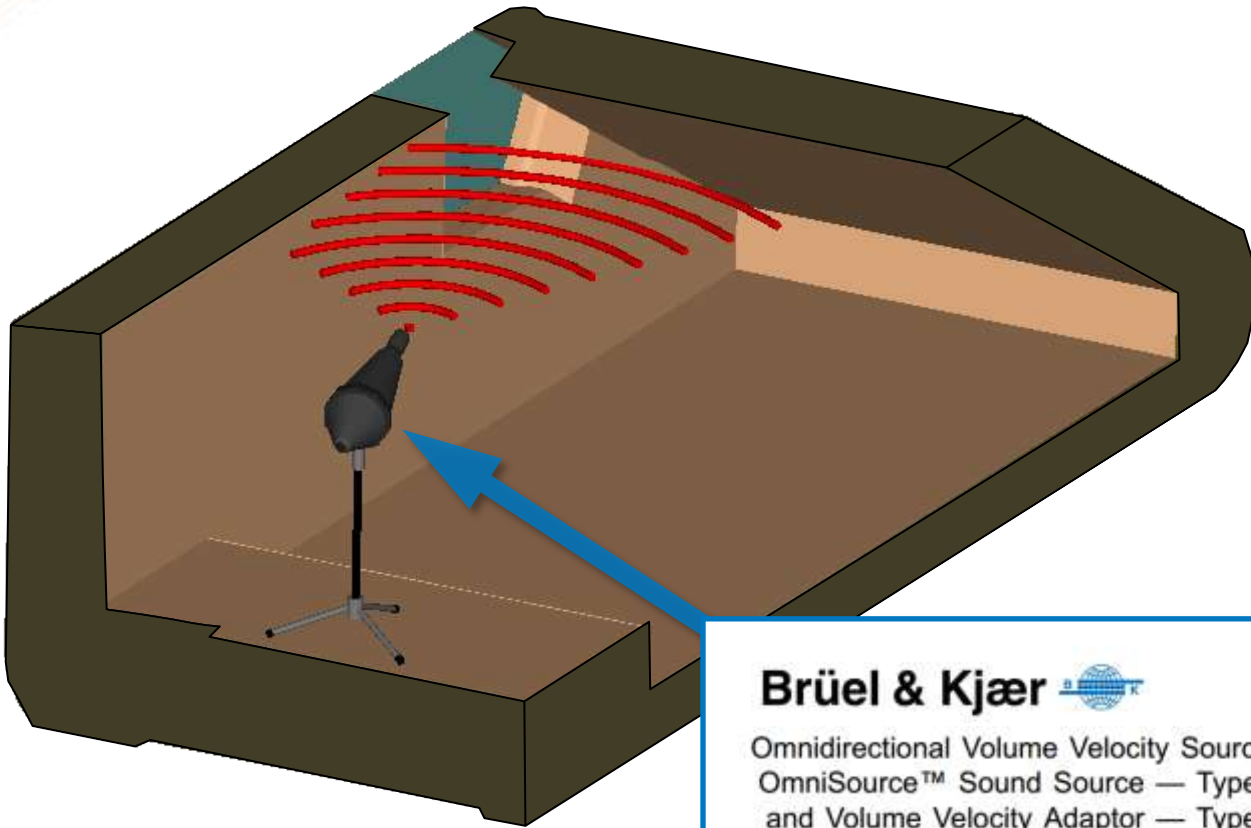
Validate that for an acoustic source inside SAE body, the VA model accuratly predicts:

- SPL at interior microphones
- Average SPL inside SAE body
- Radiated acoustic power by side glass
- SPL at exterior microphones for specific angles

Validate that for an acoustic source outside SAE body, the VA model accuratly predicts:

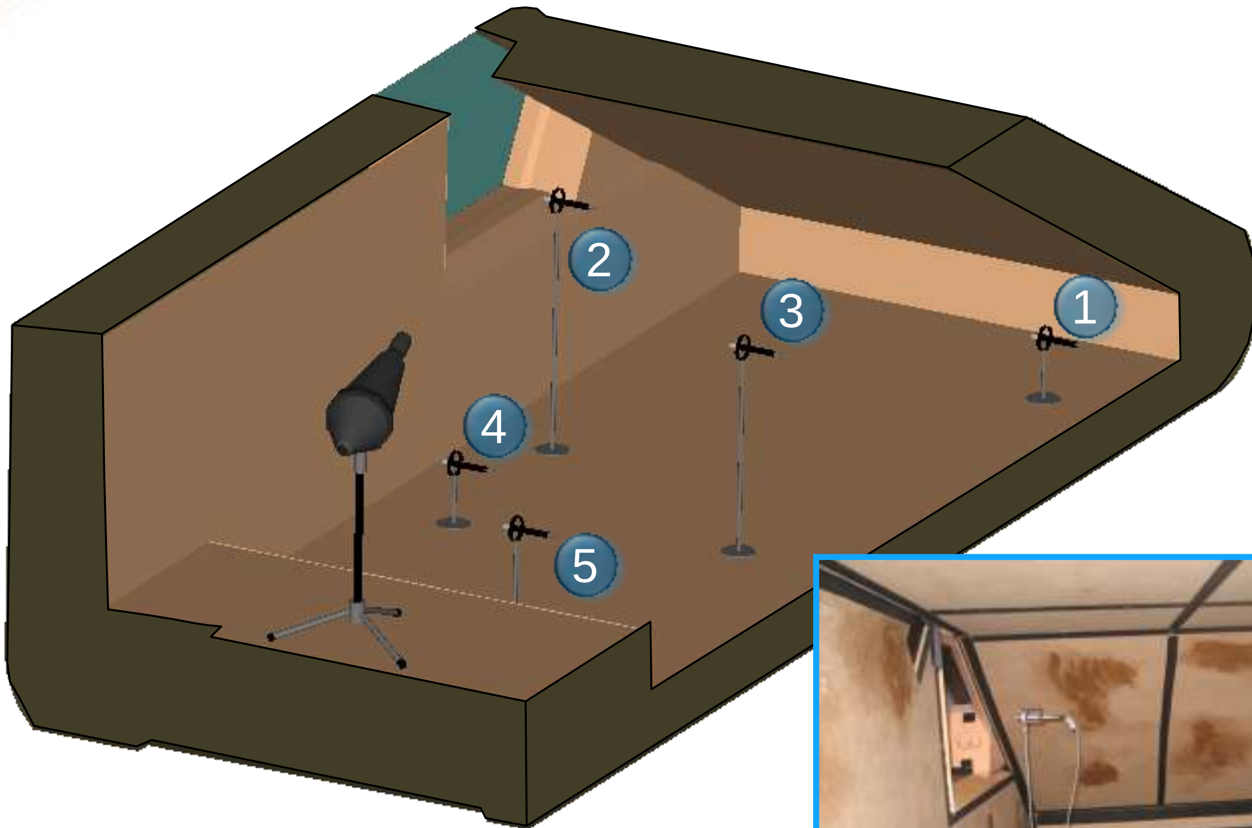
- SPL at interior microphones
- Average SPL inside SAE body

Noire Reduction (NR) measurements



- An omnisource is located inside the SAE body to fill interior volume with a strong acoustic field

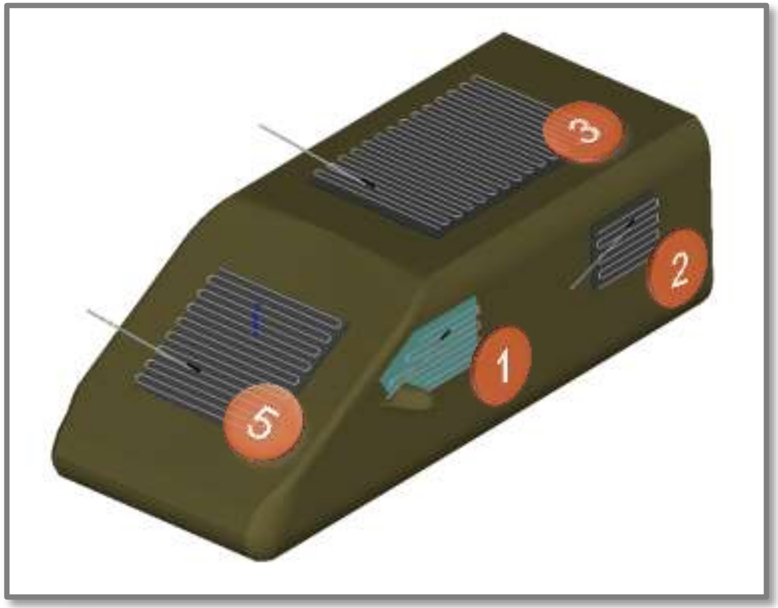
Noire Reduction (NR) measurements

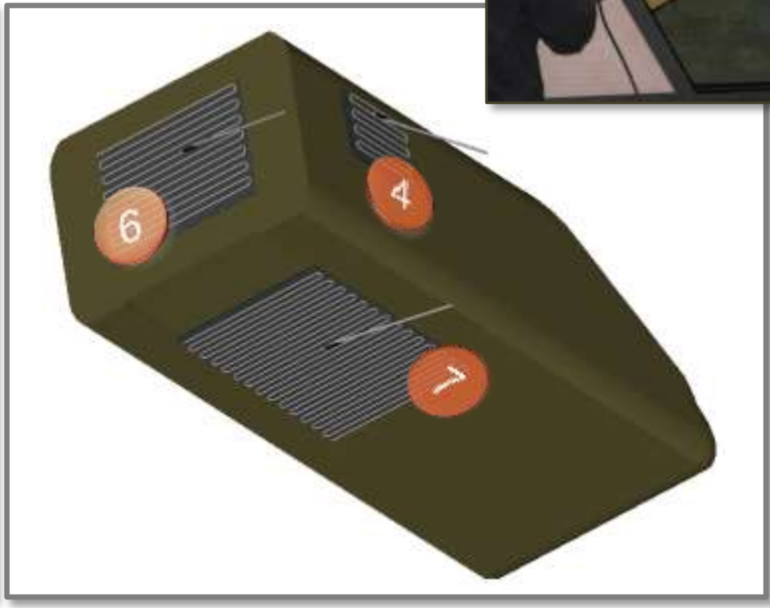


- 5 microphones are located inside SAE body to monitor interior sound field

Noise Reduction (NR) measurements

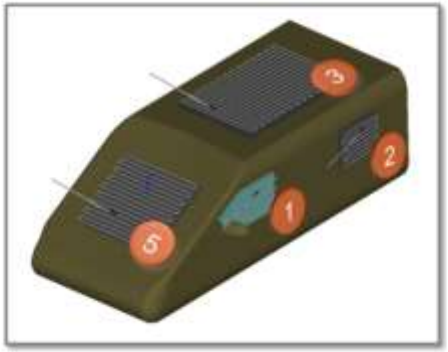
- Noise Reduction (NR) measurements provide an indication of how acoustic wave can travel through the SAE body surfaces compared to the side glass
- NR is the ratio of the average acoustic pressure inside SAE body and a microphone scan over different regions.

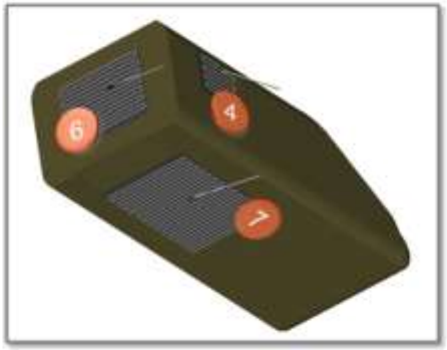


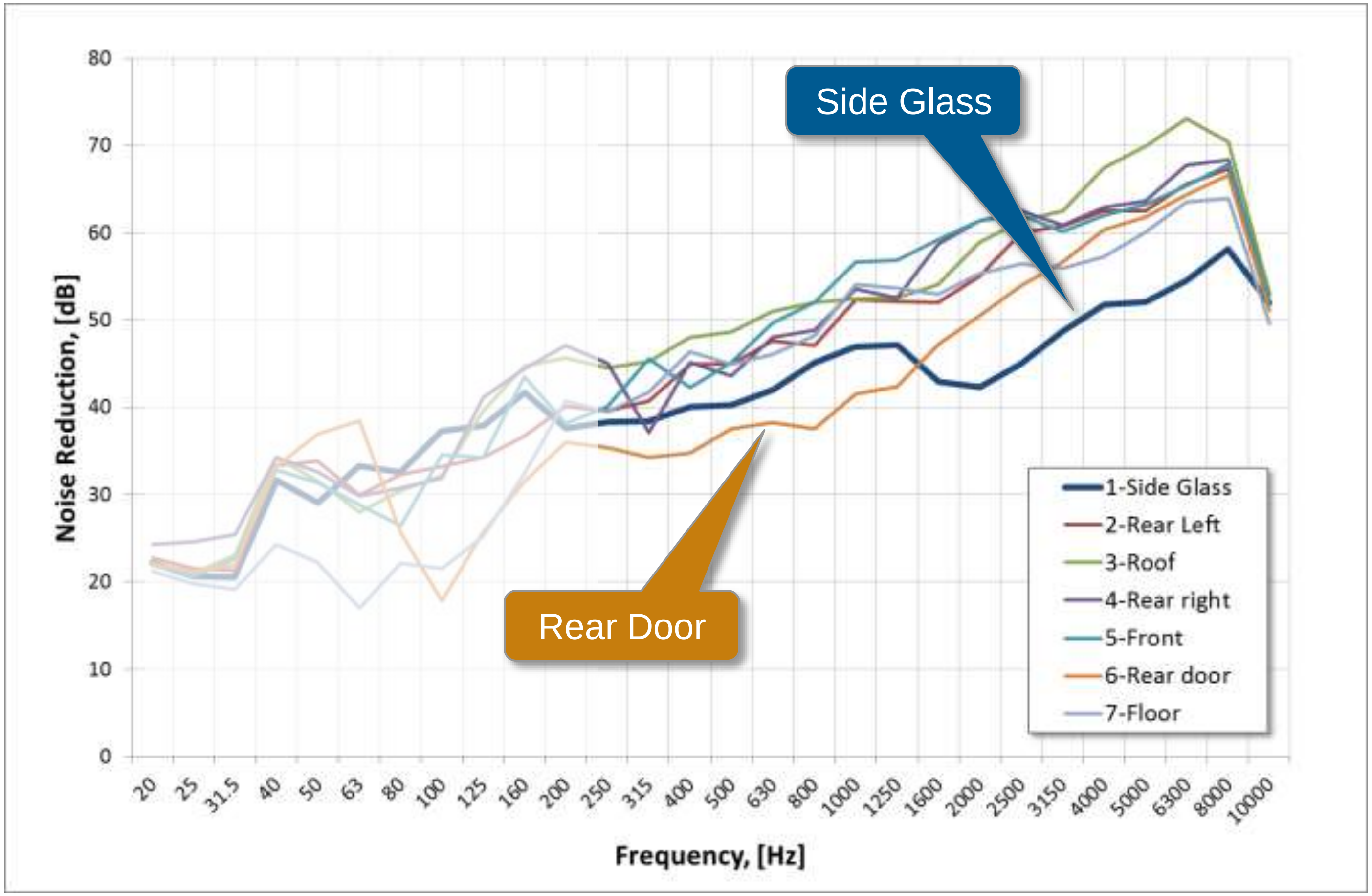


Noise Reduction (NR) measurements

Test results show that NR SAE body roof, wall and floor are in average 10 dB higher than the side glass at frequency higher than 250 Hz. Region of interest around glass resonance frequency (~3 kHz) are showing higher NR. Since the rear door is located far from side glass, its low NR is not considered a problem.







Validate VA model against test
Objectives:

Validate assumptions concerning SAE body walls

- Rigid surfaces
- NR larger than side glass

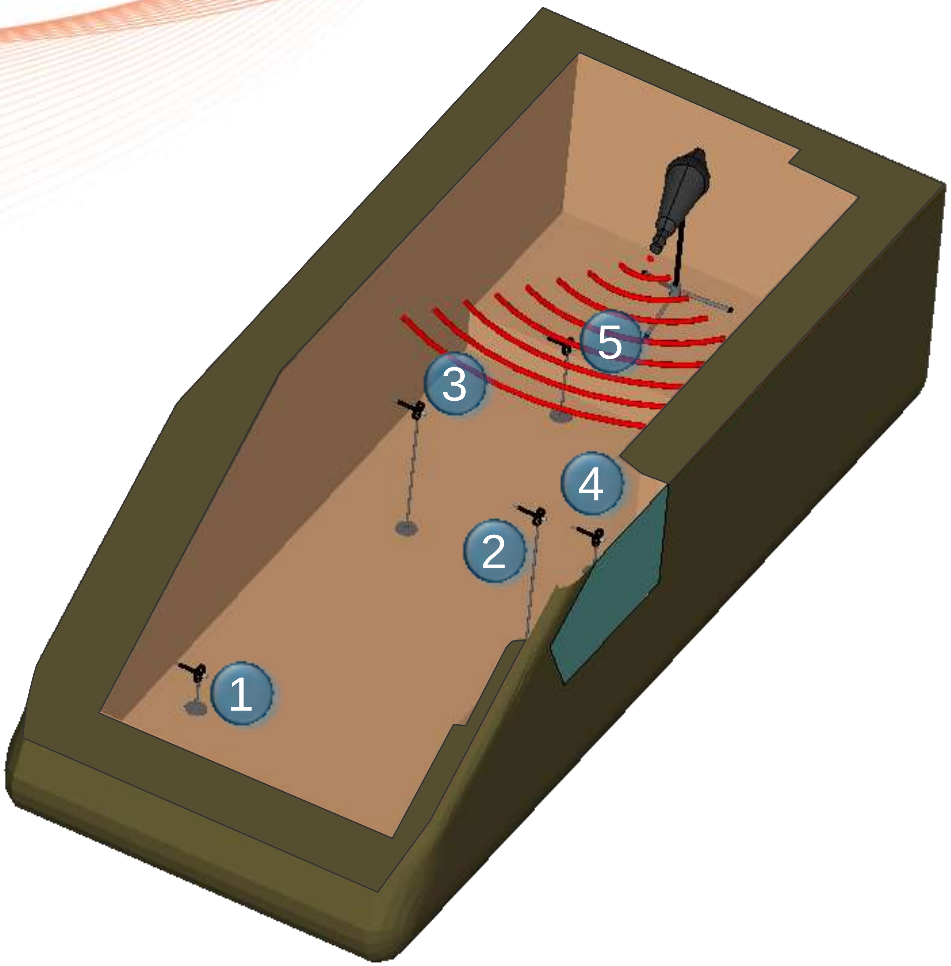
Validate that for an acoustic source inside SAE body, the VA model accuratly predicts:

- SPL at interior microphones
- Average SPL inside SAE body
- Radiated acoustic power by side glass
- SPL at exterior microphones for specific angles

Validate that for an acoustic source outside SAE body, the VA model accuratly predicts:

