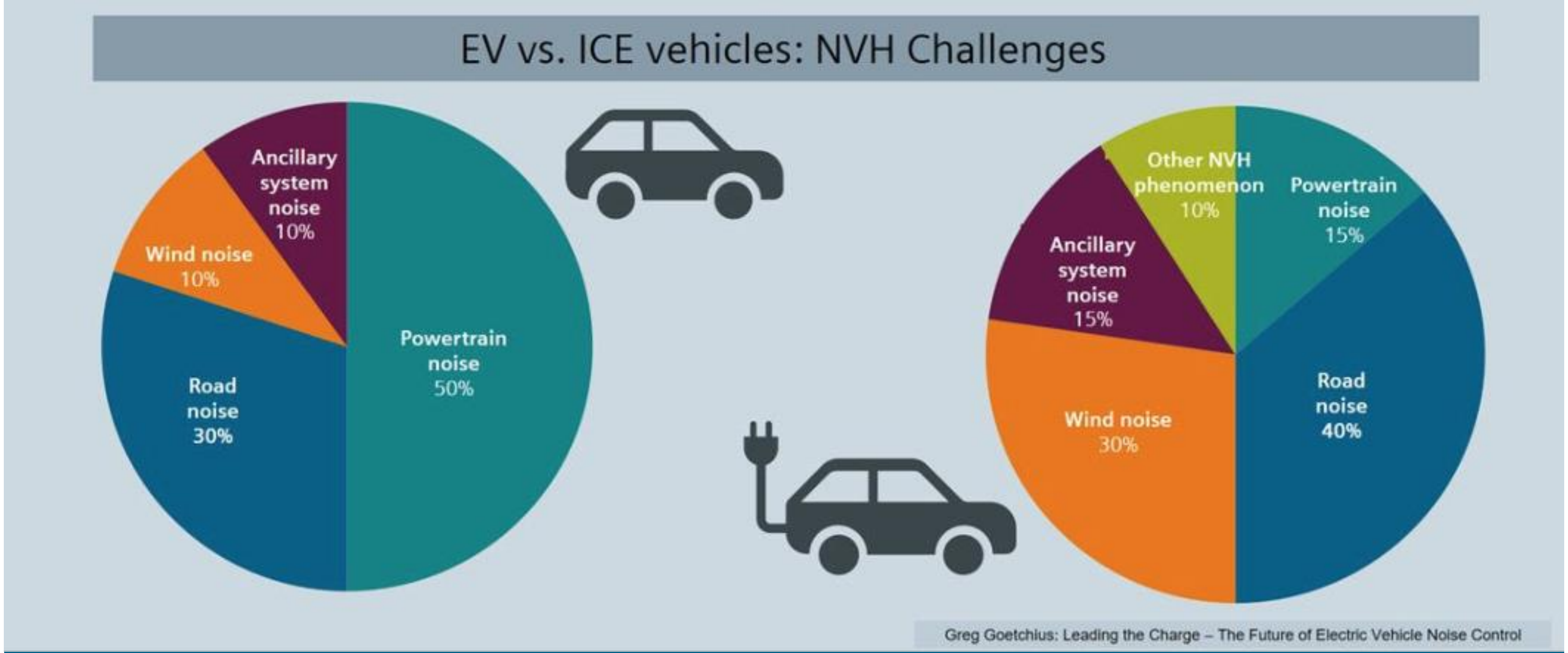
3 validated aero-(vibro)-acoustic scenarios to predict noise levels

The supremacy of lean FE models to solve flow-induced wind, fan and HVAC noise

Realize innovation.

Shift towards increased effort to reduce wind noise

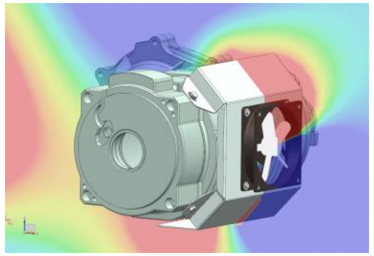


Reduction of wind noise is highly increasing in importance with new cars
Leading to increased need of wind noise testing & simulation

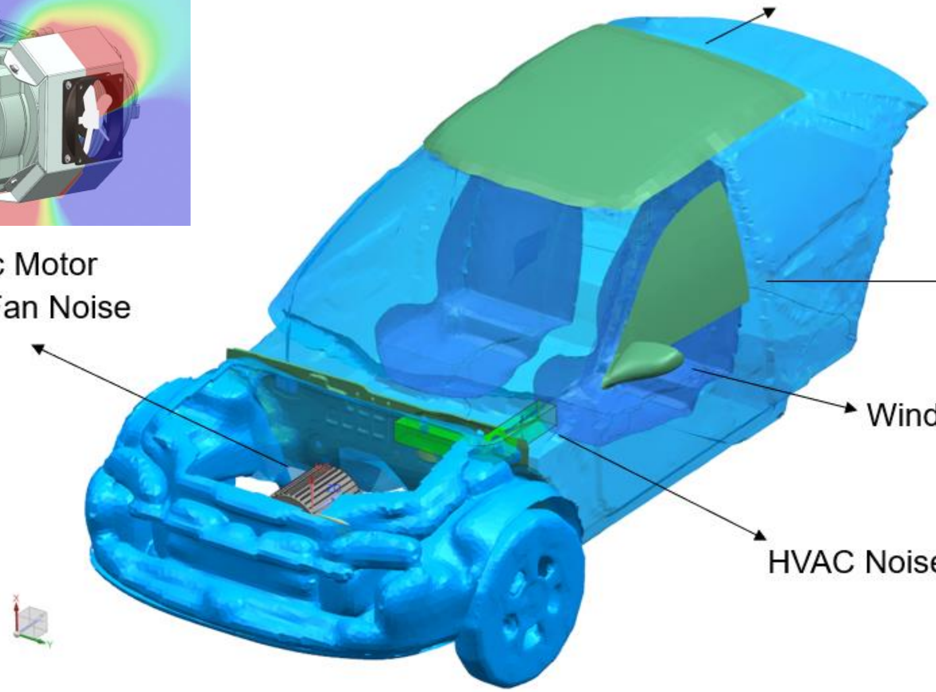
Why simulating flow-induced-noise?

SIEMENS
Ingenuity for life

Noise radiated by the internal combustion engine is not an issue for electric vehicles
the noise generated by other existing sources will be "heard" by the driver and passenger



Electric Motor
Cooling Fan Noise



Flow-induced-noise

Broadband characteristic of the acoustic response

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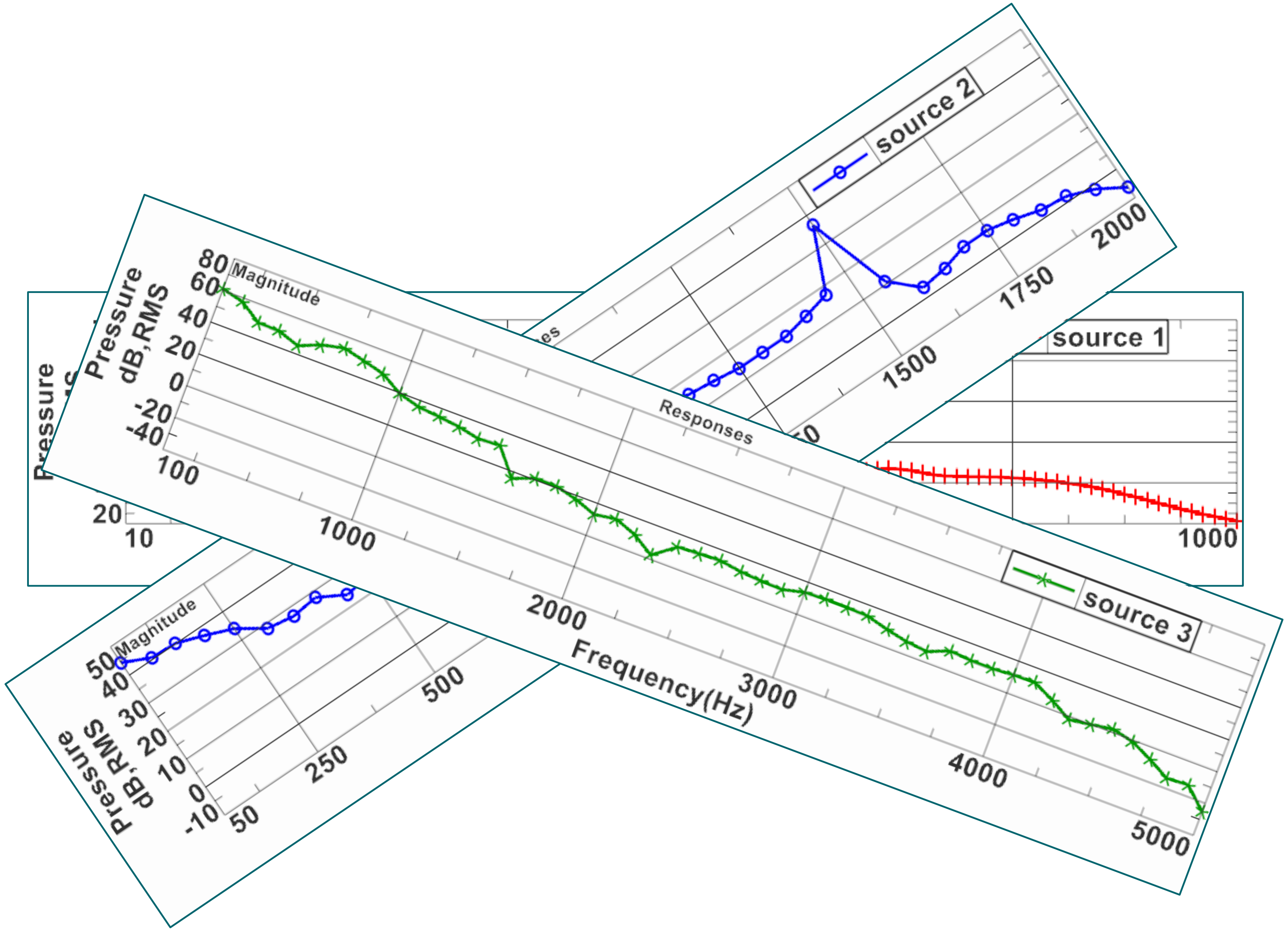
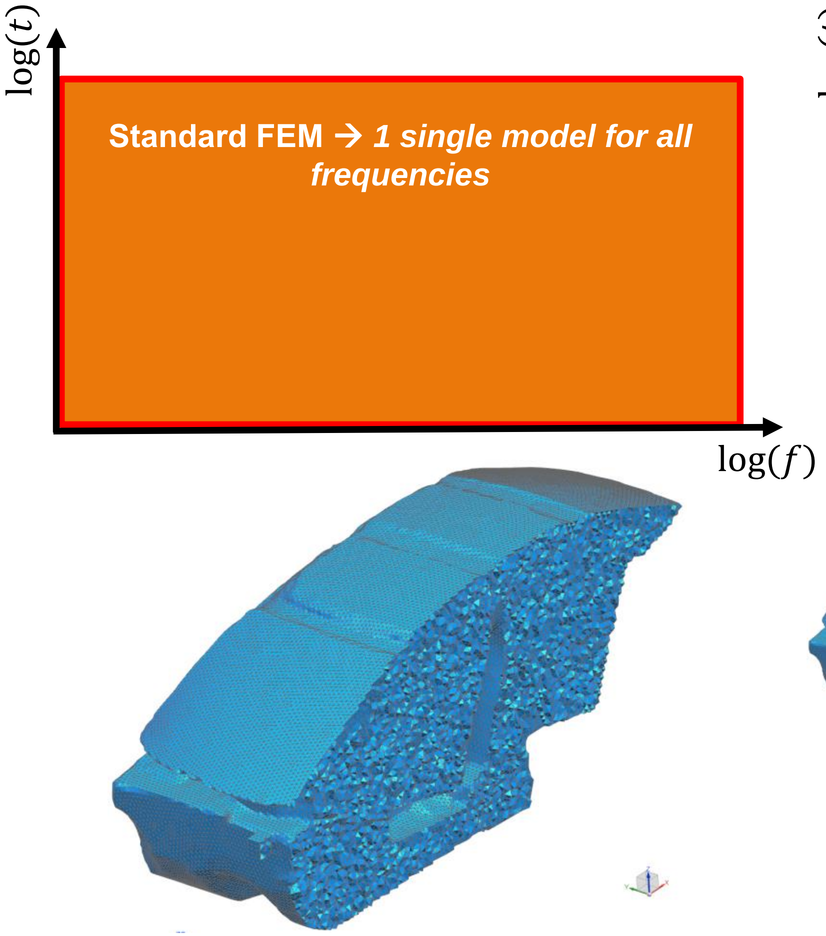