- SPL at interior microphones
- Average SPL inside SAE body

SPL inside SAE body

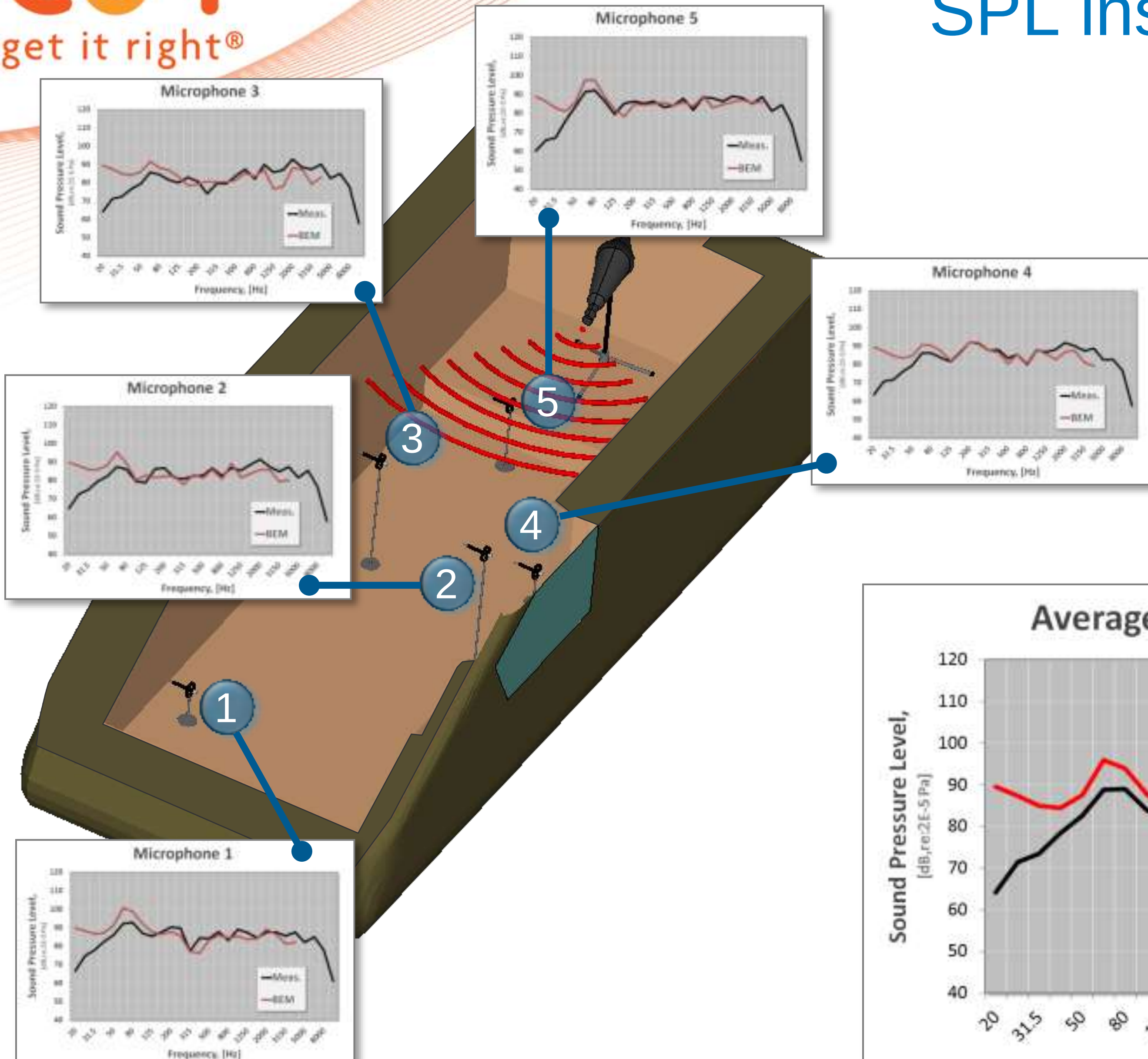


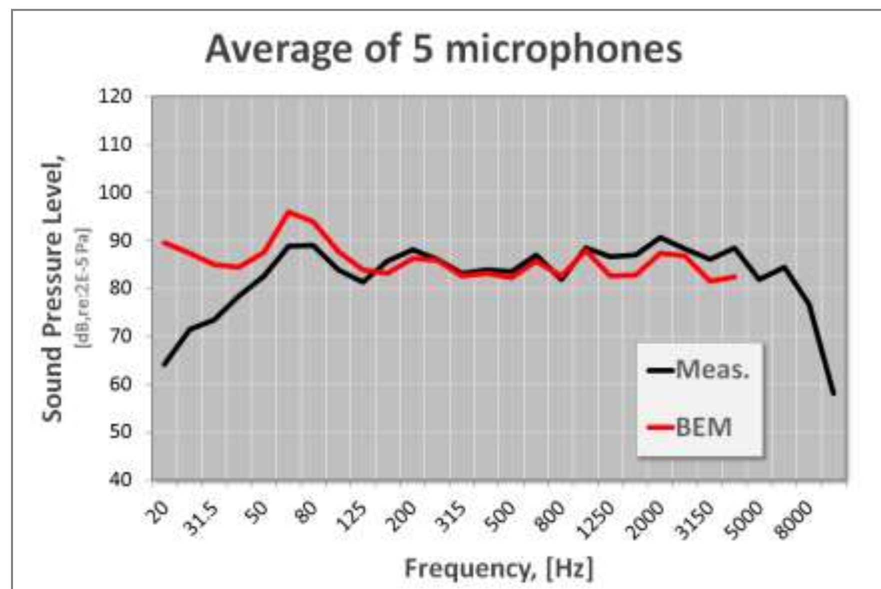
Objective:

Predict SPL at each interior microphones

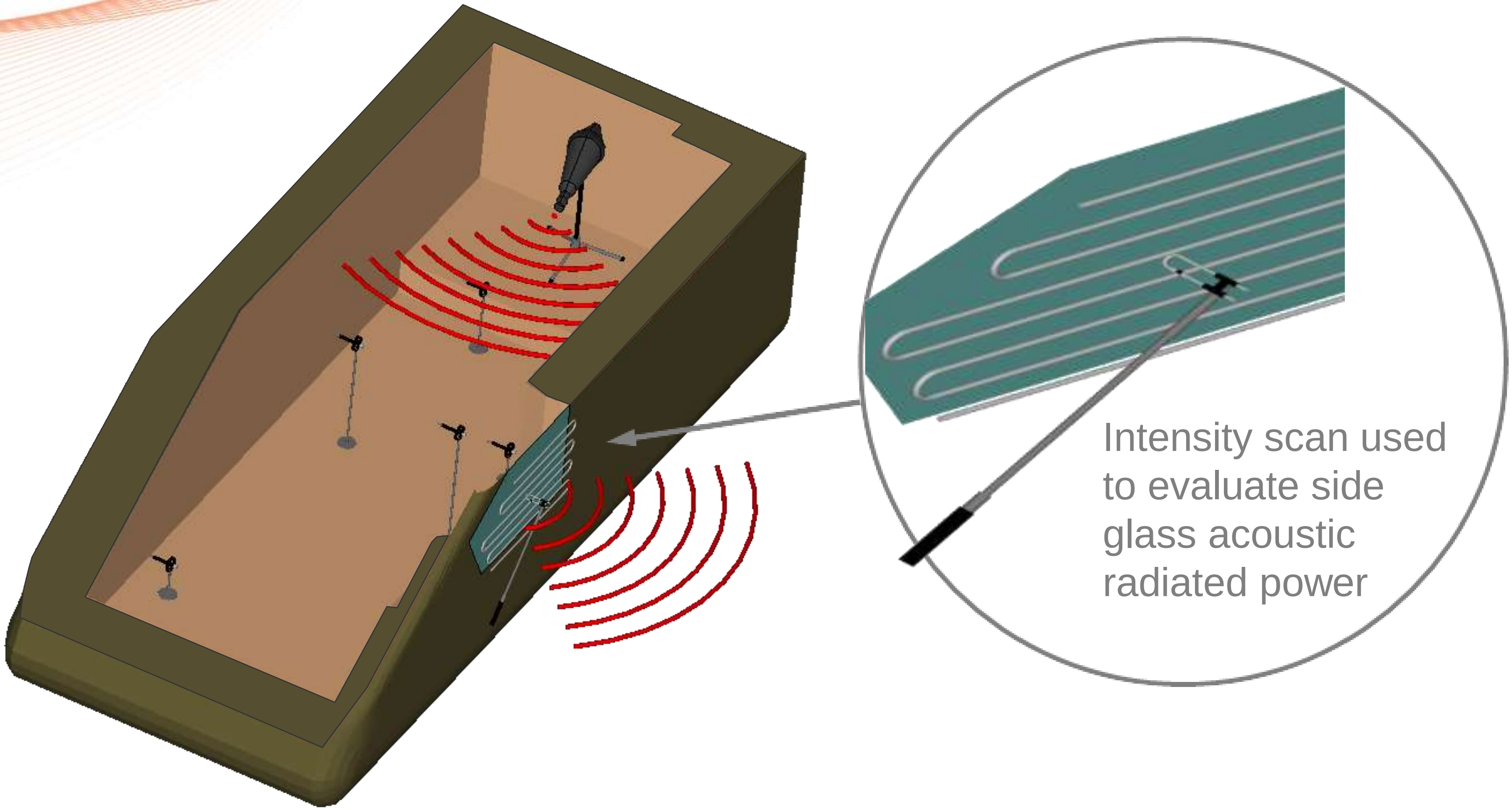
SPL inside SAE body

SPL at microphones can be predicted with reasonable accuracy suggesting that the Omnisource model is acceptable

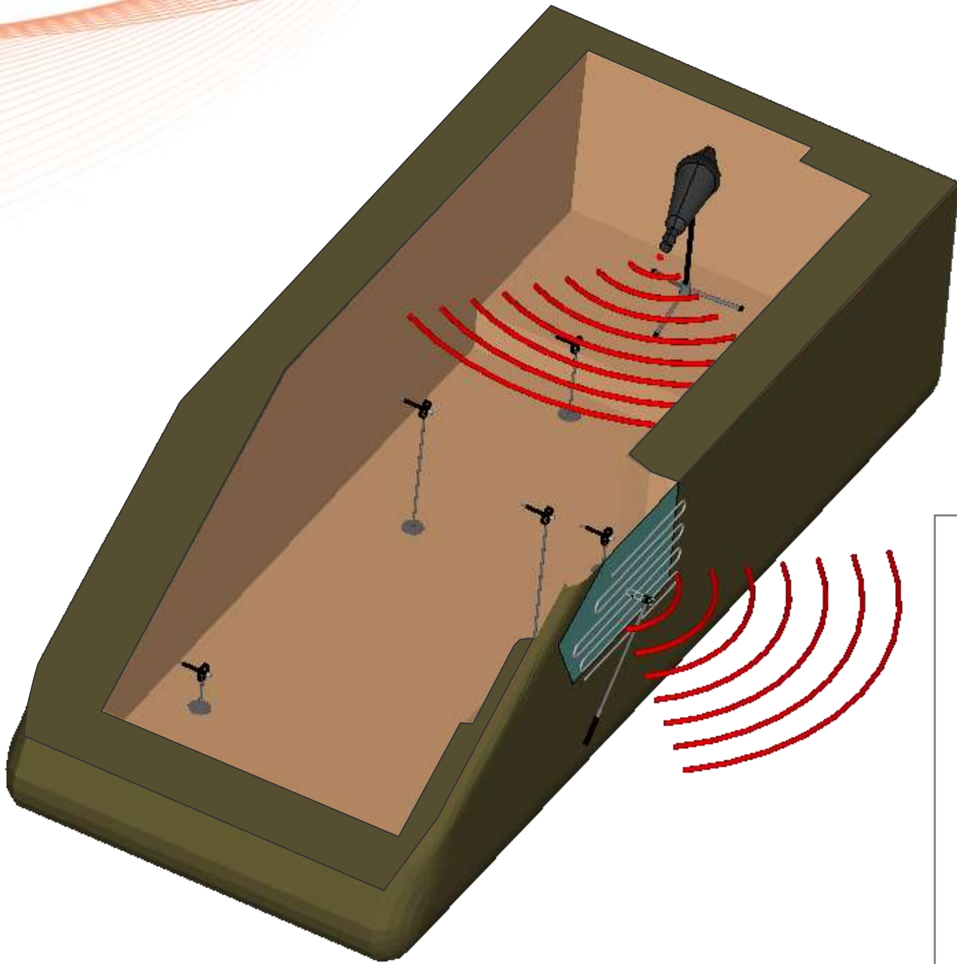




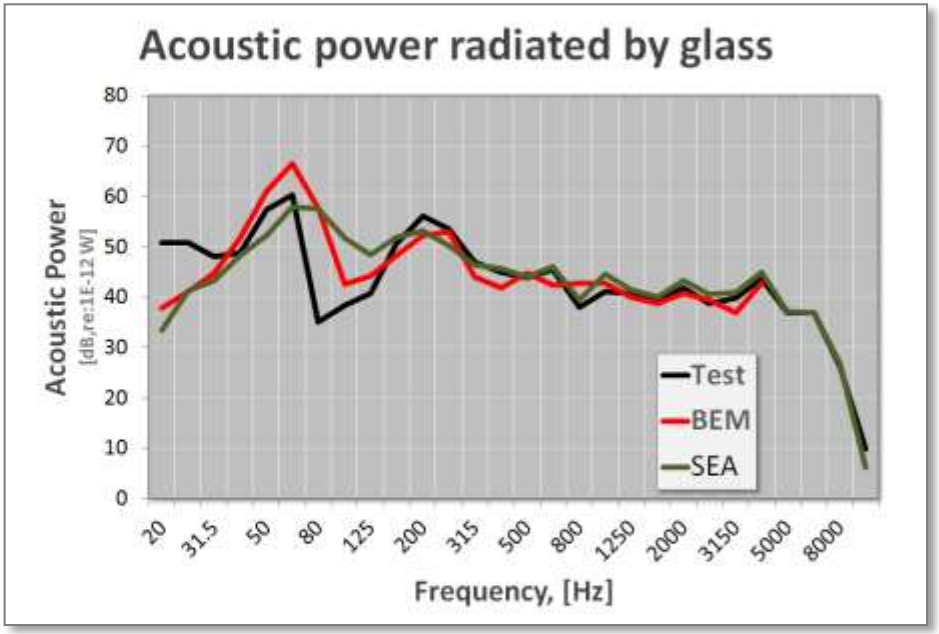
Side Glass Radiated Acoustic Power



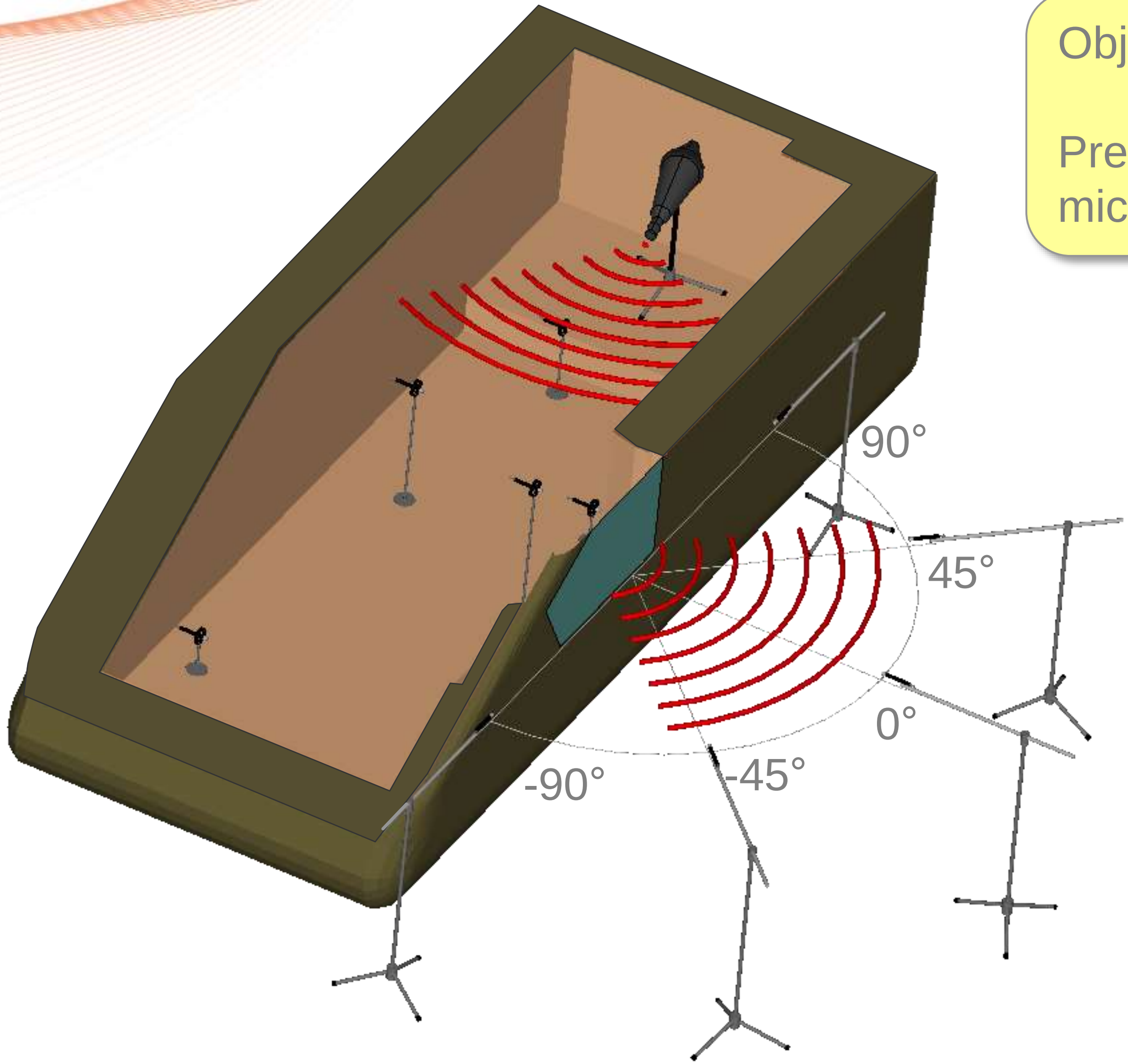
Side Glass Radiated Acoustic Power



Acoustic power radiated by side glass is predicted with high accuracy using either BEM-FEM-BEM or a pure SEA approach.