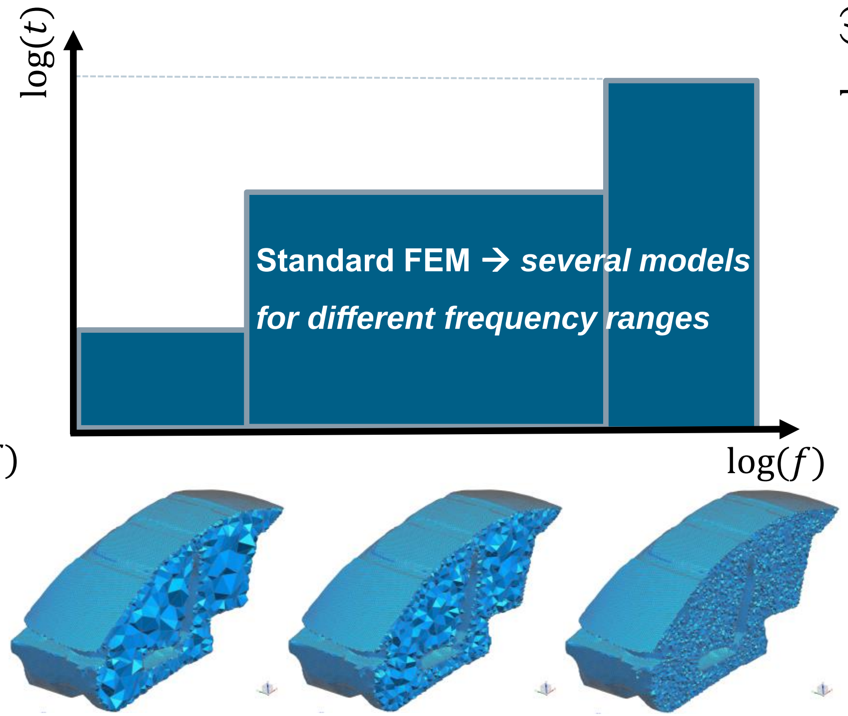
Random turbulent flow field around the source causing both **Tonal** and **Broadband** acoustic response

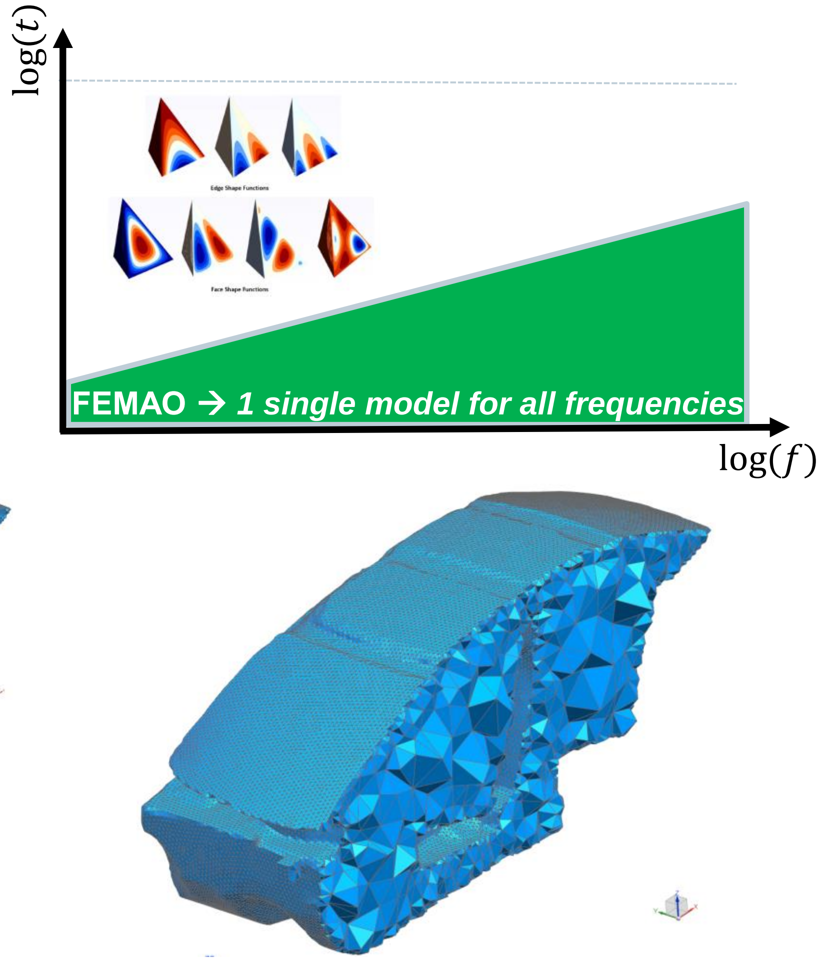
Requirement of an efficient solution of a multi-frequency problem