Exterior SPL at specific angles

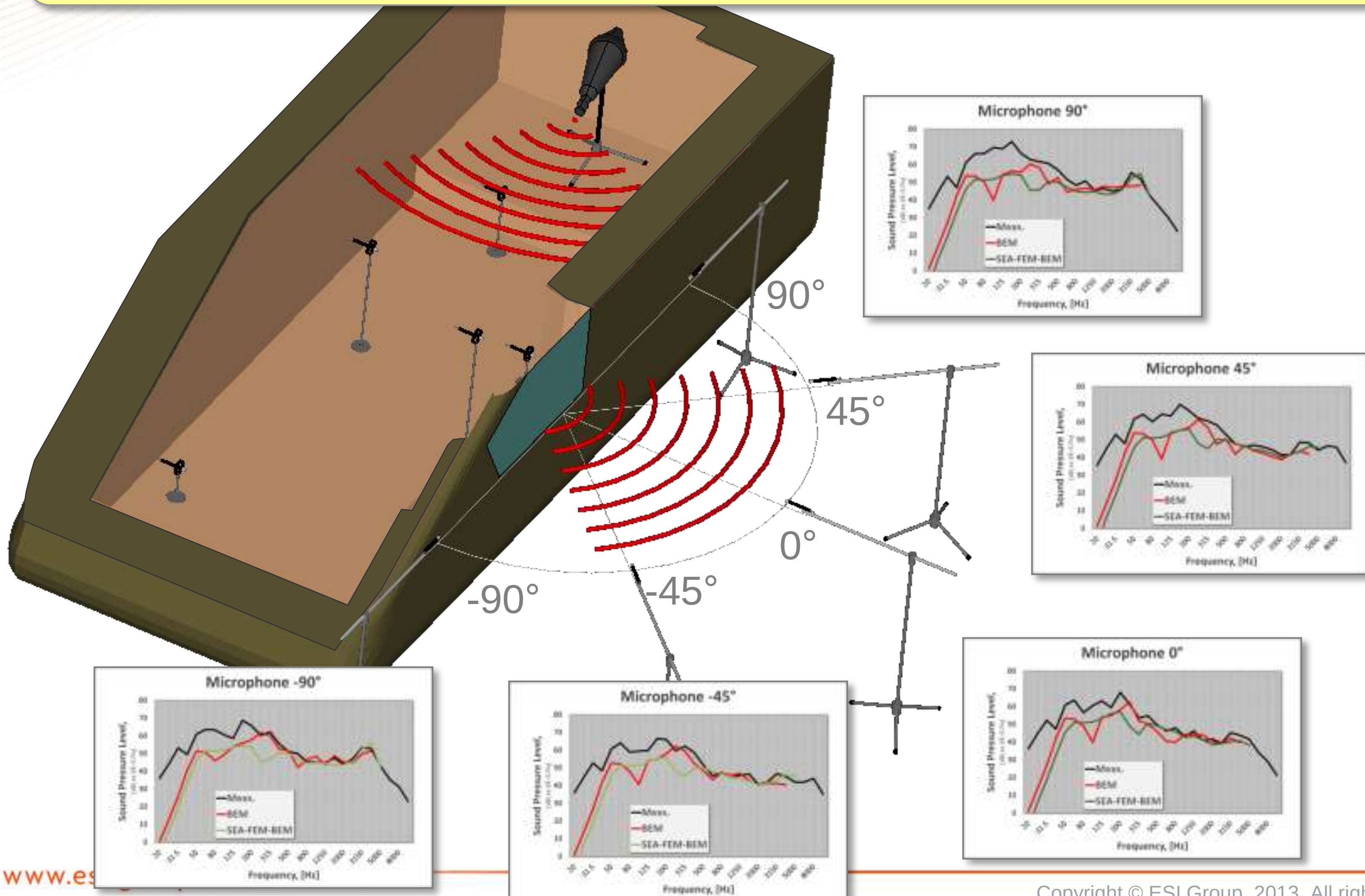


Objective:

Predict SPL at each exterior microphone

Exterior SPL at specific angles

At low frequencies, measurements results show higher contribution due to transparency (low NR) of SAE body walls. At high frequencies, NR is sufficiently different from glass to provide adequate correlation between test and simulation. Both BEM and SEA-FEM-BEM yield similar trend.



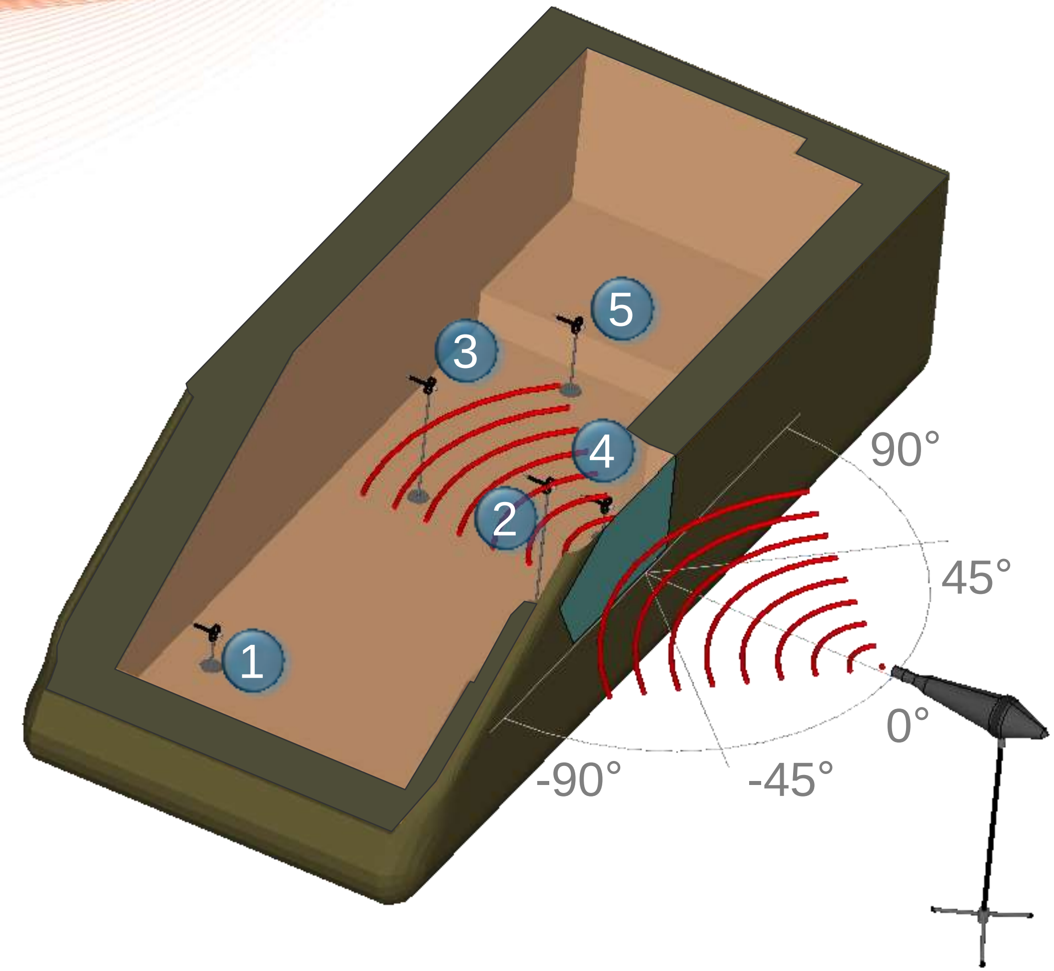
Validate VA model against test
Objectives:

Validate assumptions concerning SAE body walls
- Rigid surfaces
- NR larger than side glass

Validate that for an acoustic source inside SAE body, the VA model accuratly predicts:
- SPL at interior microphones
- Average SPL inside SAE body
- Radiated acoustic power by side glass
- SPL at exterior microphones for specific angles

Validate that for an acoustic source outside SAE body, the VA model accuratly predicts:
- SPL at interior microphones
- Average SPL inside SAE body

Interior SPL for 0°

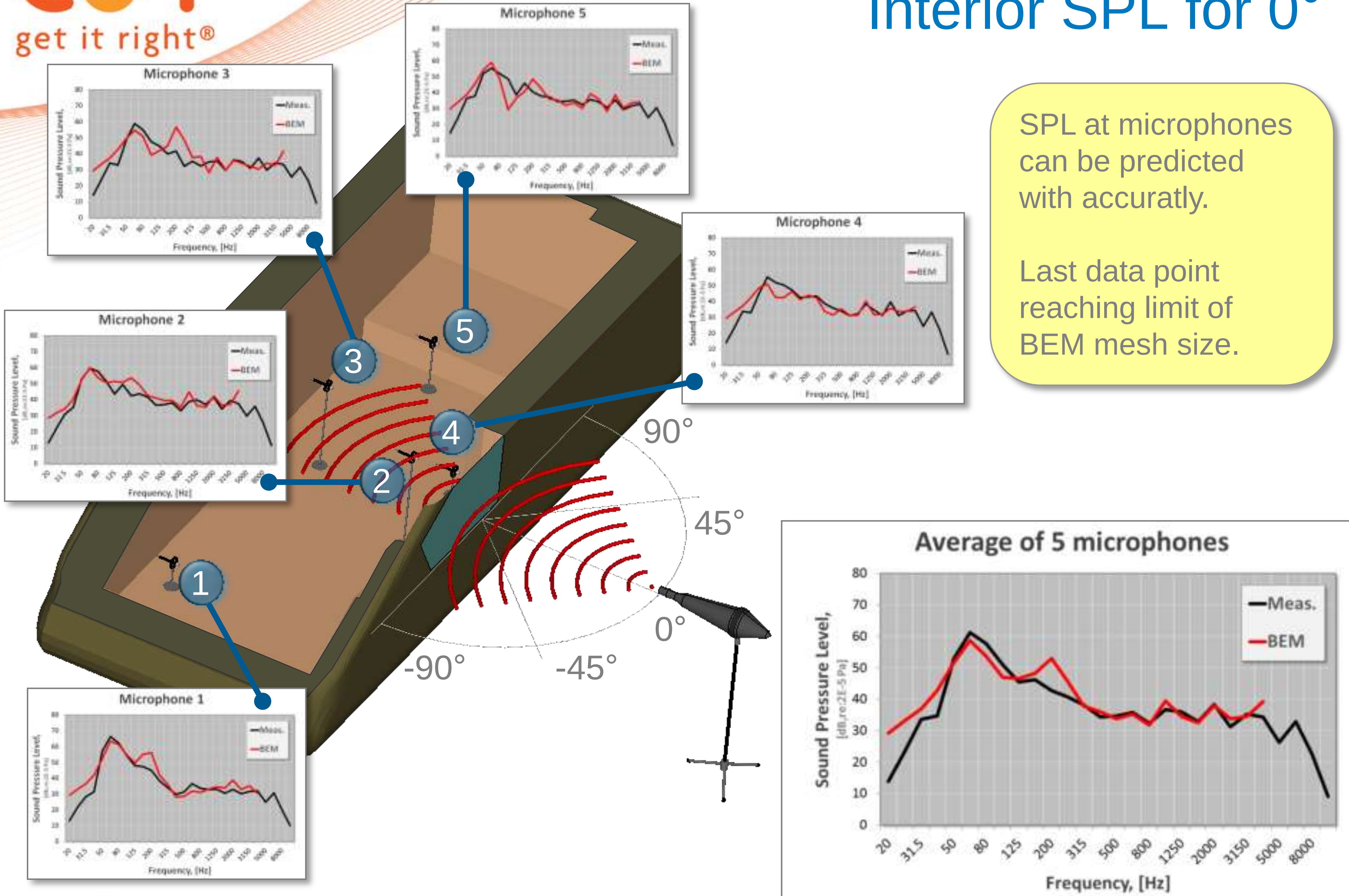


Objective:

Predict SPL at each interior microphone for a directional source outside

(Setup close to windnoise excitation of side glass)

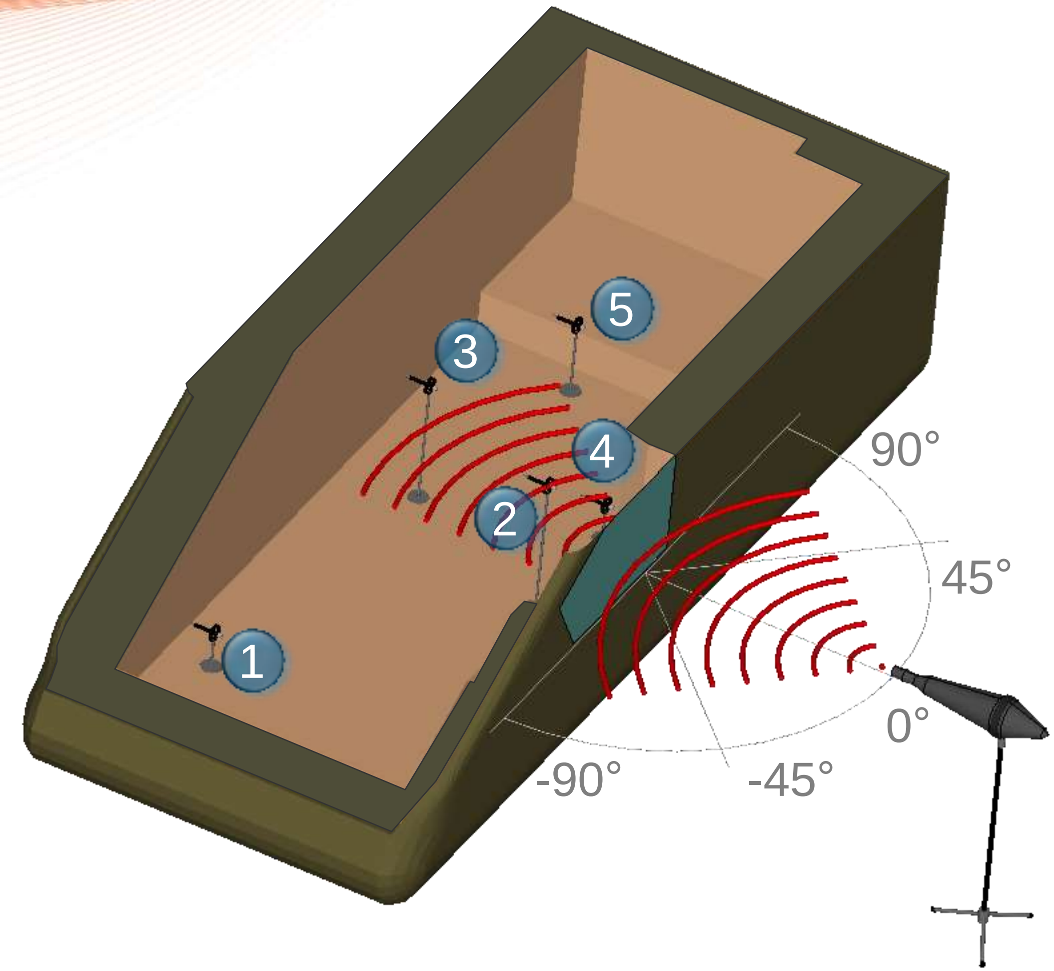
Interior SPL for 0°



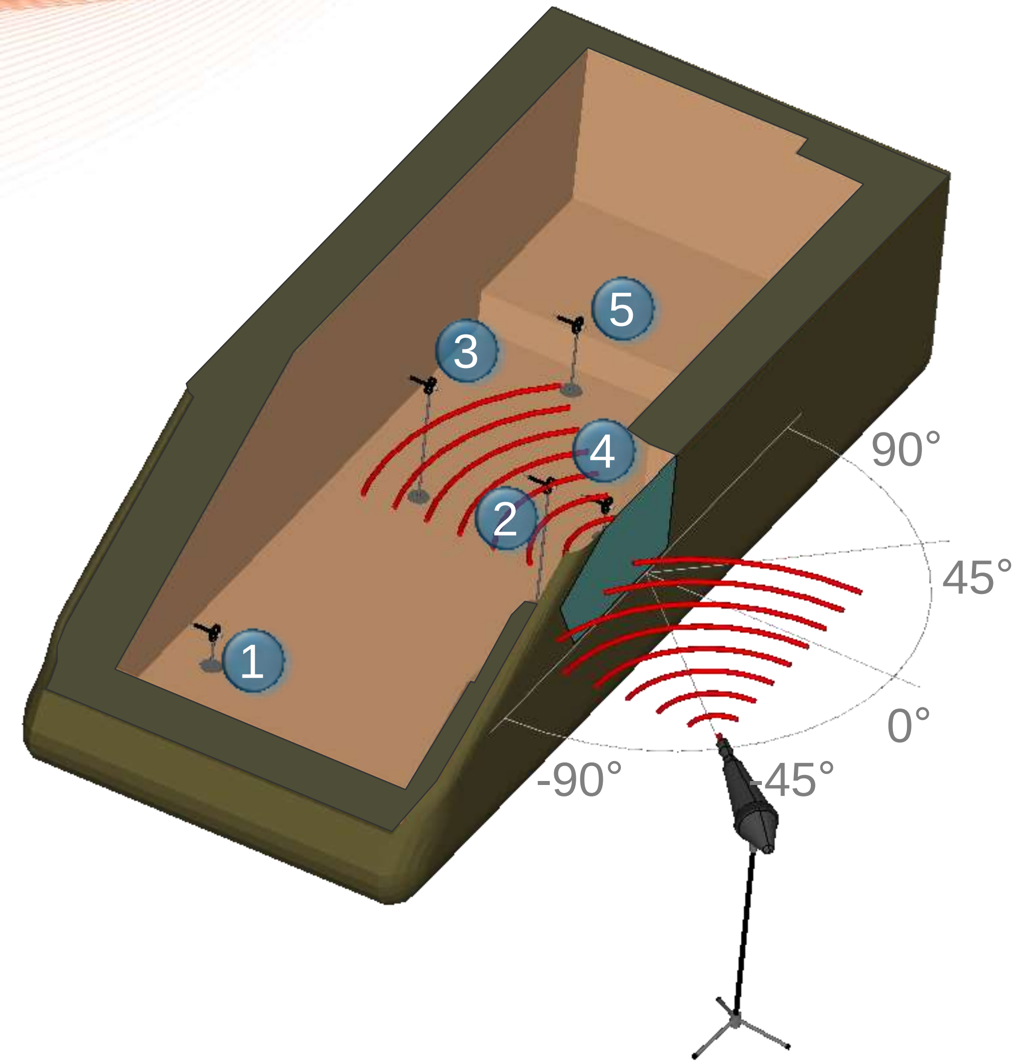
SPL at microphones can be predicted with accuratly.

Last data point reaching limit of BEM mesh size.

Interior SPL for 0°



Interior SPL for -45°

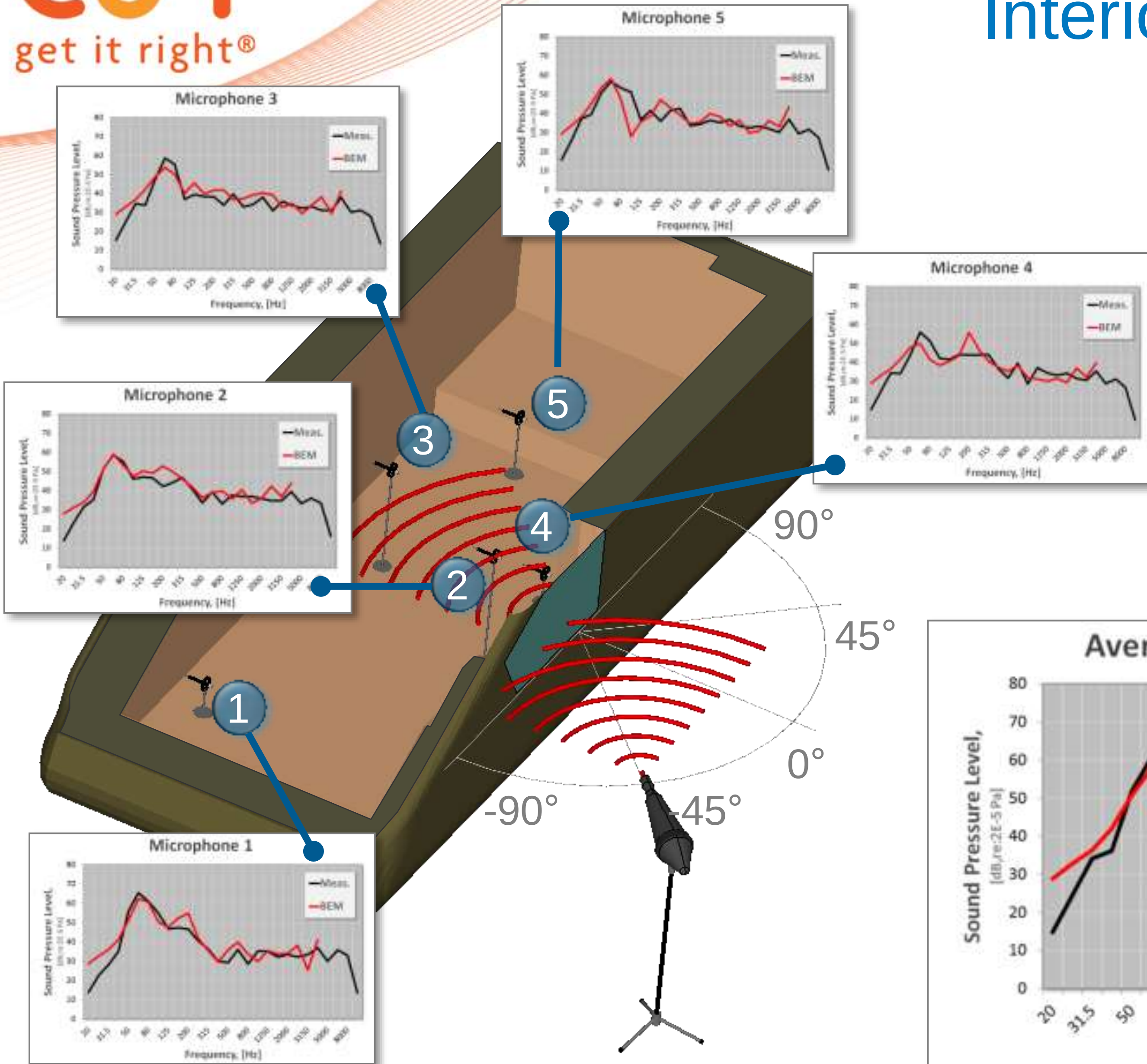


Objective:

Predict SPL at each interior microphone for a directional source outside

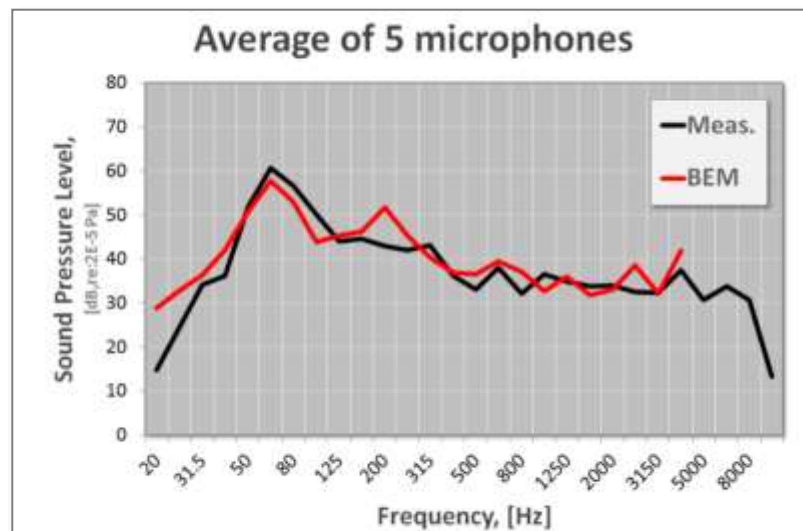
(Setup close to windnoise excitation of side glass)

Interior SPL for -45°

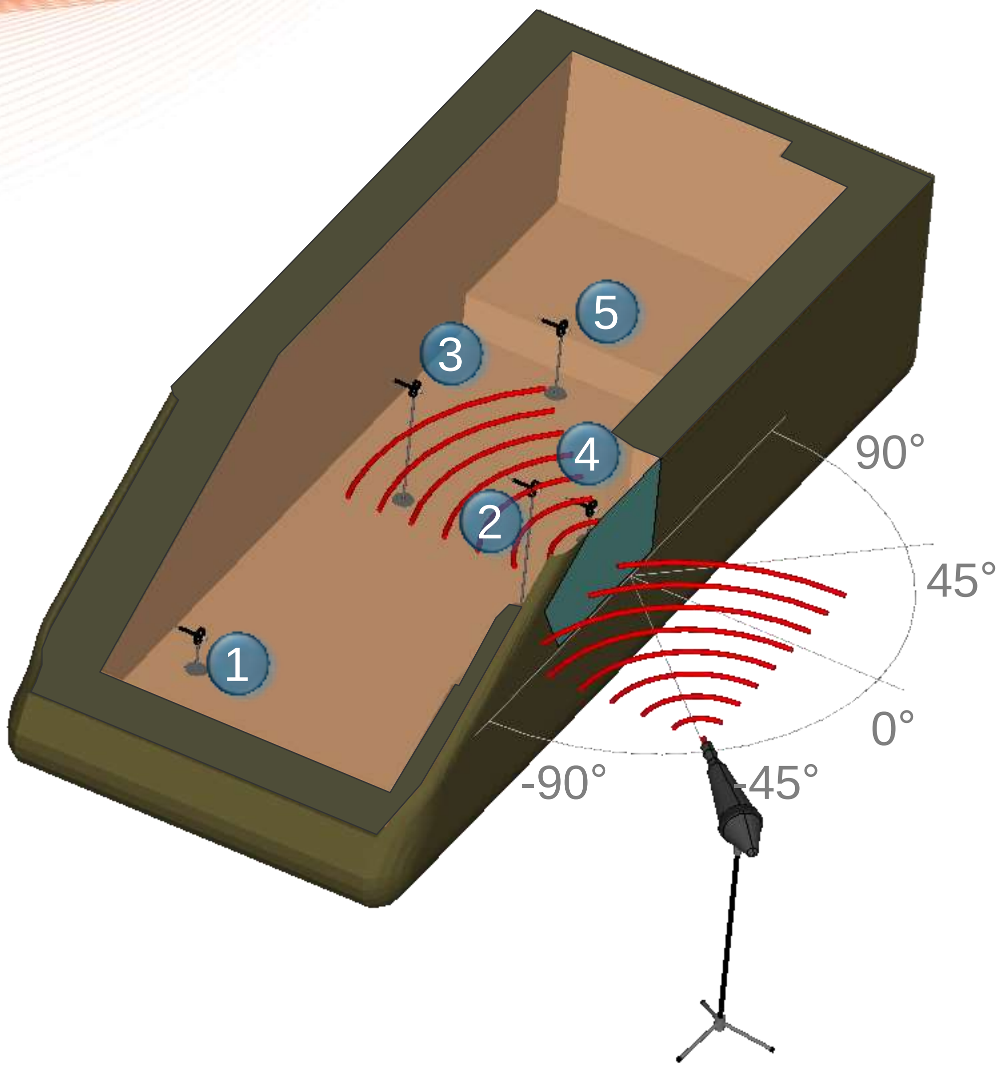


SPL at microphones can be predicted with accuratly.

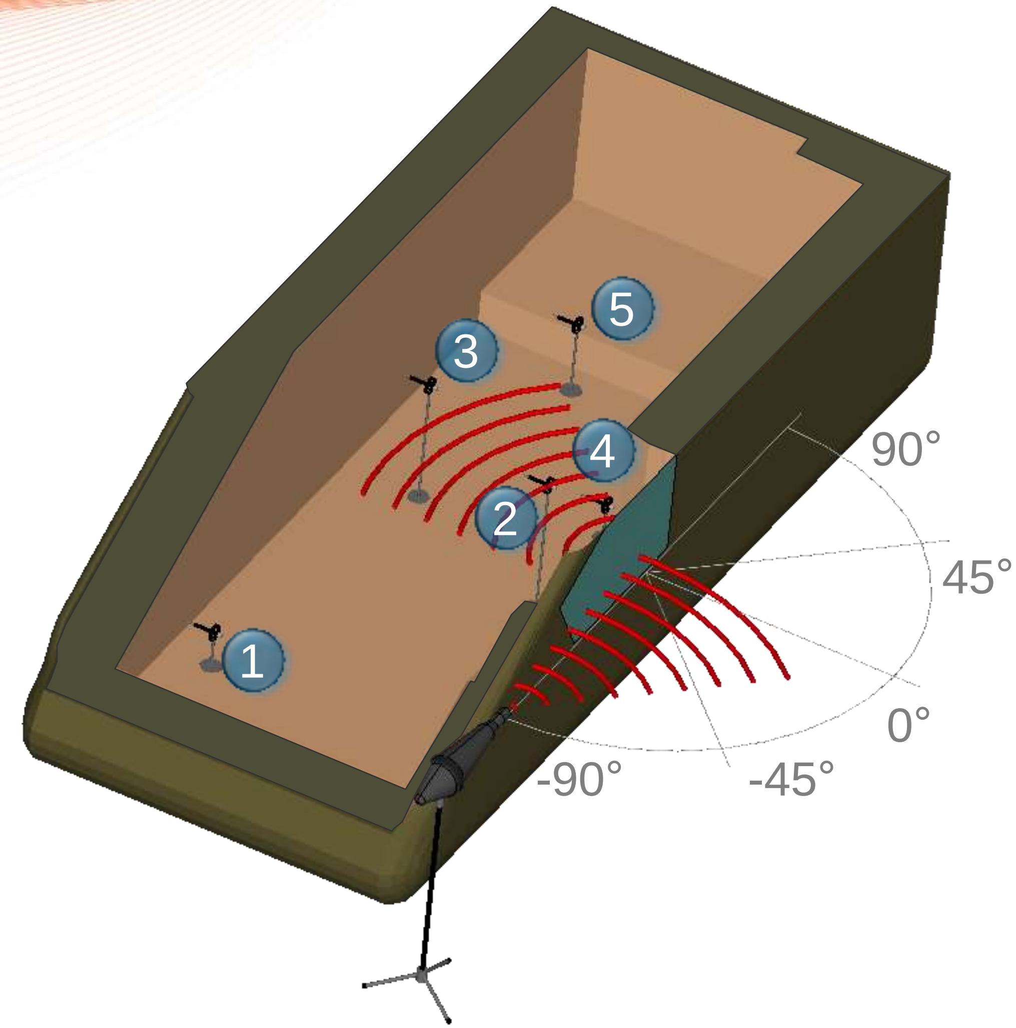
Last data point reaching limit of BEM mesh size.



Interior SPL for -45°



Interior SPL for -90°



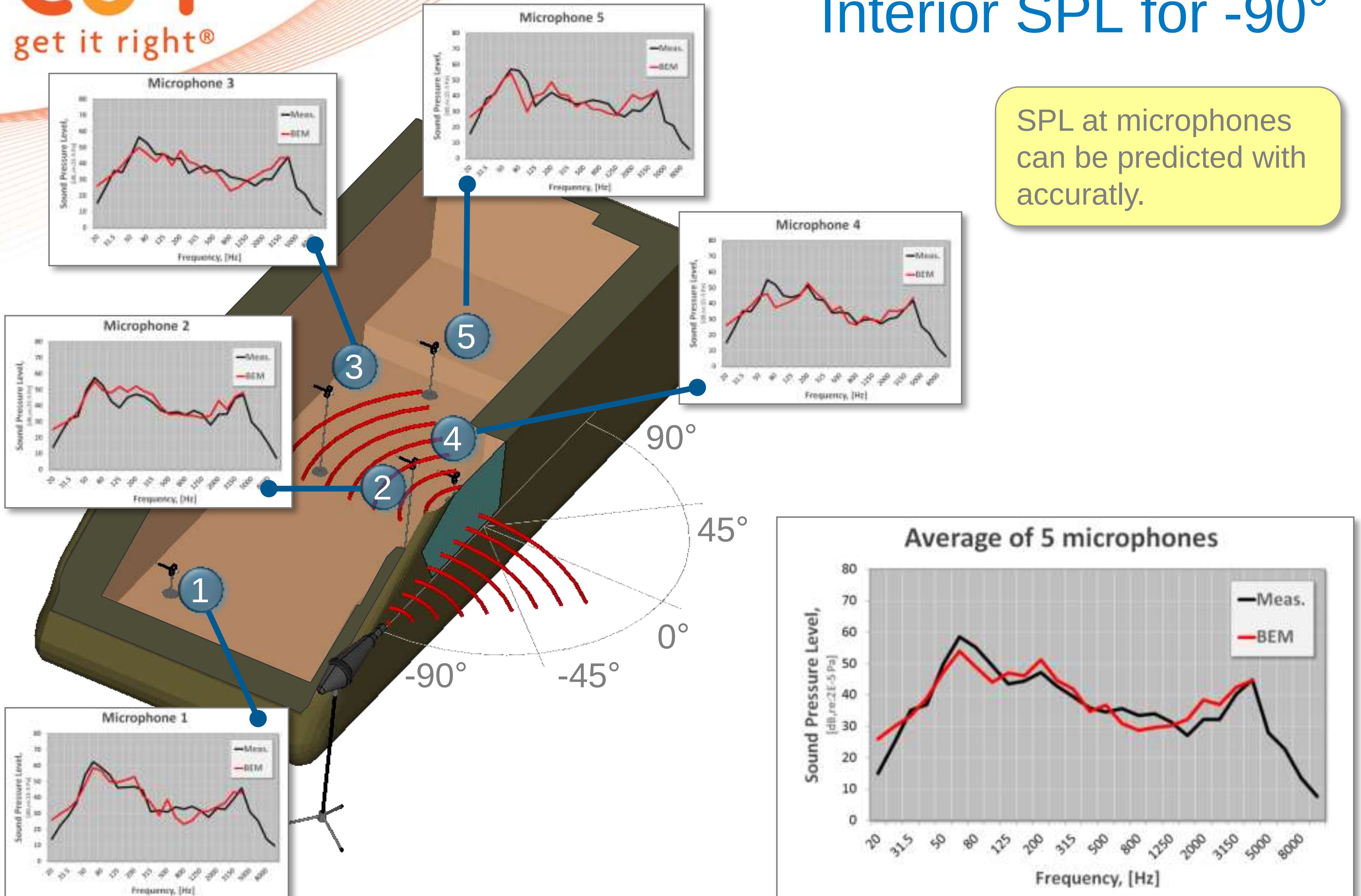
Objective:

Predict SPL at each interior microphone for a directional source outside

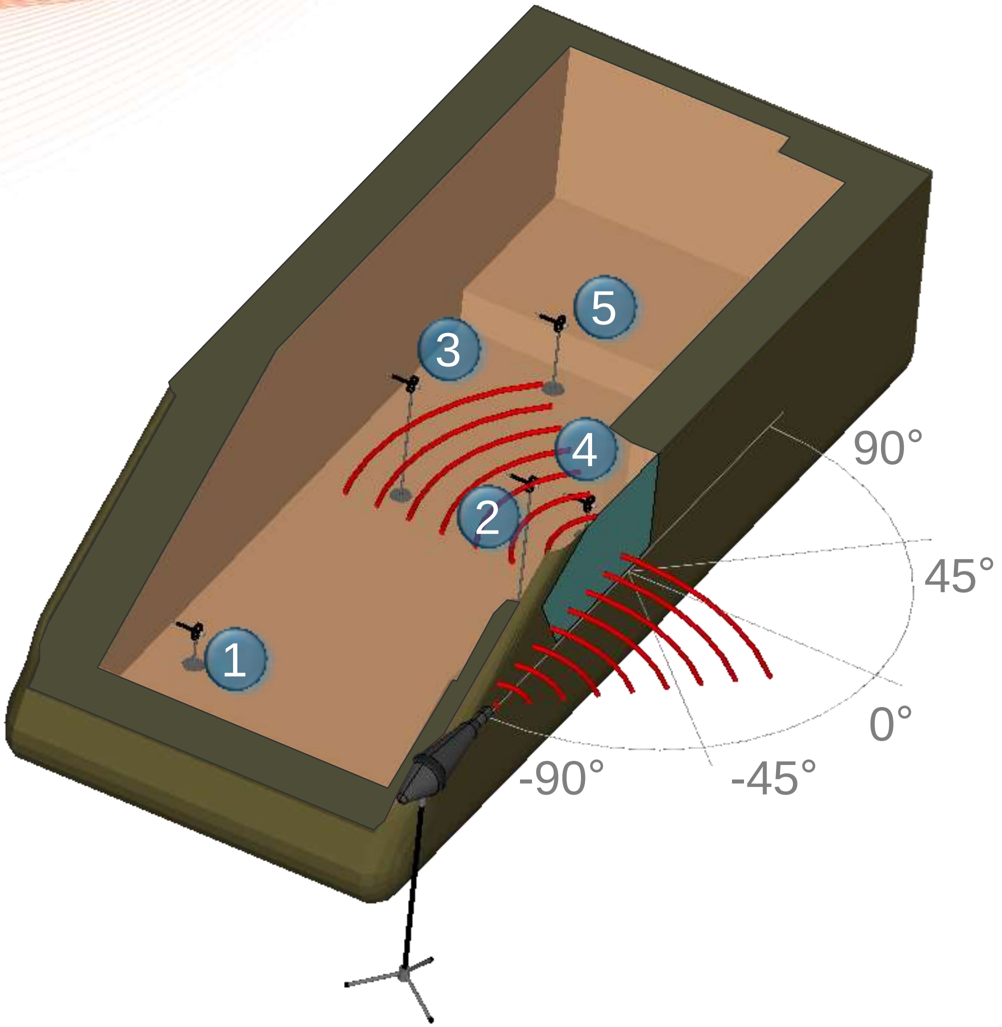
(Setup close to windnoise excitation of side glass)

Interior SPL for -90°

SPL at microphones can be predicted with accuratly.



Interior SPL for -90°



Conclusion

- Validation of several vibro-acoustic models of a generic vehicle shape (SAE body) was performed
- Several methods have been used and coupled to show level of accuracy
- Correlation is acceptable at frequencies higher than 300 Hz . This allows the VA models to be used with windnoise sources
- The accuracy reference method is FEM-BEM. Other methods such as FE/SEA coupled and pure SEA are faster methods that can be used in the design process when fast turn around time is needed

Thank you

Wind Noise Source Characterization and How it Can be Used to Predict Vehicle Interior Noise

Denis Blanchet

Anton Golota

Nov 16 2013

Global Objectives

Vibro-Acoustic session - Morning

Create an accurate vibro-acoustic model that represents the SAE body so it can be used for windnoise prediction

Validate the vibro-acoustic model against semi-anechoic room Measurements

Create predictive windnoise model to predict SPL inside SAE body using the vibro-acoustic model coupled to CFD source model

Validate windnoise predictions against wind tunnel measurements

Aero-Vibro-Acoustic session - Afternoon

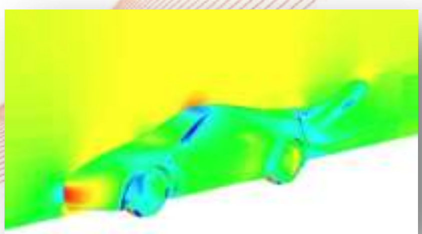
Global Objectives

Vibro-Acoustic session - Morning

- Create an accurate vibro-acoustic model that represents the SAE body so it can be used for windnoise prediction
- Validate the vibro-acoustic model against semi-anechoic room Measurements
- Create predictive windnoise model to predict SPL inside SAE body using the vibro-acoustic model coupled to CFD source model
- Validate windnoise predictions against wind tunnel measurements