From lowest frequencies to higher frequencies of interest

Simcenter 3D Acoustics – FEMAO
Alternative solutions







Simcenter 3D Acoustics – FEMAO
Benefits

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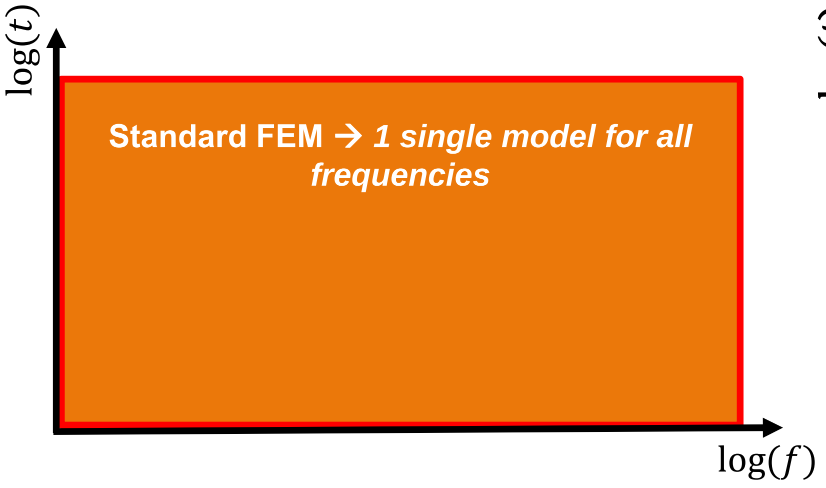
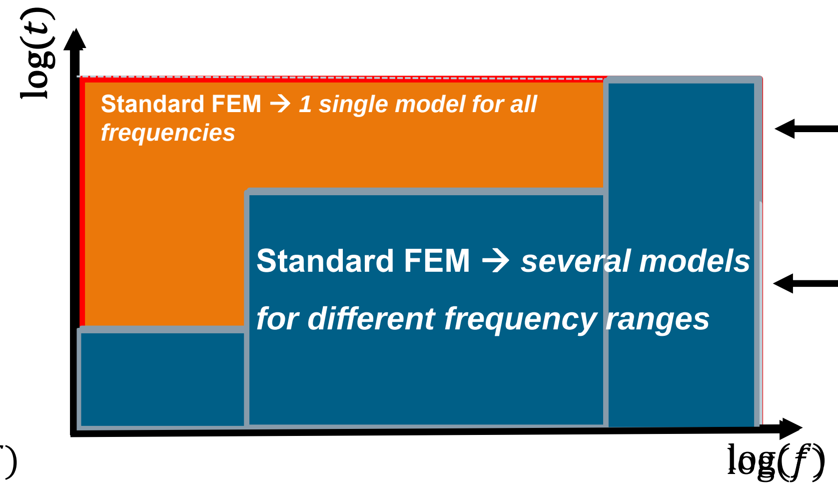
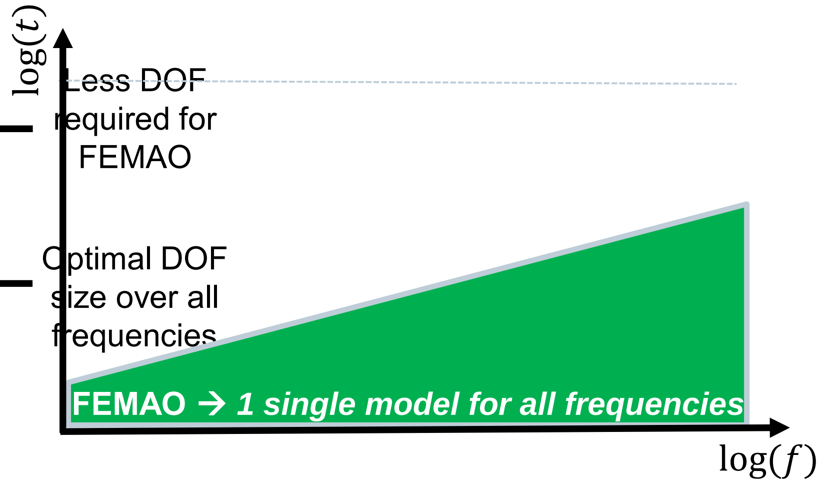
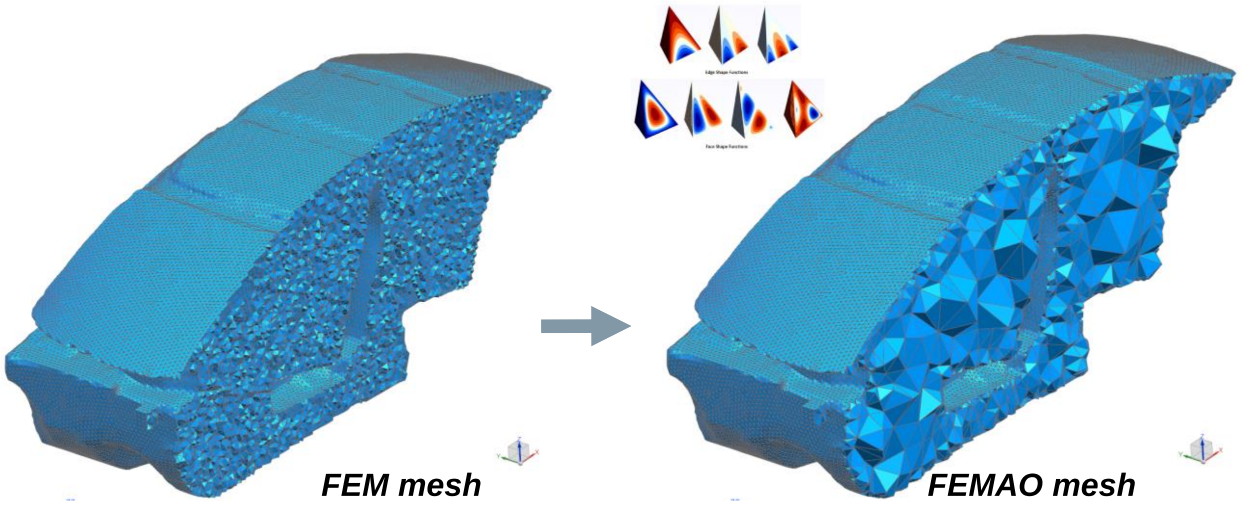






- Auto-adapting (f) fluid element order
- Leaner models in pre-processing
- Faster at lower frequencies
- More efficient at higher frequencies
- 2 to 10 times faster compared to standard FEM