Aero-Vibro-Acoustic session - Afternoon

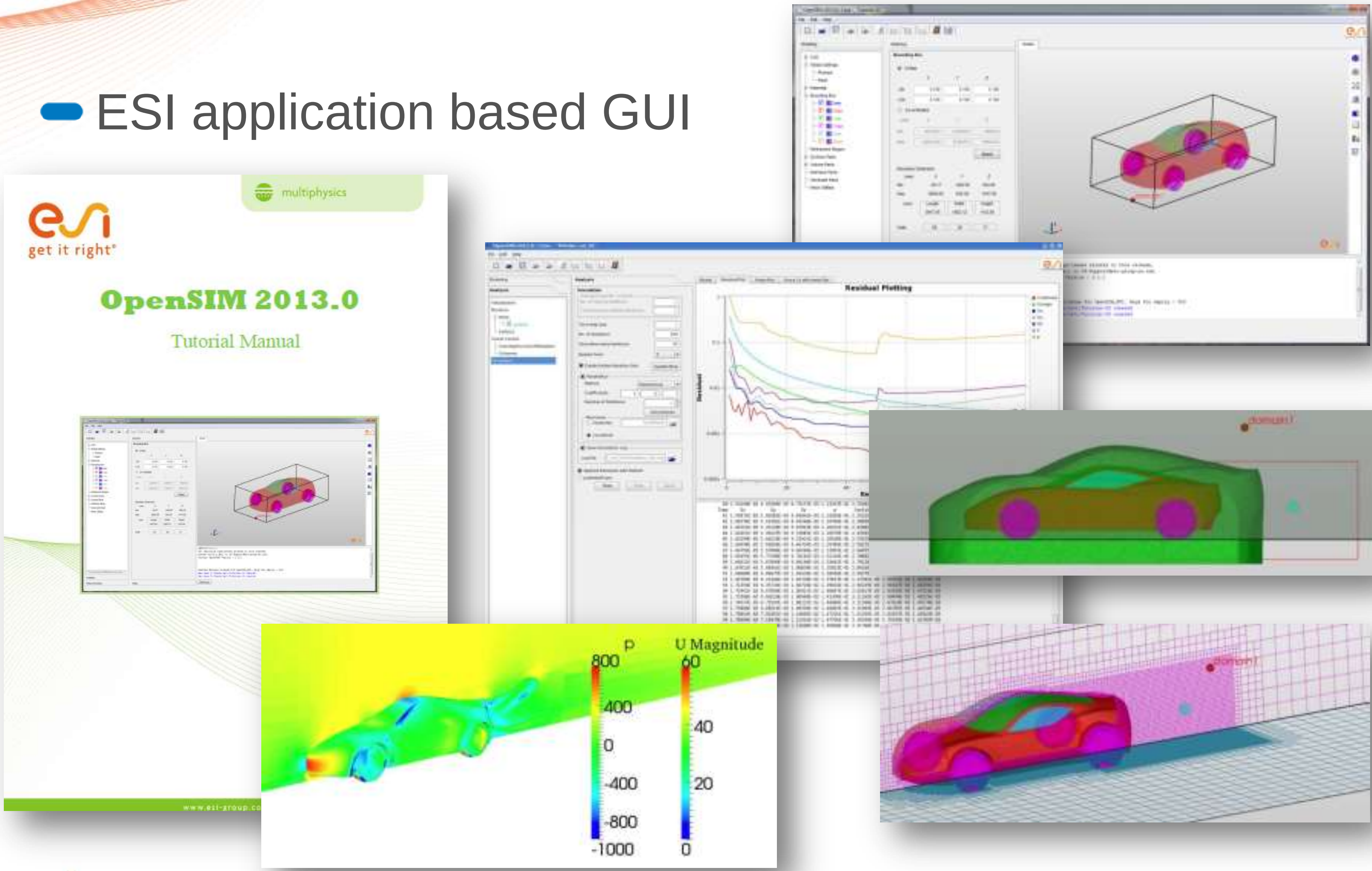
OpenCFD Ltd. Acquisition



- **OpenFOAM®** is a free, open source CFD software toolbox
- **OpenCFD Ltd** contributes software, integrates modules and generates documentation to the OpenFOAM® software
- **OpenFOAM Foundation** is a non-profit organization which was established for the purpose of ensuring the sustainable distribution of OpenFOAM®
- **11 September 2012**
  - Acquisition of OpenCFD Ltd., the leader in Open Source software in Computational Fluid Dynamics, now called ESI-OpenCFD
  - ESI becomes owner of OpenFOAM® trademark
  - ESI becomes producer of OpenFOAM® software
- **ESI-OpenCFD** will continue to manage the development, production and maintenance of the OpenFOAM® Software, for distribution through the OpenFOAM Foundation

OpenFOAM GUI

- ESI application based GUI



ESI Group CFD BU
Experience and Resources

CFD = Computational Fluid Dynamics
BU = Business Unit

- Offices for Engineering Services in
  - NA
  - Europe
  - East Asia
  - India
    - **Therefore, ESI is very competitive for cost**

- Over 100 CFD engineers (40% Ph.D.'s, 50% MS's) specialized in variety aspects of Computational Fluid Dynamics (CFD), such as:
  - Automotive - Aerospace
  - Fuel Cell & Batteries - Plasma & Thin Film
  - Powertrain - Solar & Green Energy
  - Medical - Vibroacoustics
  - Ocean Waves (SPH) - EMAG
    - **Therefore, no challenge is considered too big (try us!)**

- Access to major commercial solvers
    - **Therefore, it can handle any type of projects and develop customized solutions**
    - **Unique for a CFD proprietary software and services provider!**

ESI Group CFD BU Experience and Resources

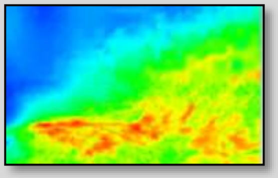
- CFD experience for a wide range of applications since 1990
- OpenFOAM experience since 2006
- Extensive hardware resources based in USA and Europe

- Proprietary
  - **ACE+**
  - CFX
  - **FASTRAN**
  - FLUENT
  - **PAM-FLOW**
  - PowerFlow
  - RadTherm
  - STAR-CCM+
  - **UH3D**
  - AMESIM
  - Dymola
  - Flowmaster
  - GT-Suite
  - KULI
- Open Source
  - Dakota
  - FDS
  - **OpenFOAM**
- PRE
  - ANSA
  - **CFD-GEOM**
  - **CFD-VisCART**
  - ICEM
  - **OpenSIM**
  - T-GRID
- POST
  - CFD-POST
  - **CFD-View**
  - Ensight
  - ParaView

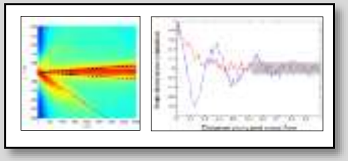
Tools in **ORANGE** denote ESI licensed software

From Turbulent Flow to Interior Noise

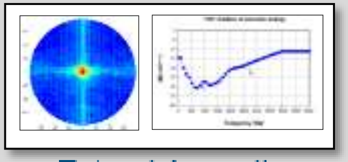
Source characterization



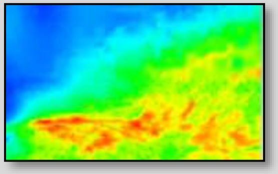
Experimental



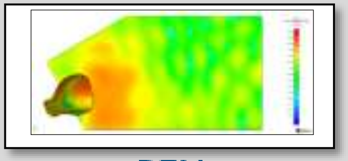
Extract Convective component



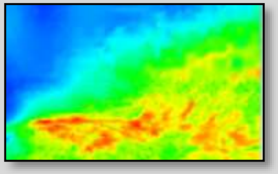
Extract Acoustic component



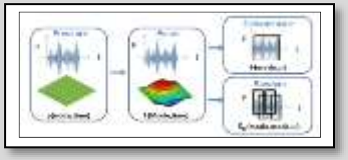
CFD Incompressible



BEM



CFD Compressible



Modal Forces (F,Sff)

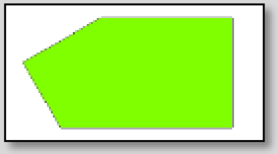
Source

Corcos

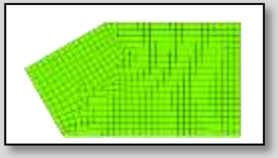
PWF

F, Sff

Glass

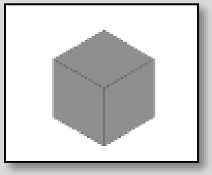


SEA

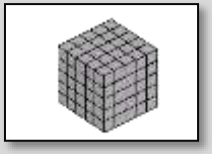


FEM

Interior



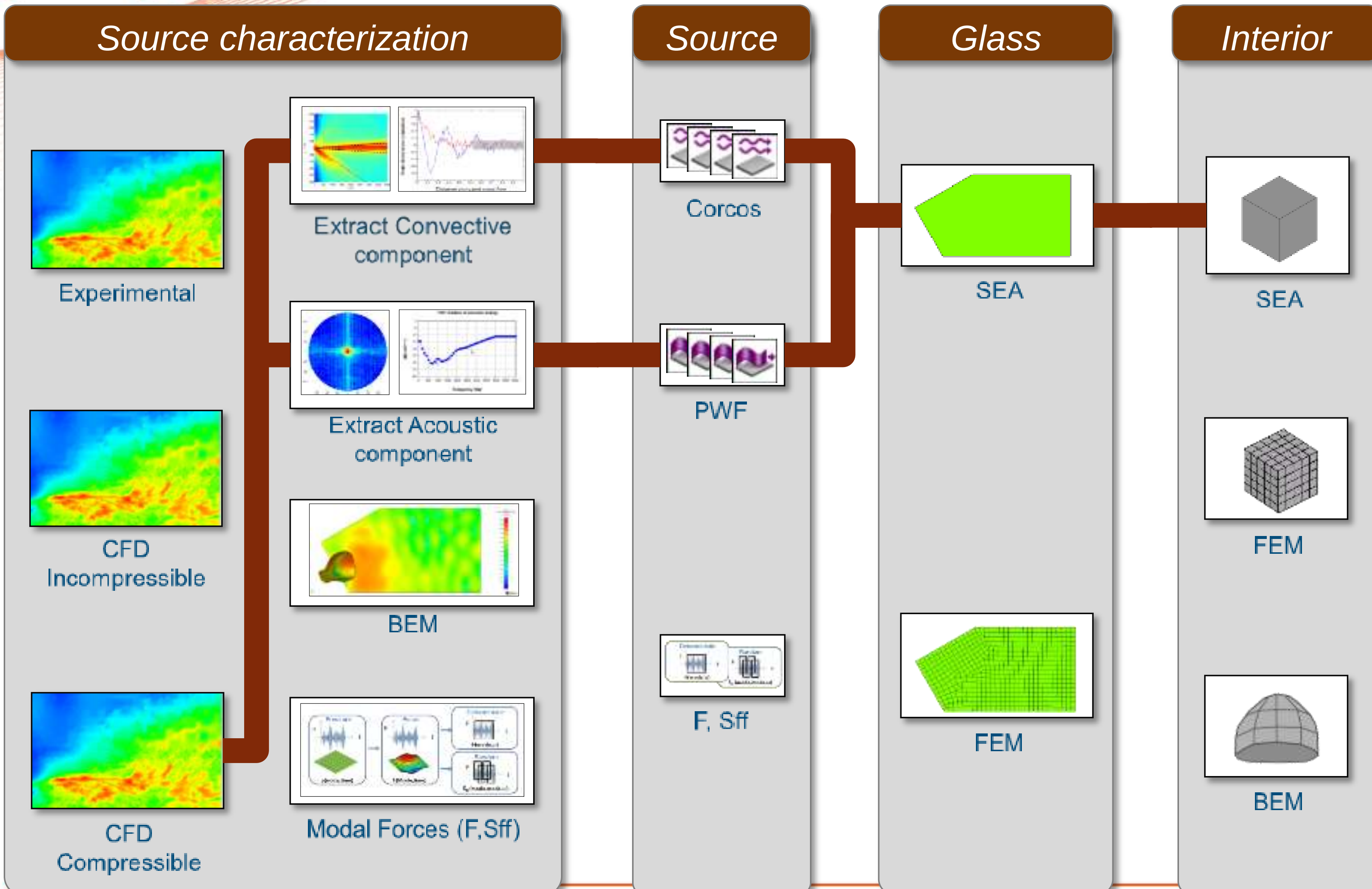
SEA



FEM

BEM

A few options studied so far…

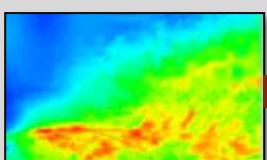


A few options studied so far…

Source characterization	Source	Glass	Interior

Experimental

CFD Incompressible



CFD Compressible

- StarCCM+ Version 6.06.017
- Half model of SAE body, with side mirror (+side glass & 10mm downset)
- Model size: 45 up to 46 million fluid cells (dependent on configuration)
- Compressible Detached Eddy Simulation (DES) based on Spalart-Allmaras (S-A)
- Δt CFD = 2E-05s
- First 0.1s of simulated physical time has been cut away: spurious transition phenomena when starting a transient computation based on steady state results
- Pressure-time histories on A-pillar, side glass and rear mirror surface of each model

A few options studied so far…

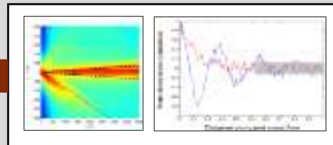
get it right®

Source characterization

Experimental

CFD Incompressible

CFD Compressible



Extract Convective component

Extract Acoustic component

BEM

Modal Forces (F,Sff)

Source

Glass

Interior

Corcos model of Turbulent Flow

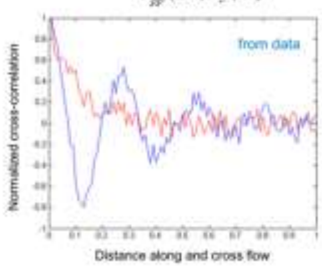
Corcos model describes a spatially stationary pressure field:
Spp depends on distances between points along the flow and cross flow

Average surface pressure — Convection wavenumber

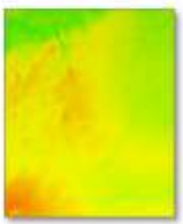
$$\mathbf{S}_{pp}(\Delta x,\Delta y,\omega) = p(\omega)^2 e^{-\alpha_x|\Delta x|-\alpha_y|\Delta y|} e^{-ik_c\Delta x}$$

Spatial correlation decay coefficients

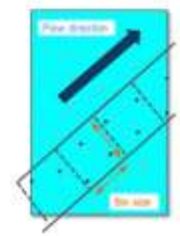
$\mathbf{S}_{pp}(\Delta x,\Delta y,\omega)$



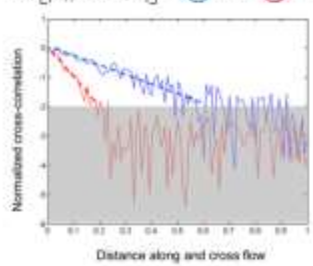
$p(\omega)^2 = \langle\{\mathbf{S}_{pp}(\omega)\}_{ii}\rangle_{node}$



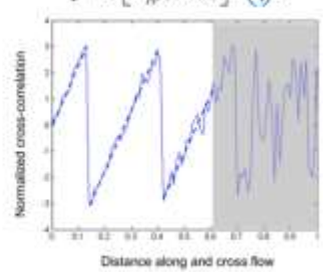
R_{pp} -> spatial average



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



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

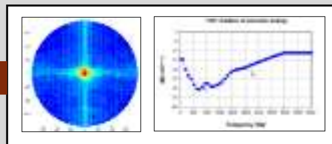


A few options studied so far…

Source characterization | **Source** | **Glass** | **Interior**

Experimental

Extract Convective component



Extract Acoustic component

CFD Incompressible

BEM

CFD Compressible

Modal Forces (F,Sff)

SEA

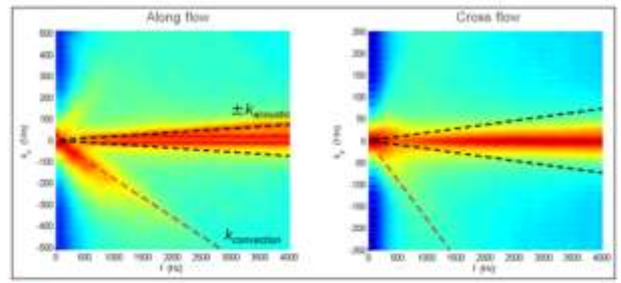
FEM

BEM

1 1D wavenumber transforms

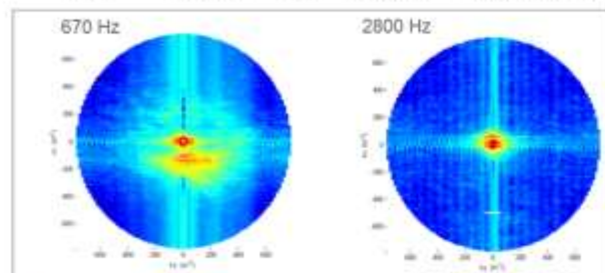
$P(X,t) \rightarrow P(X,\omega)) \rightarrow Rpp(\Delta x,\omega) \rightarrow Rpp(kx,\omega)$

$P(X,t) \rightarrow P(X,\omega)) \rightarrow Rpp(\Delta y,\omega) \rightarrow Rpp(ky,\omega)$



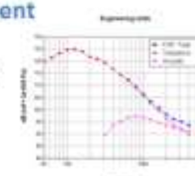
2 2D wavenumber transforms

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

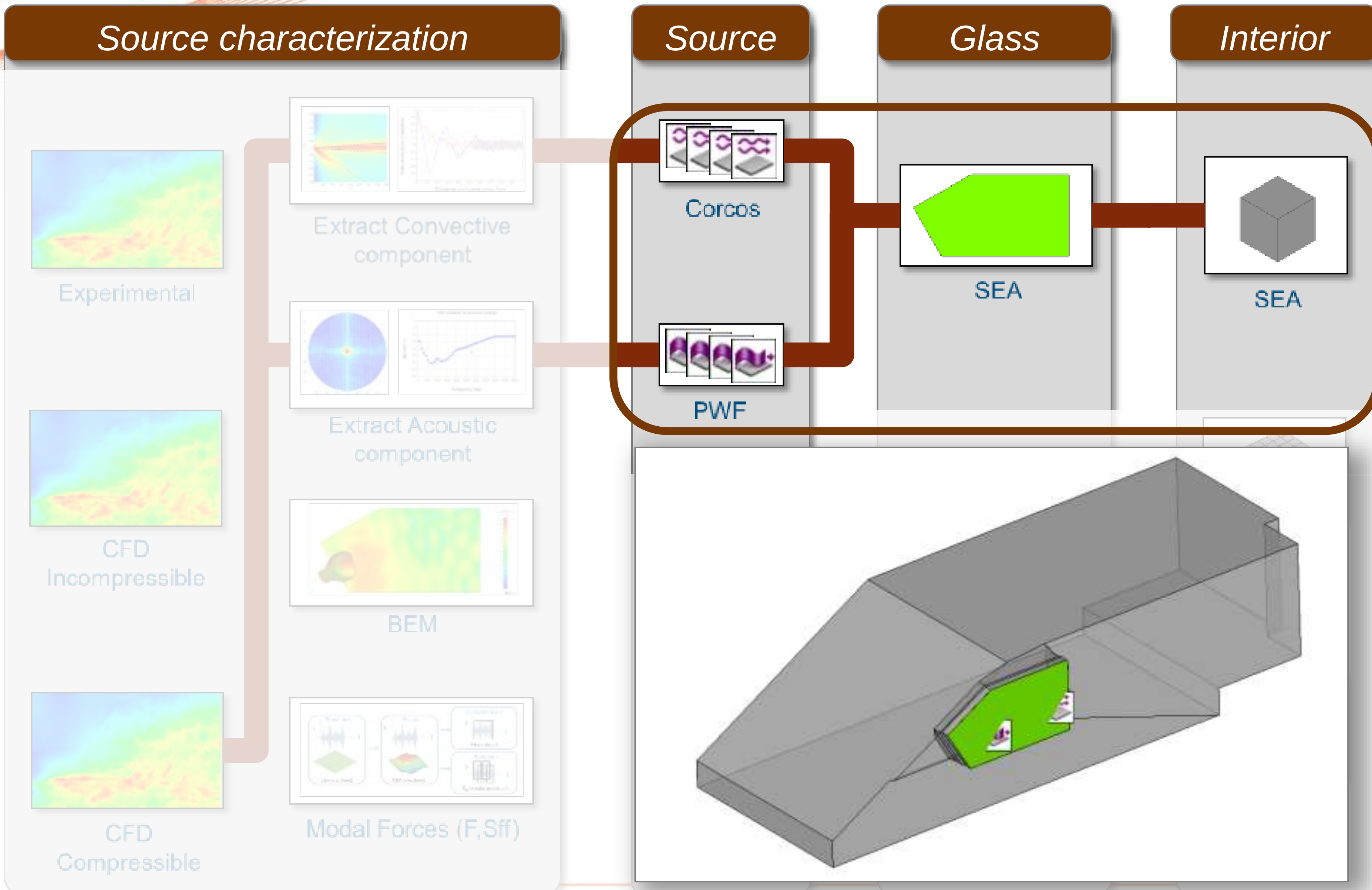


3 Computing acoustic component

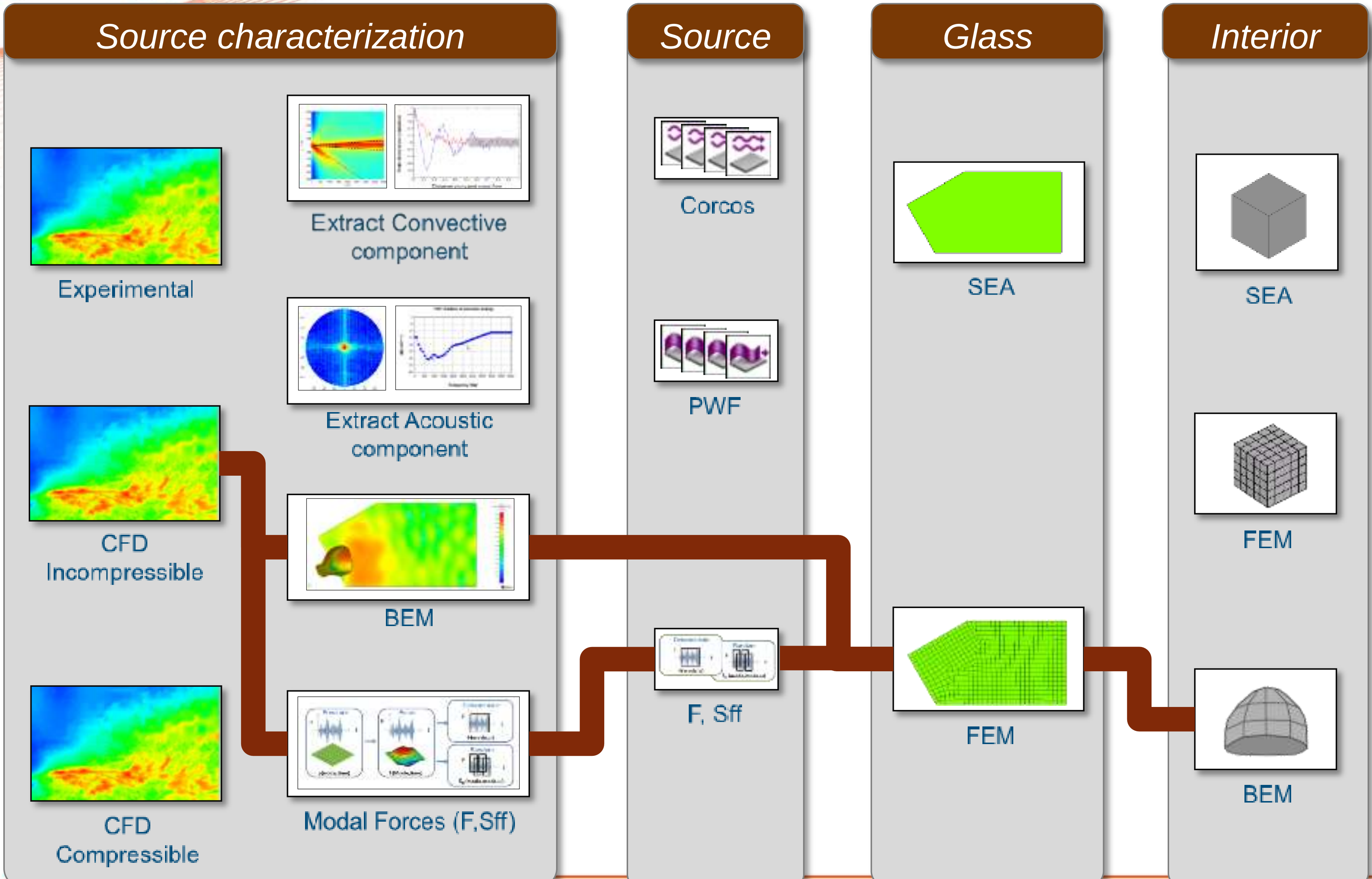
Computed by integrating 2D spatial correlation function within the acoustic circle



A few options studied so far…



A few options studied so far…

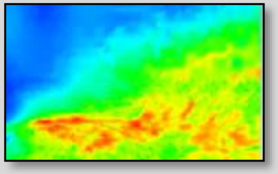


A few options studied so far…

Source characterization | *Source* | *Glass* | *Interior*

Experimental

CFD
Incompressible



CFD
Compressible

Modal Forces (F,Sif)

- StarCCM+ Version 6.06.017
- Half model of SAE body, with side mirror (+side glass & 10mm downset)
- Model size: 45 up to 46 million fluid cells (dependent on configuration)
- Compressible Detached Eddy Simulation (DES) based on Spalart-Allmaras (S-A)
- Δt CFD = 2E-05s
- First 0.1s of simulated physical time has been cut away: spurious transition phenomena when starting a transient computation based on steady state results
- Pressure-time histories on A-pillar, side glass and rear mirror surface of each model

A few options studied so far…

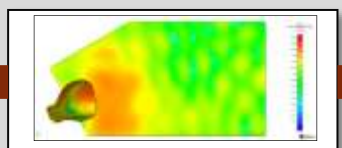
Source characterization

Experimental

Extract Convective component

Extract Acoustic component

CFD Incompressible



BEM

CFD Compressible

Modal Forces (F,Sff)

Source

Glass

Interior

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

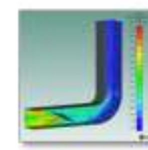
$$(1/2)p_a(\mathbf{y}) = \int_S p_s \frac{\partial G}{\partial x_i} n_i(\mathbf{x})\mathrm{d}S(\mathbf{x}) - \int_V \frac{\partial^2 (G-G_0)}{\partial x_i \partial x_j}[\cdots \rho u_i u_j)_s]\mathrm{d}V(\mathbf{x})$$

Equivalent to volume source term

Equivalent to surface source term $\rightarrow + \int_S p_s \frac{\partial (G-G_0)}{\partial x_i} n_i(\mathbf{x})\mathrm{d}S(\mathbf{x})$

1 Compute incompressible CFD

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



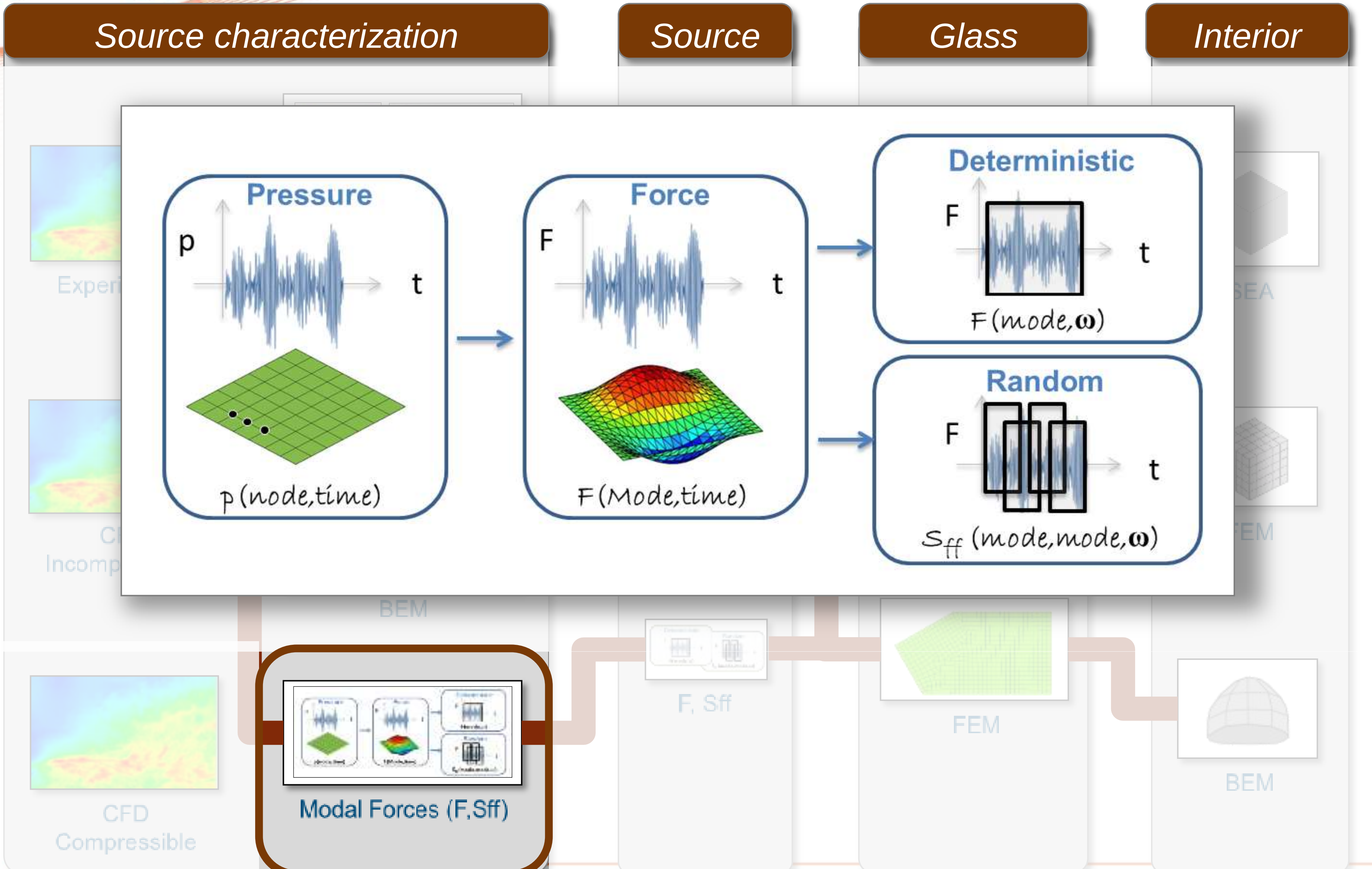
2 Apply hydrodynamic (CFD) loads to BEM model

$$(1/2)p_a(\mathbf{y}) = \int_S p_s \frac{\partial G}{\partial x_i} n_i(\mathbf{x})\mathrm{d}S(\mathbf{x}) + \int_S p_s \frac{\partial (G-G_0)}{\partial x_i} n_i(\mathbf{x})\mathrm{d}S(\mathbf{x})$$

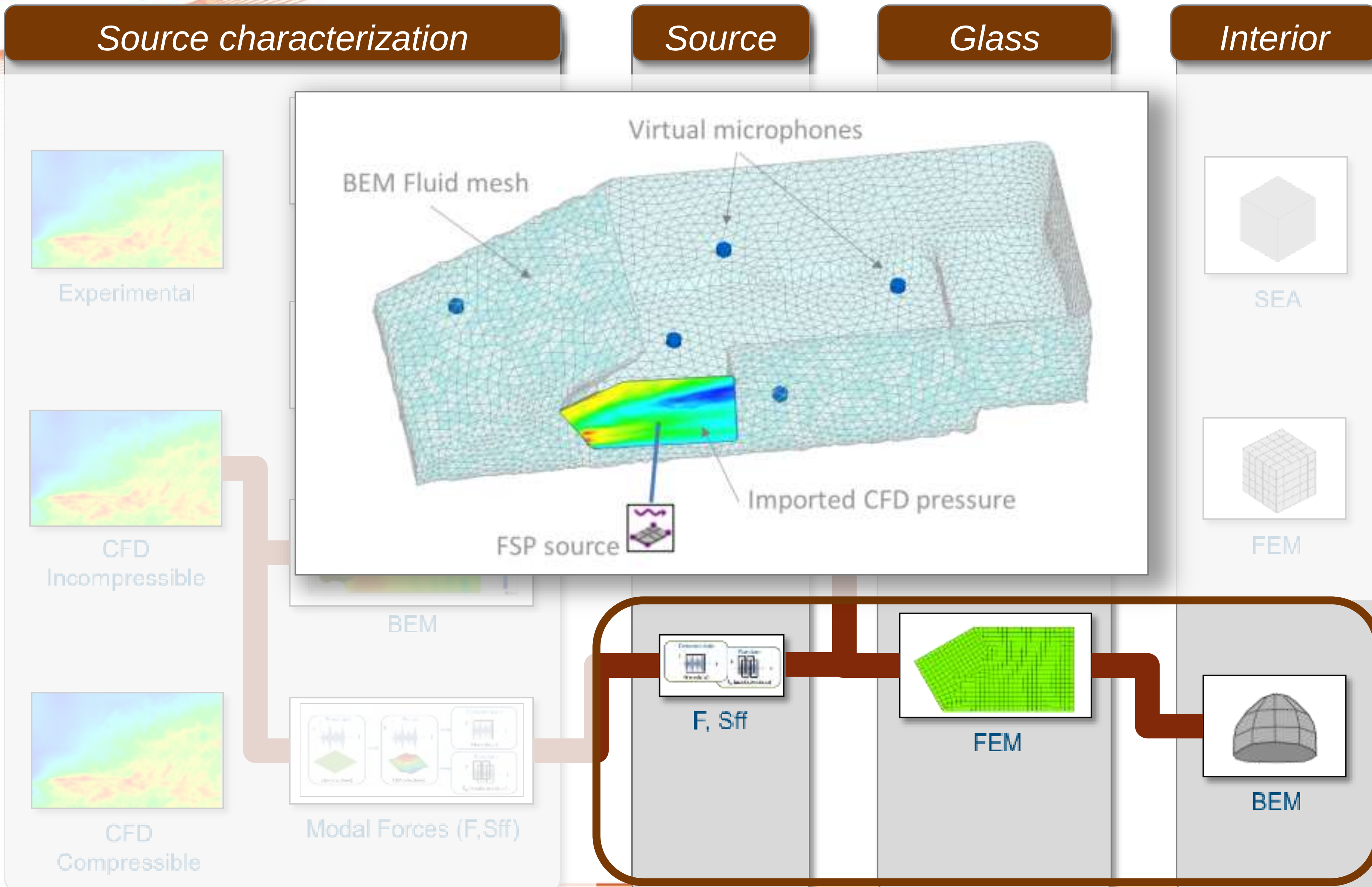
3 Recover pressure at any field point

$$p_a(\mathbf{y}) = \int_S p_s \frac{\partial G}{\partial x_i} n_i(\mathbf{x})\mathrm{d}S(\mathbf{x}) + \int_S p_s \frac{\partial (G-G_0)}{\partial x_i} n_i(\mathbf{x})\mathrm{d}S(\mathbf{x})$$