The supremacy of lean FE models to solve flow-induced noise

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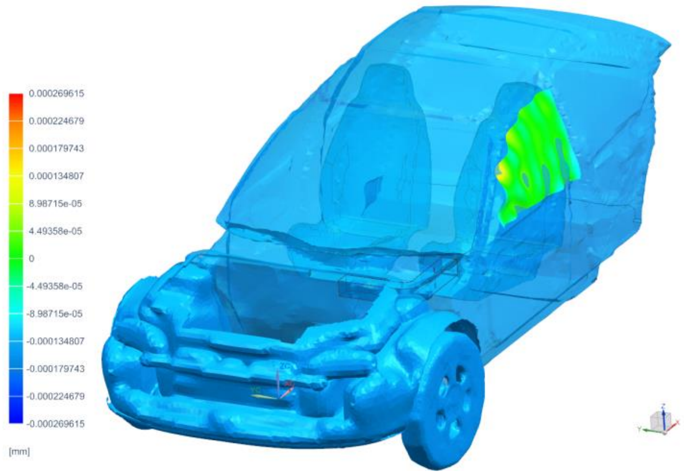
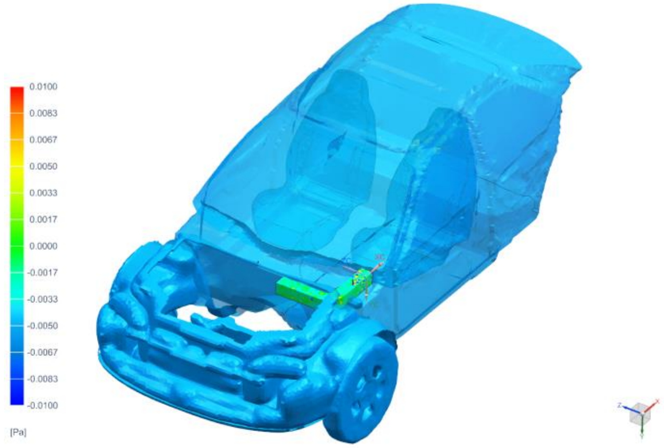
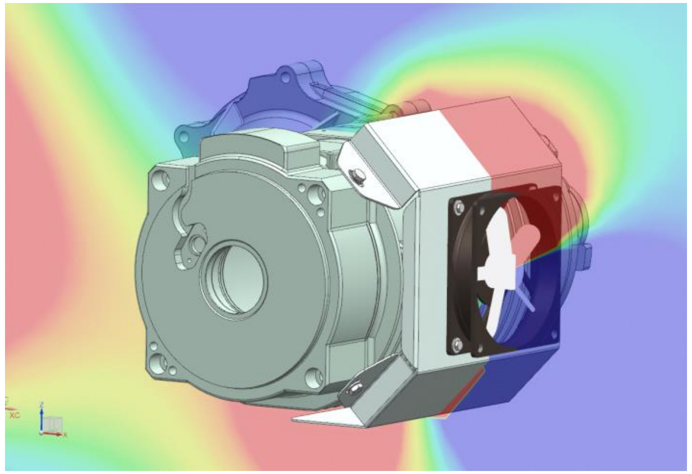
Three flow-induced noise applications examples with FEMAO

Windnoise	HVAC noise	Fan noise







Acoustics: What happens in the presence of flow?

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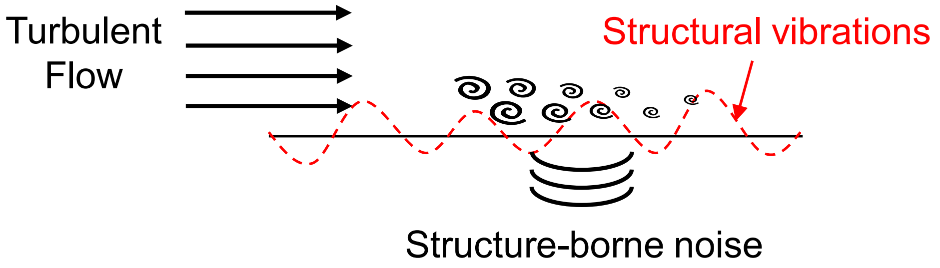
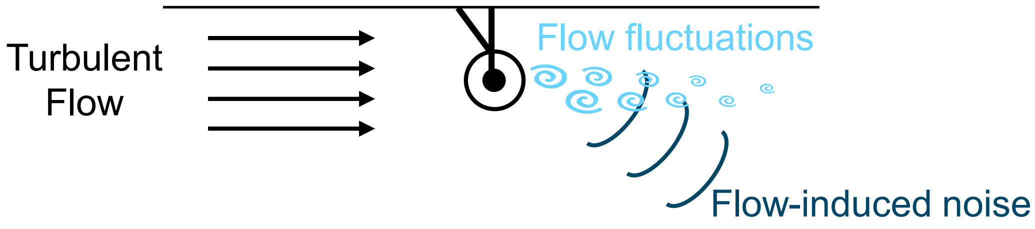
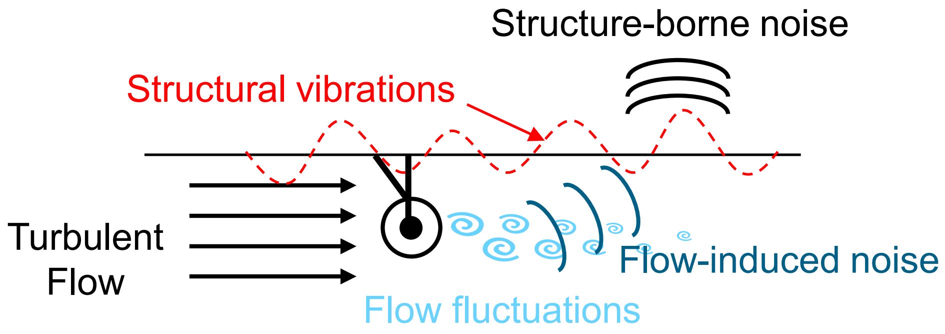


Flow-induced vibrations → Vibro-acoustics



Flow-induced noise → Aero-acoustics

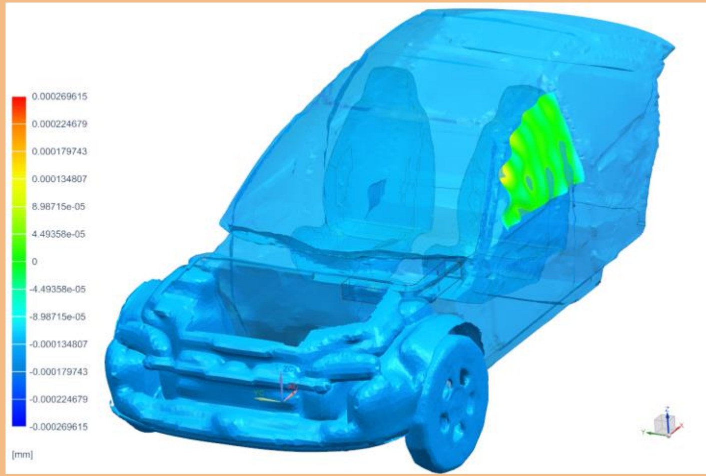
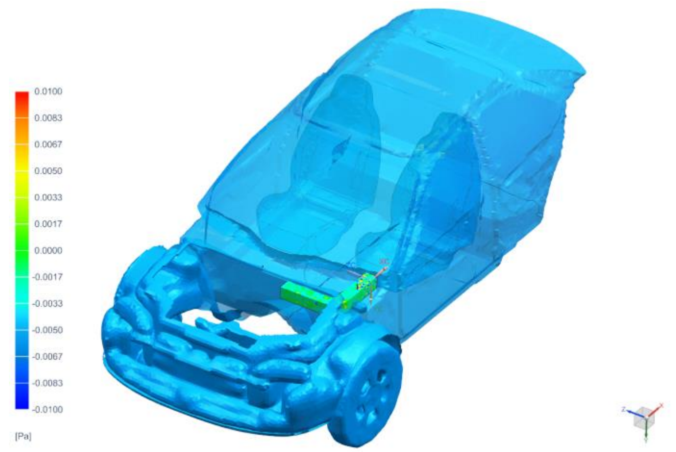
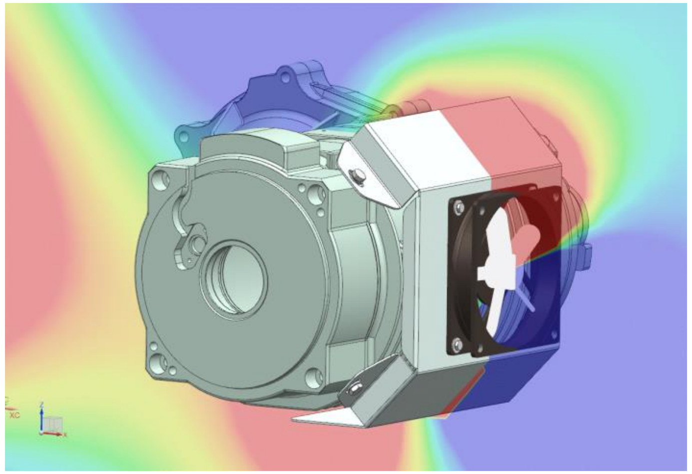


Flow-induced vibrations→ Aero-vibro-acoustics

The supremacy of lean FE models to solve flow-induced noise

SIEMENS
Ingenuity for life

Three flow-induced noise applications examples with FEMAO

Windnoise	HVAC noise	Fan noise
		

Cabin Wind Noise – Aero-Vibro-Acoustics

Which frequency range? Which loading?

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Low-frequency wind noise f < 500 Hz Underbody and green house	High-frequency wind noise 1000 Hz < f < 5000 Hz Side window and/or windshield	High-frequency wind noise 500 Hz < f Underbody and green house
Structure: Simcenter Nastran FEM Acoustics: Simcenter Nastran FEM/FEMAO	Structure: Simcenter Nastran FEM Acoustics: Simcenter Nastran FEMAO	Virtual SEA+ / SEA+
Covered by FEM and FEMAO		Covered by SEA

Windnoise simulation workflow

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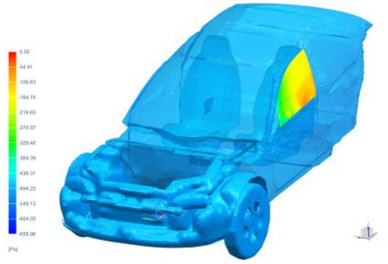
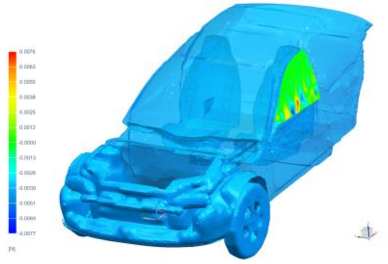
Aerodynamic field	**Starting from external aerodynamic loading on the CFD mesh boundaries**
Load Preparation	**Preparation of wind loads for the vibro-acoustic model via advanced mapping**
Vibro-acoustic solution	**Vibro-acoustic computation of the side-window and car interior using wind loads**


Windnoise simulation workflow

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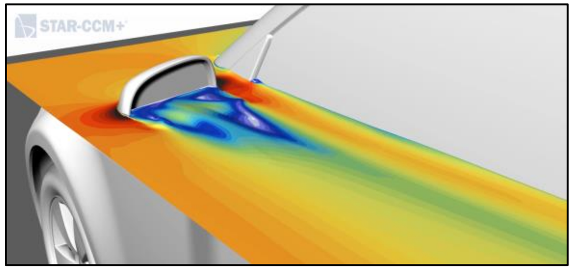
Ingenuity for life

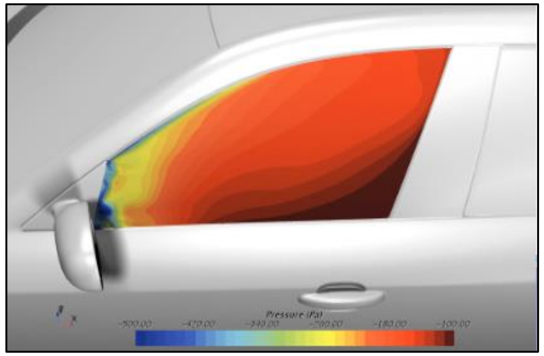
Aerodynamic field

Load Preparation

Vibro-acoustic solution

External aerodynamic field around the car





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Sidewindow_01002.cgns	CGNS File	2,928 KB
Sidewindow_01003.cgns	CGNS File	2,928 KB
Sidewindow_01004.cgns	CGNS File	2,928 KB
Sidewindow_01005.cgns	CGNS File	2,928 KB
Sidewindow_01006.cgns	CGNS File	2,928 KB