A few options studied so far…



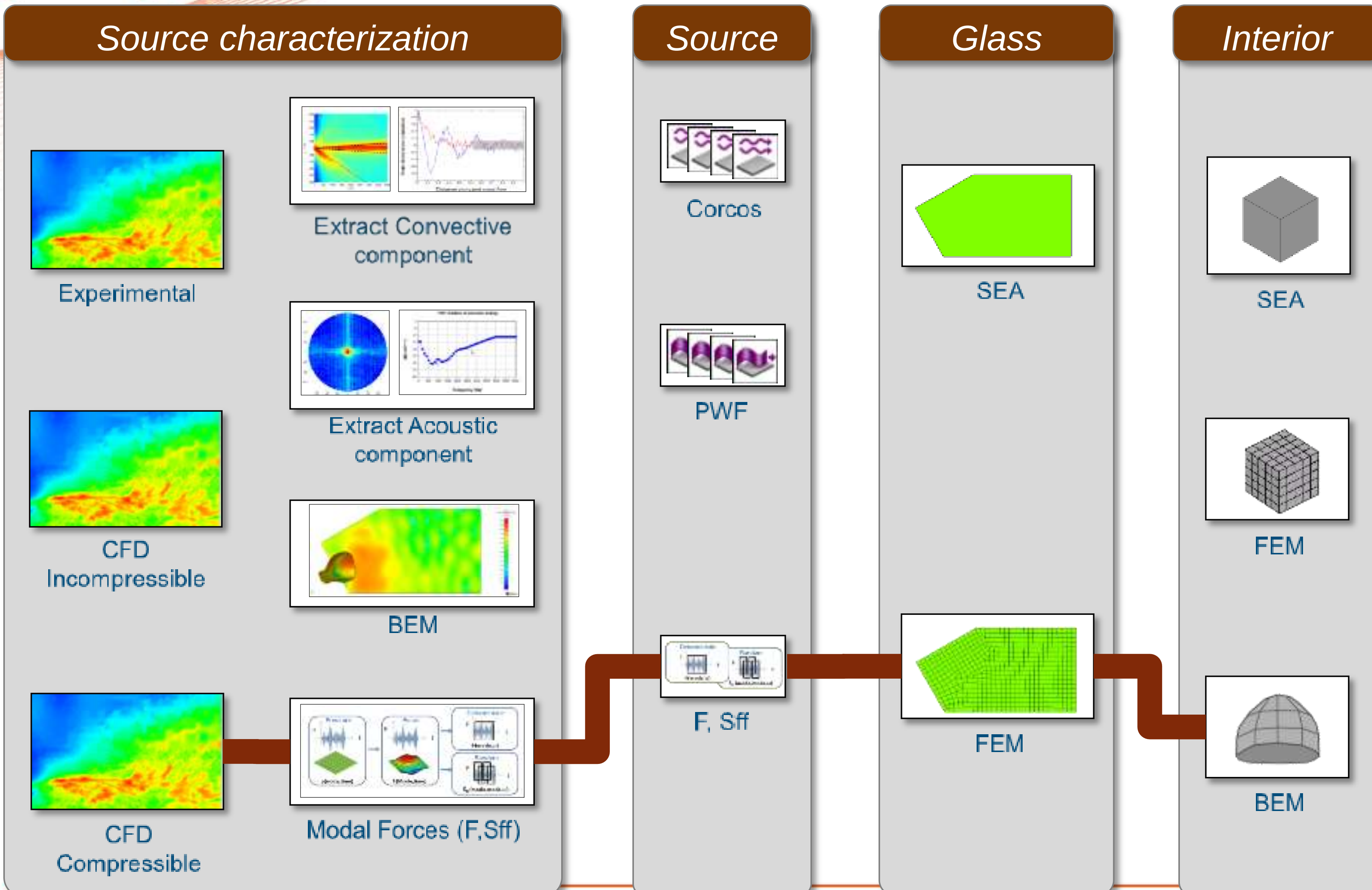
A few options studied so far…



Predicted SPL inside SAE body

- Actively working on this configuration
- Results to be published soon …

A few options studied so far…

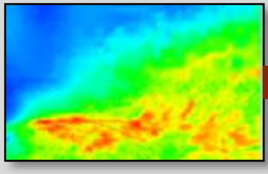


A few options studied so far…

Source characterization | *Source* | *Glass* | *Interior*

Experimental

CFD Incompressible



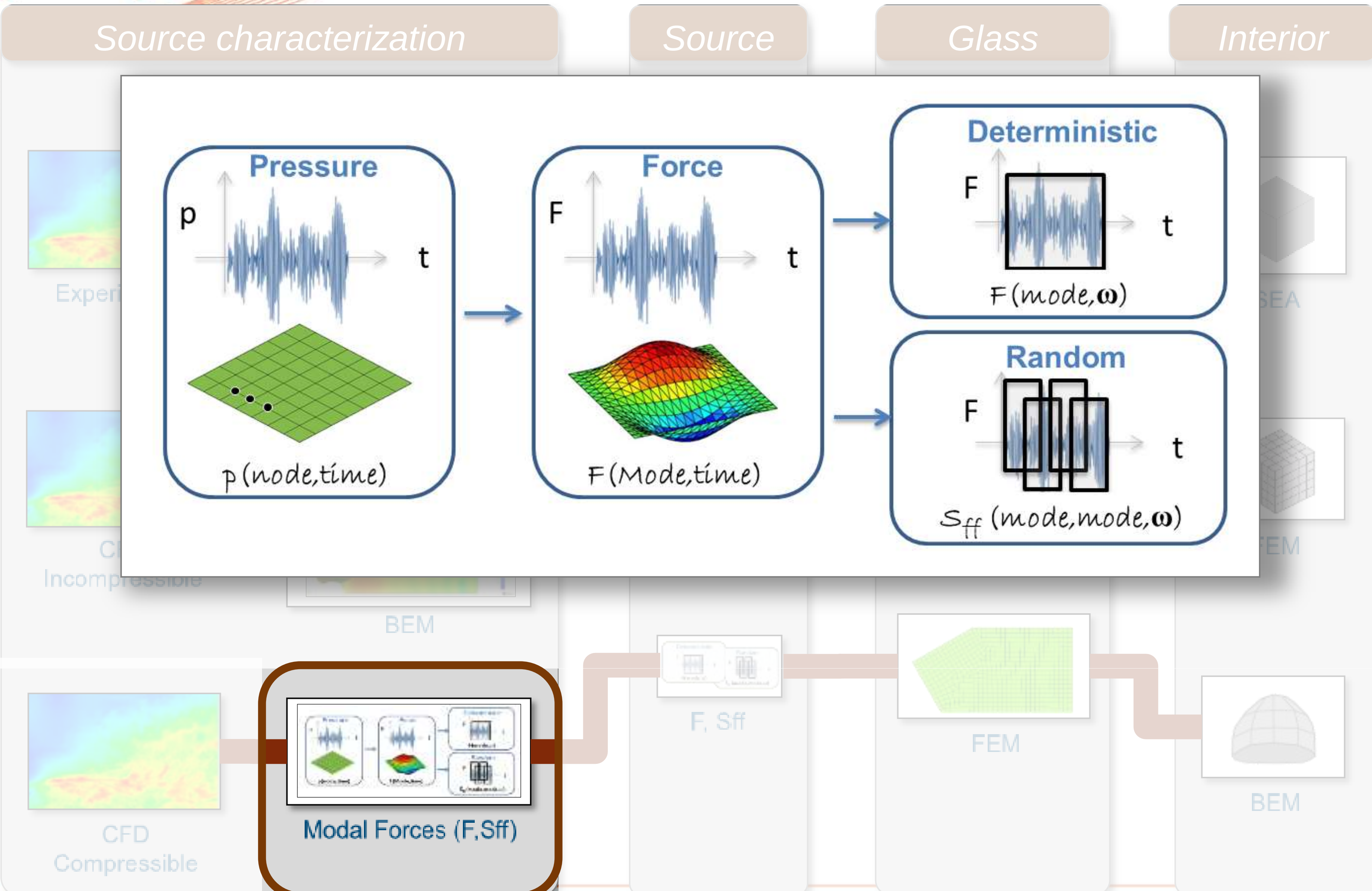
CFD Compressible

Modal Forces (T,SIT)

- StarCCM+ Version 6.06.017
- Half model of SAE body, with side mirror (+side glass & 10mm downset)
- Model size: 45 up to 46 million fluid cells (dependent on configuration)
- Compressible Detached Eddy Simulation (DES) based on Spalart-Allmaras (S-A)
- Δt CFD = 2E-05s
- First 0.1s of simulated physical time has been cut away: spurious transition phenomena when starting a transient computation based on steady state results
- Pressure-time histories on A-pillar, side glass and rear mirror surface of each model

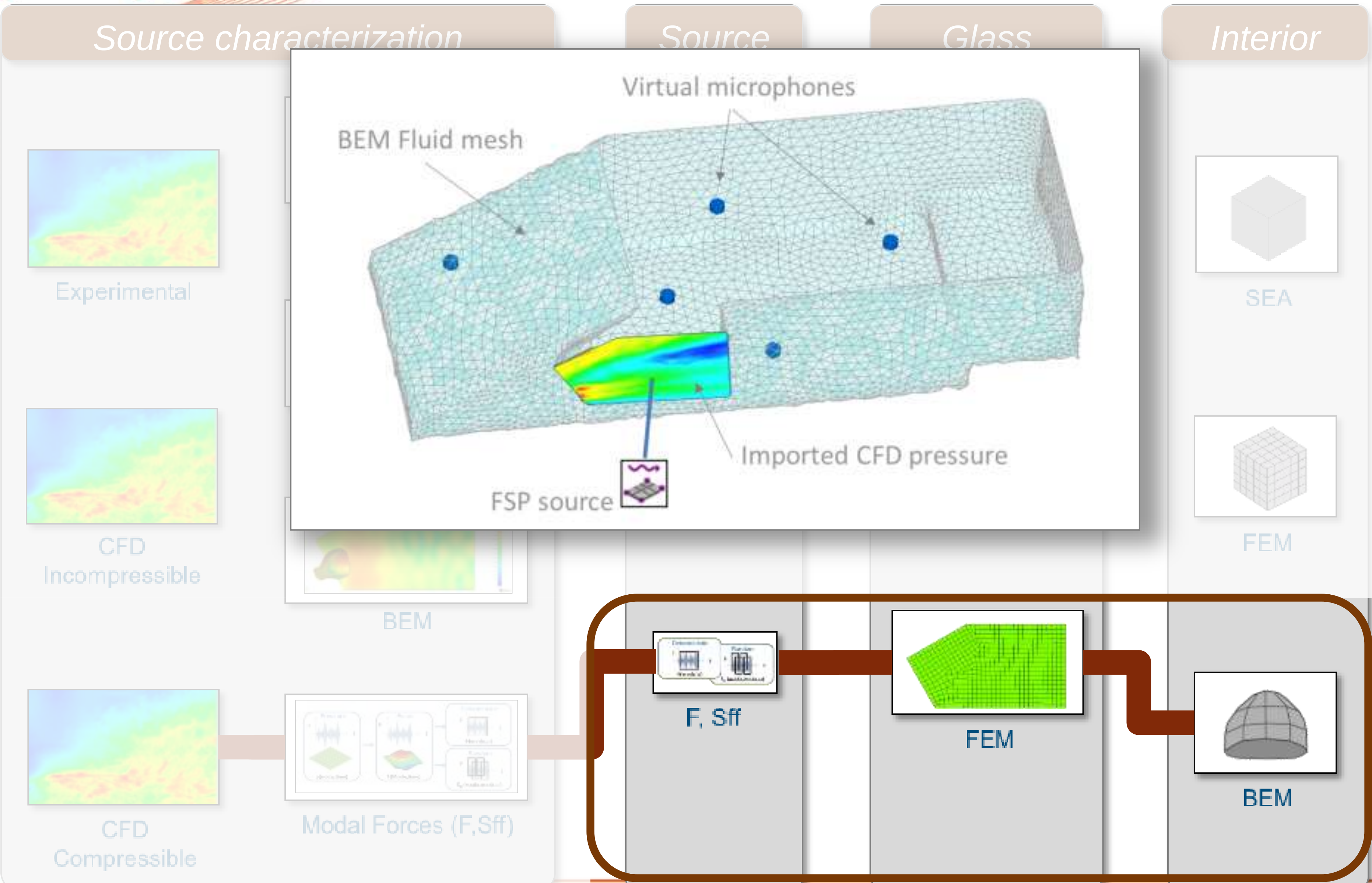
A few options studied so far…

Convert nodal time domain pressure into modal forces

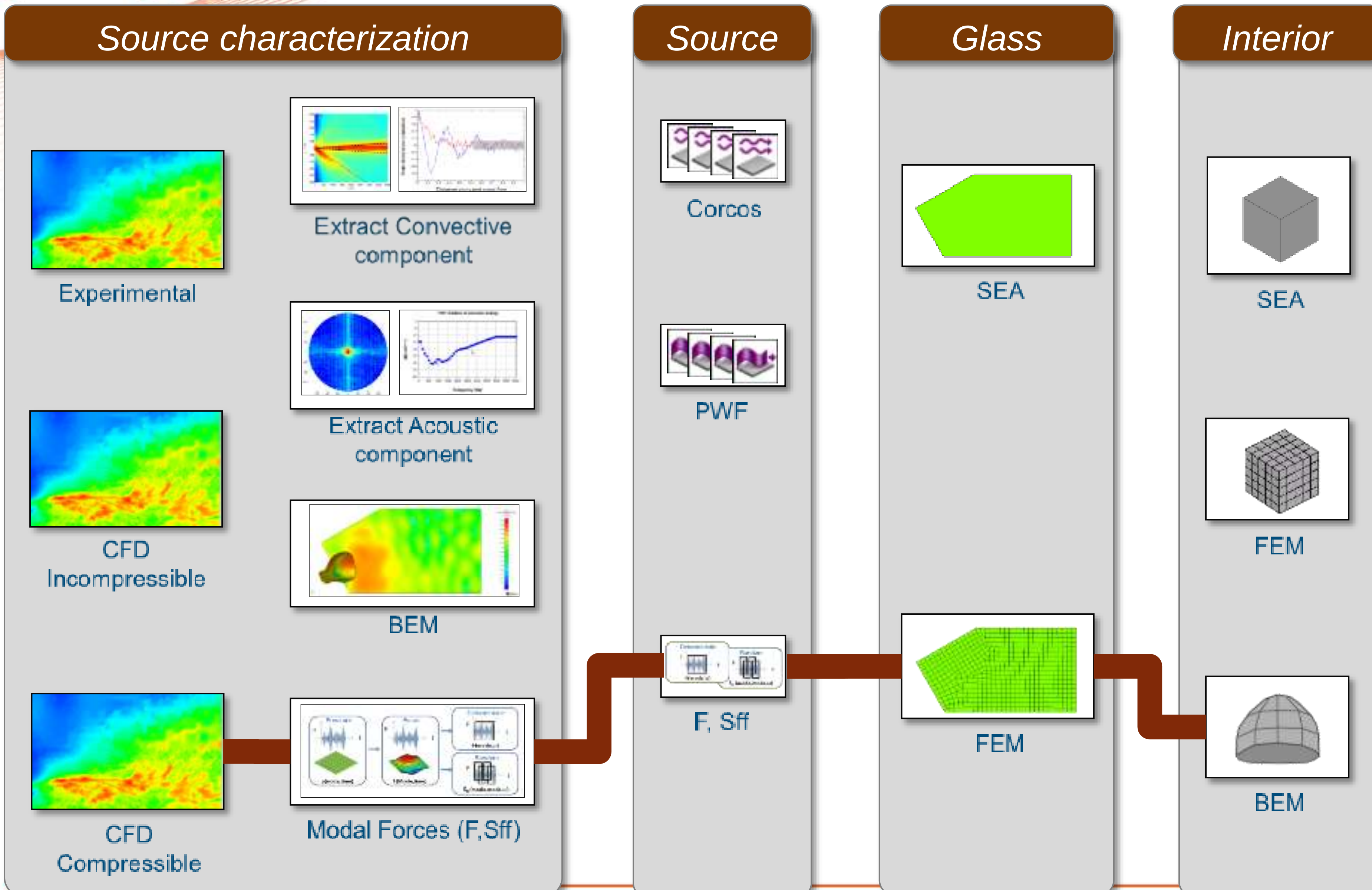


A few options studied so far…

FSP-FEM-BEM model



A few options studied so far…



Objectives

Create an accurate vibro-acoustic model that represents the SAE body so it can be used for windnoise prediction

Validate the vibro-acoustic model against semi-anechoic room Measurements

Create predictive windnoise model to predict SPL inside SAE body using the vibro-acoustic model coupled to CFD source model

Validate windnoise predictions against wind tunnel measurements

Description of test setup

(refer to CAA GWG paper: 22_05_22_hartmann_ocker_at_all_cid_1276980.4)

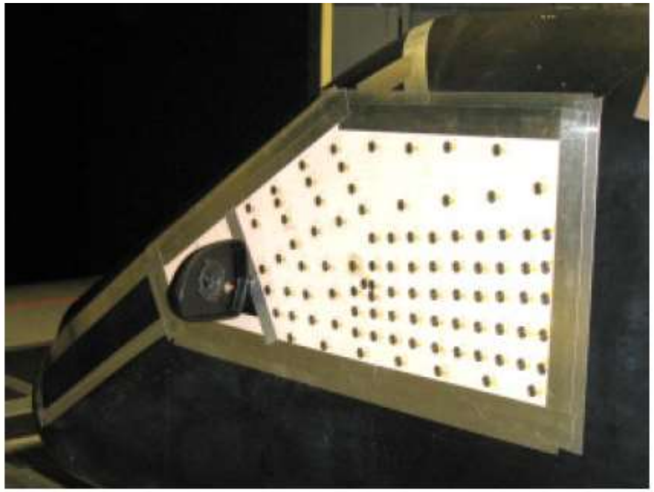
- All tests were performed in the Audi aero-acoustic wind-tunnel.
- The measurement campaign includes:
  - Dynamic pressure measurements in the side window area to characterize the aero-acoustic excitation (Fig. 14b)
  - Interior noise measurements (Fig. 14a).

Figure 14. Wind-tunnel test: (a) glass module, (b) sensor module

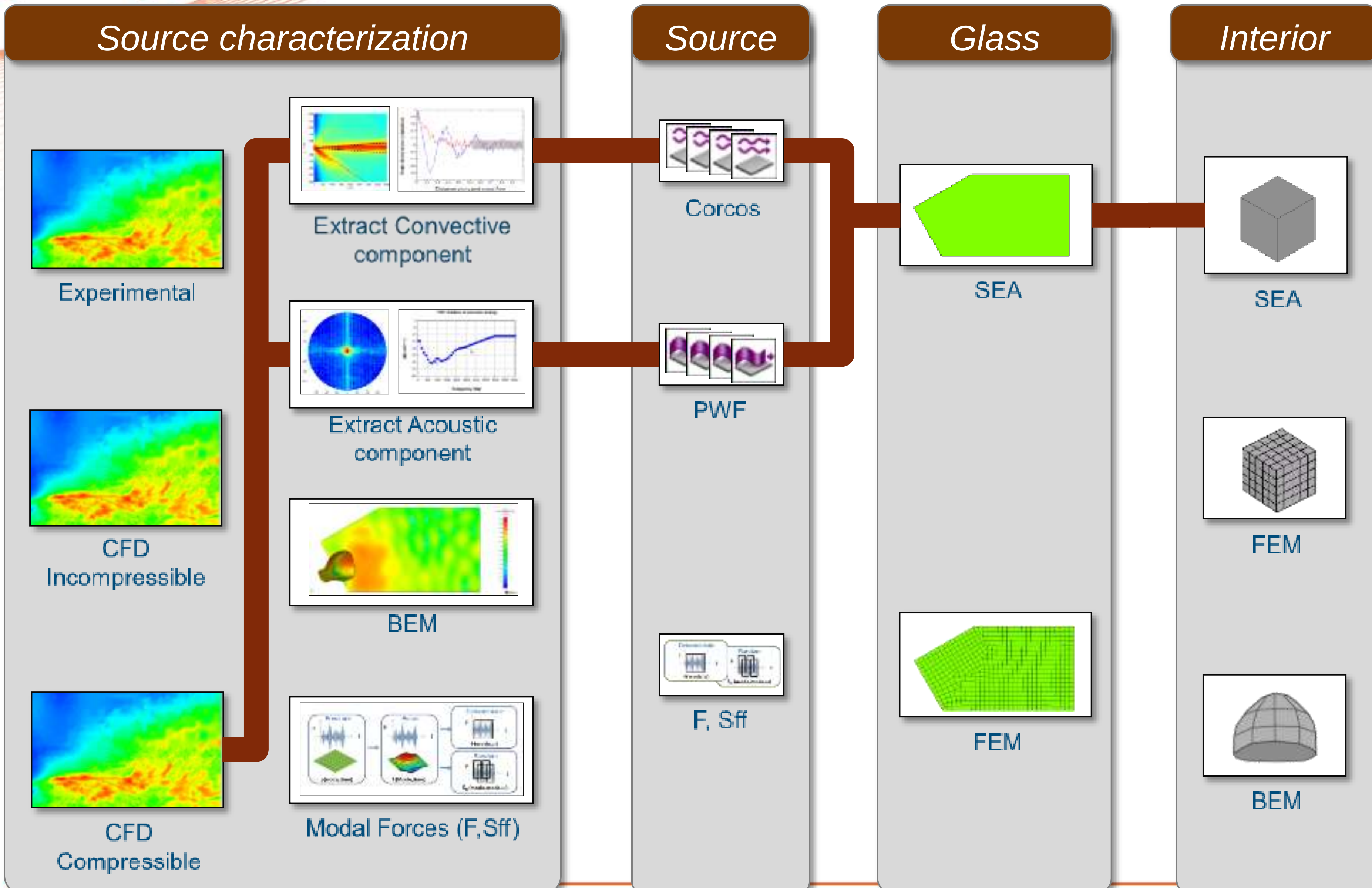
Description of test setup

(refer to CAA GWG paper: 22_05_22_hartmann_ocker_at_all_cid_1276980.4)

- Due to the modular build-up of the model, investigations of many configurations representing a wide range of excitation were possible.
- The pressure loading of the window was measured with 96 automotive surface microphones, type 4949 from Brüel & Kjaer absolutely flush mounted in a high-density foam window module

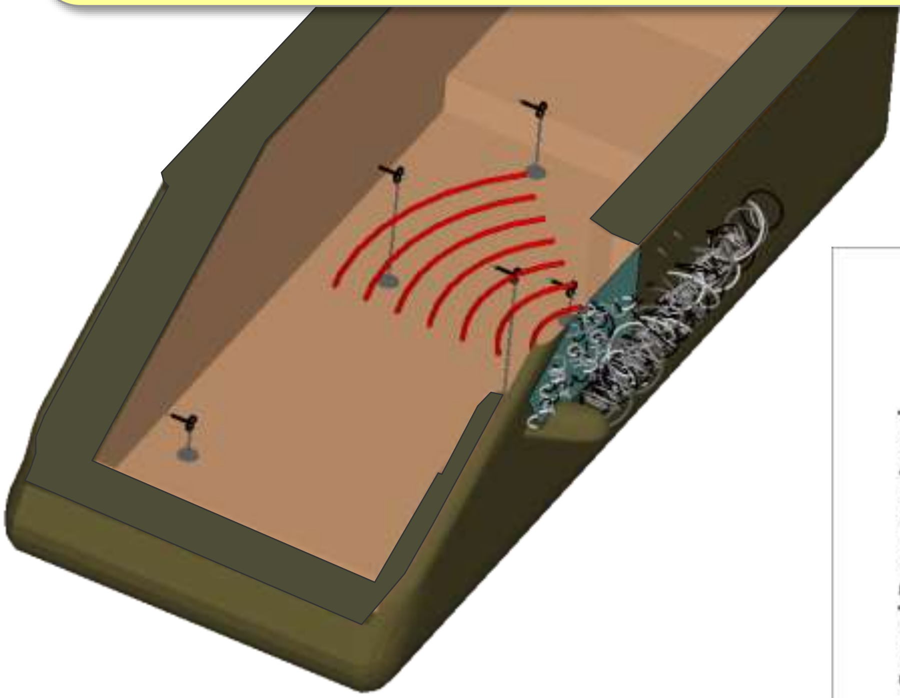


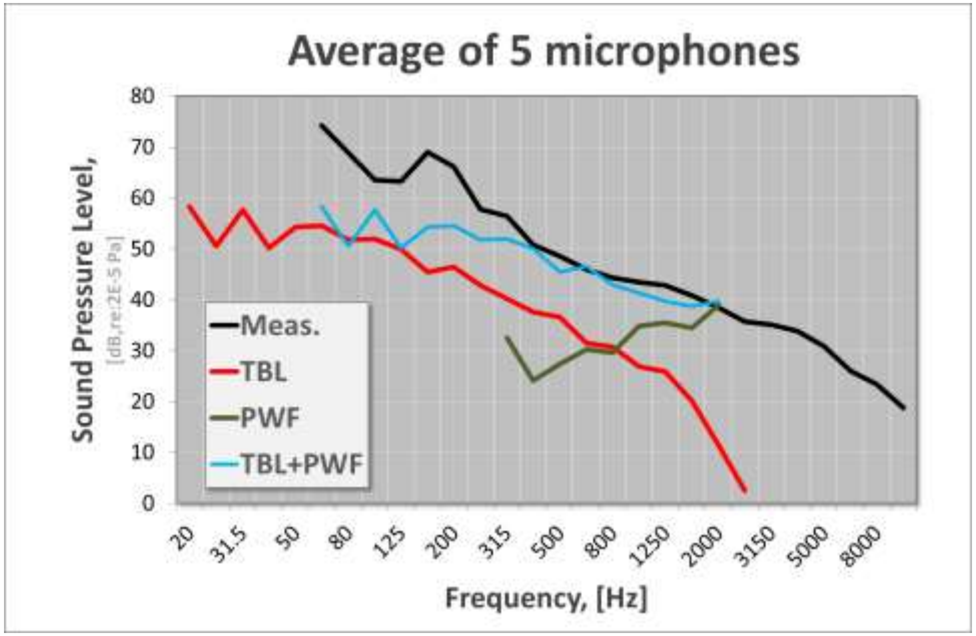
A few options studied so far…



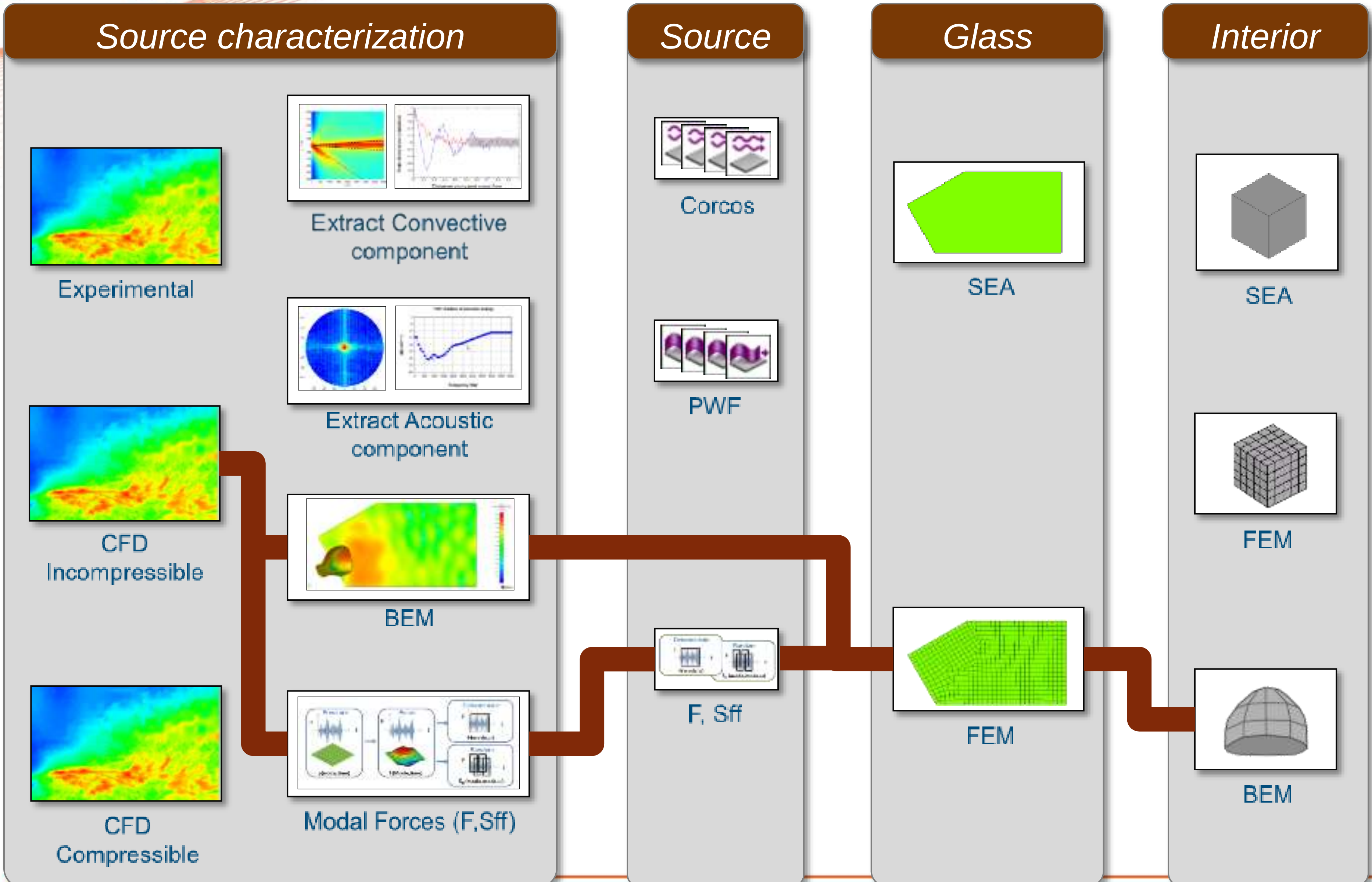
Predicted SPL inside SAE body

At low frequencies, measurements results show higher contribution due to transparency (low NR) of SAE body walls. SPL at microphones can be predicted accurately at frequencies higher than 300 Hz up until 2000 Hz. Work is on-going to identify the acoustic component at higher frequencies





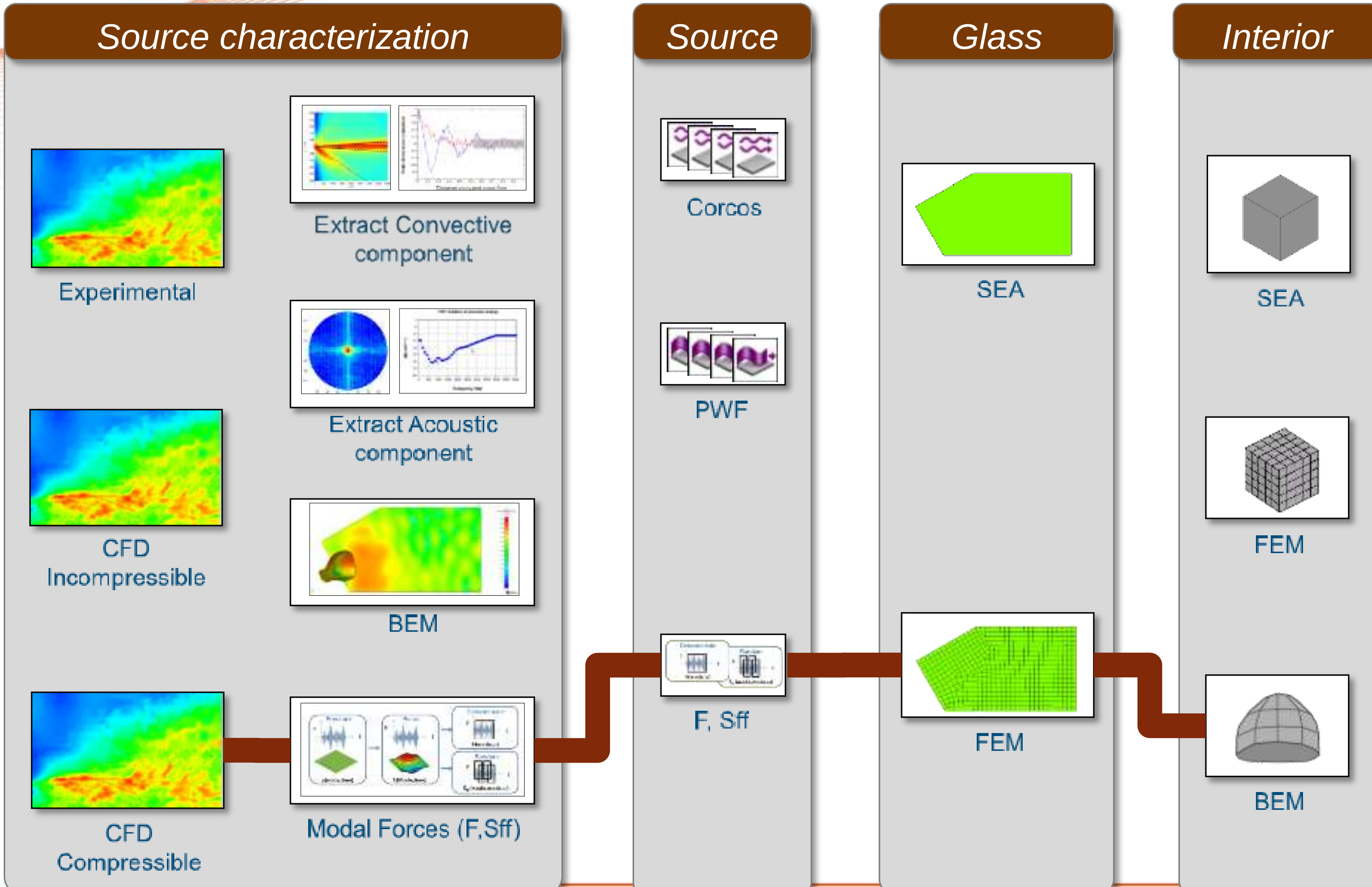
A few options studied so far…



Predicted SPL inside SAE body

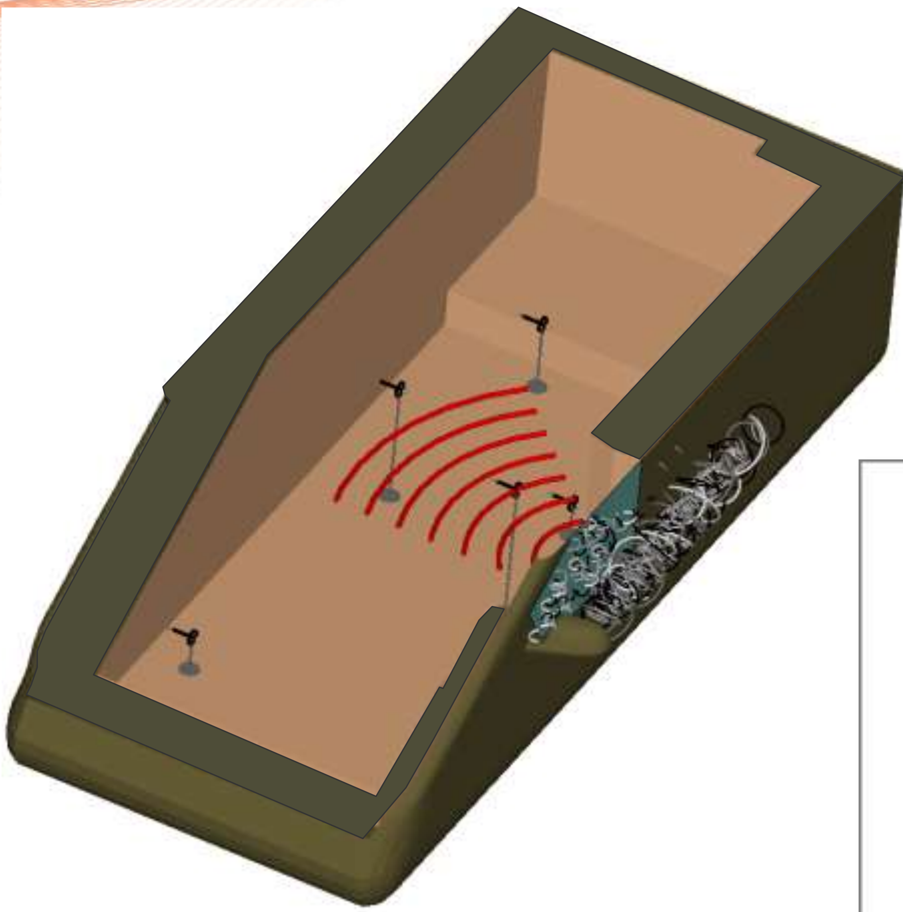
- Actively working on this configuration
- Results to be published soon …

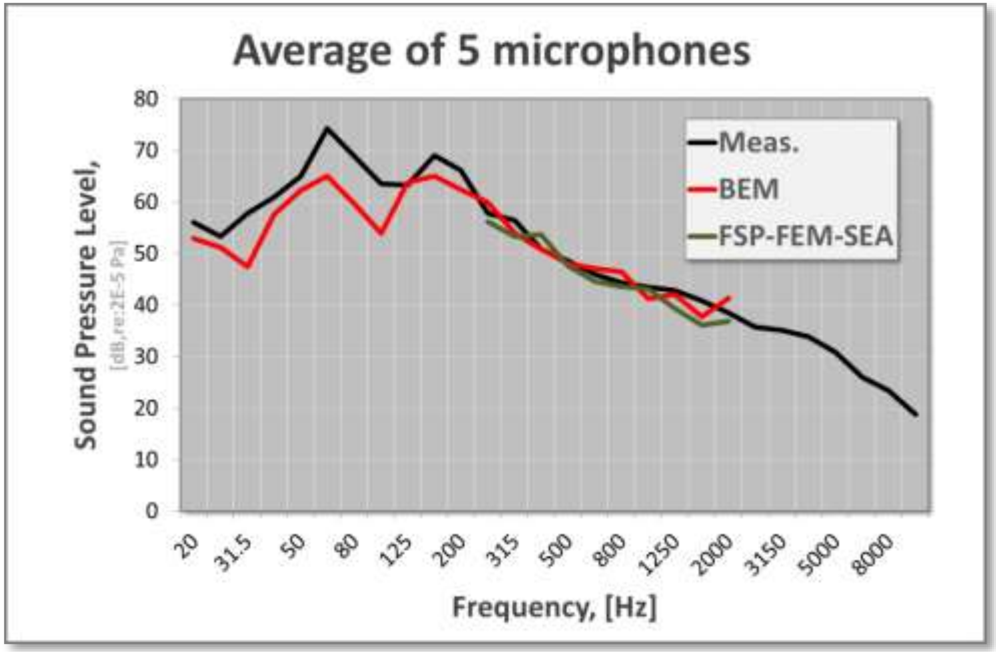
A few options studied so far…



Windnoise 140 kph

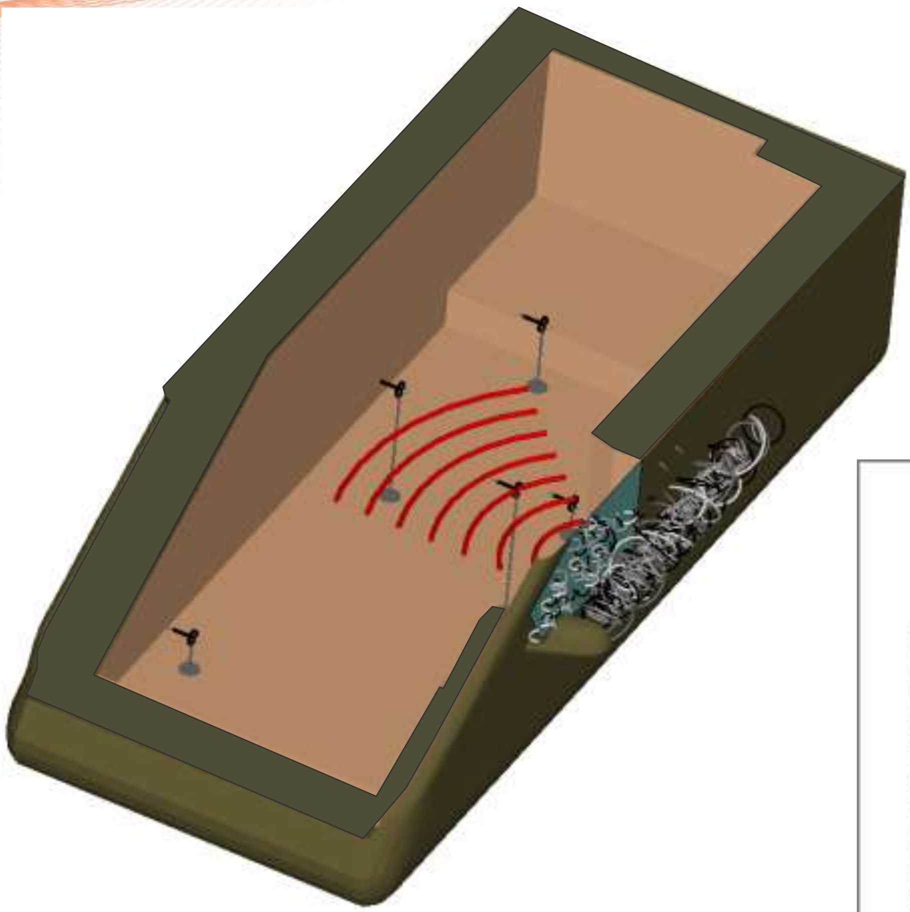
SPL at microphones can be predicted accuratly at frequency higher than 300 Hz for both BEM and CFD-FEM-SEA

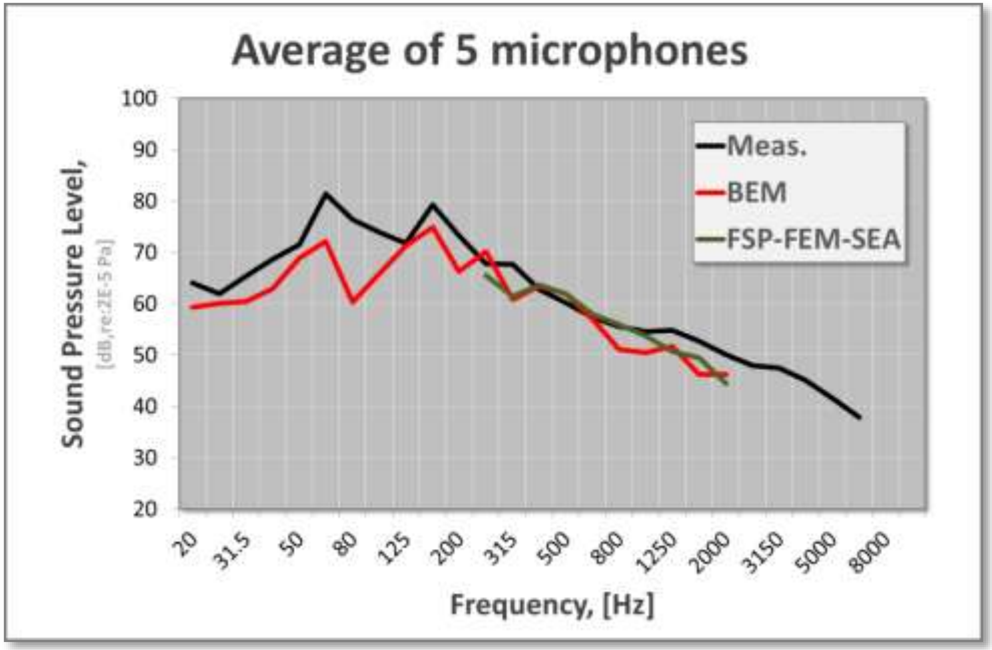




Windnoise 200 kph

SPL at microphones can be predicted accuratly at frequency higher than 300 Hz for both BEM and CFD-FEM-SEA





Conclusion

- Several modeling strategies have been presented
- The choice of modelling method should be based on desired accuracy level and time available to provide results
- CFD data has been coupled succesfully with several vibro-acoustic models
- Initial comparison with measurement results show promising results
- More investigations under way…

Thank you