Solve exterior aerodynamics of the vehicle in Simcenter STAR-CCM+

Export aerodynamic and acoustic pressure on side window in CGNS

Windnoise simulation workflow

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Ingenuity for life

Aerodynamic field

Compute exterior aerodynamics accurately

Load Preparation

Vibro-acoustic solution

Windnoise simulation workflow

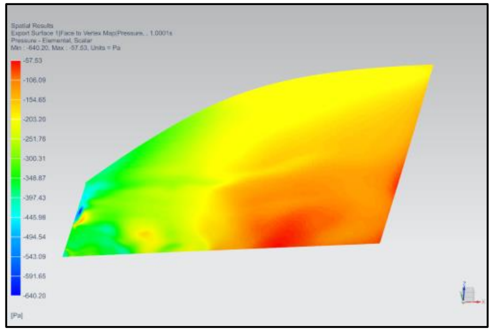
SIEMENS
Ingenuity for life

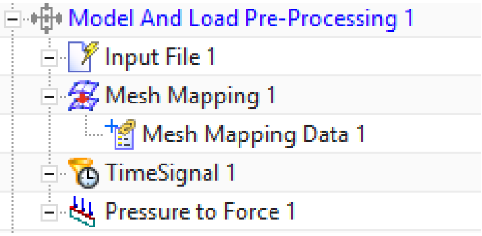
Aerodynamic field

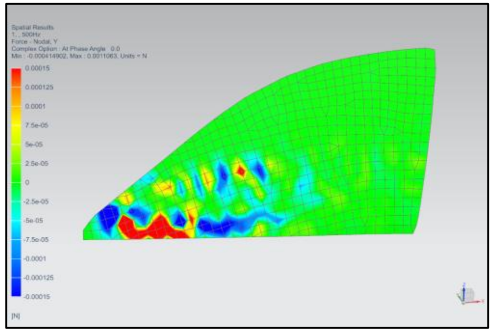
Load Preparation

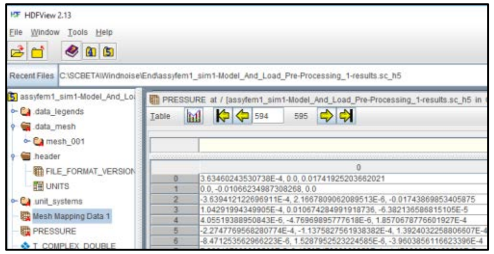
Vibro-acoustic solution

Load preparation for the vibro-acoustic simulation









Imported Pressure Fluctuations (t) on CFD model

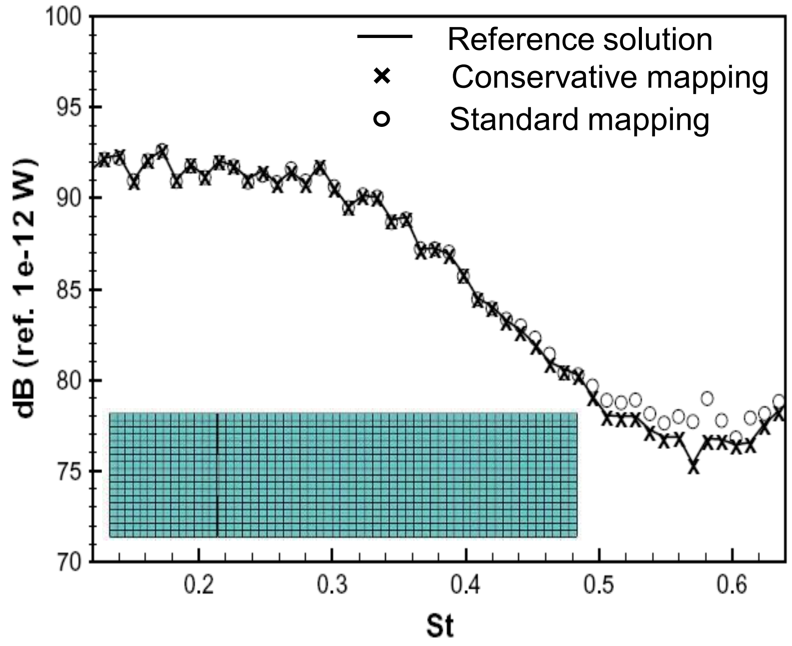
Mapped to Structural Model and converted to Forces (Hz)

hdf5 binary file export, to be picked up by Simcenter Nastran

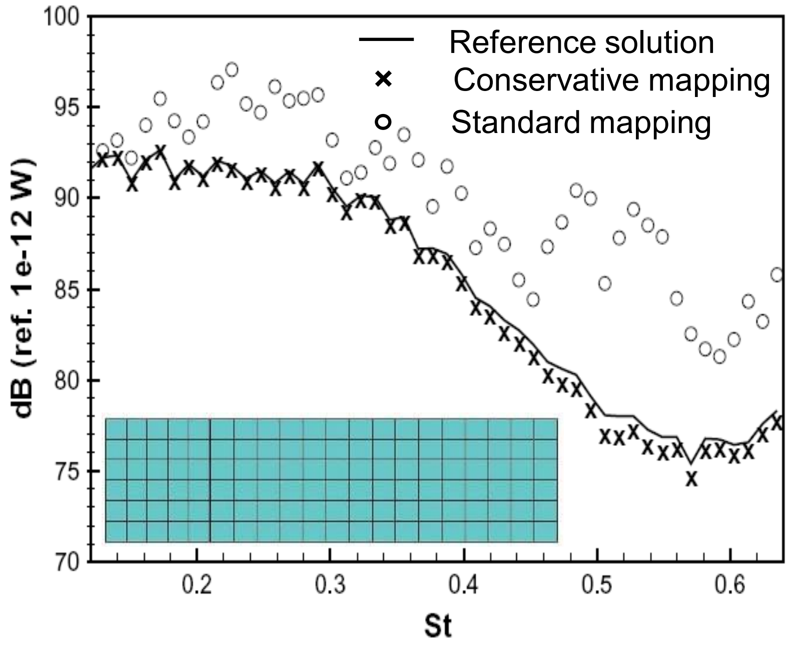
Conservative mapping

Effect of mapping on radiated acoustic power

Acoustic mesh has **~7** times fewer elements than CFD mesh



Acoustic mesh has **~72** times fewer elements than CFD mesh



Conservative mesh mapping algorithm :

- Acoustic mesh can be much coarser
- Performance improvement for solving the acoustic model
- Better accuracy of the predicted acoustic radiation

Windnoise simulation workflow

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Aerodynamic field	Compute exterior aerodynamics accurately
Load Preparation	**Prepare external loads smoothly for the vibro-acoustic model**
Vibro-acoustic solution	

Windnoise simulation workflow

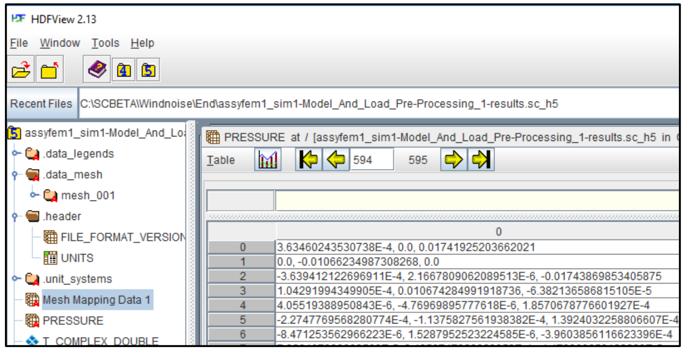
SIEMENS
Ingenuity for life

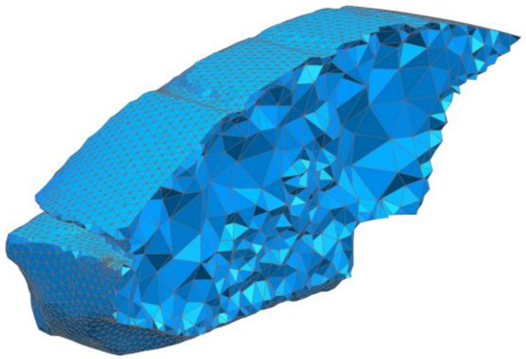
Aerodynamic field

Load Preparation

Vibro-acoustic solution

FEMAO: State-of-art FE solver with Adaptive Element Order





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ADAPTIVE ORDER STATISTICS (in % of total volume)
======================================================================
     1      2      3      4      5      6      7      8      9     10
======================================================================
   0.20  12.79  34.14  28.50  19.30   4.72   0.35   0.00   0.00   0.00
======================================================================
```

User friendly link to hdf5 binary file to be picked up by Simcenter Nastran RLOADEX

Vibro-acoustic response in the cabin with FEMAO in Simcenter Nastran

Vibro-Acoustic Transfer Vectors (VATV)
For Faster Multi-Load Case Response Analysis

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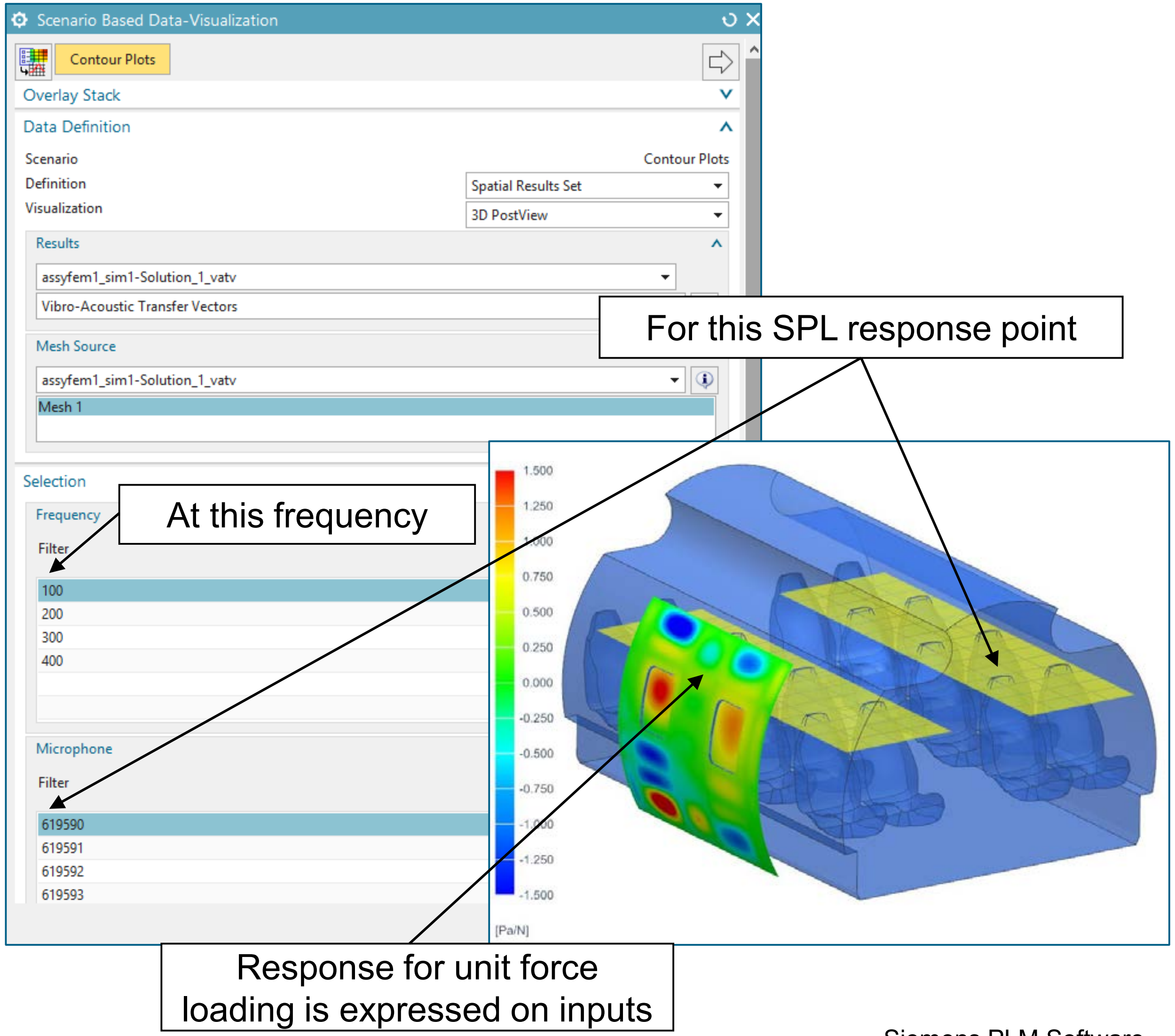
VATV = SPL response to unit surface loads ~ FRF
Computed using reciprocity principle

Key benefit

- No need to re-compute VATV as long as model remains the same
- Response is quickly computed for different loads:
  - TBL loads for aircraft panel x VATV
  - CFD loads on a car side window x VATV
  - Acoustic loads on car window from tailpipe x VATV



Windnoise simulation workflow

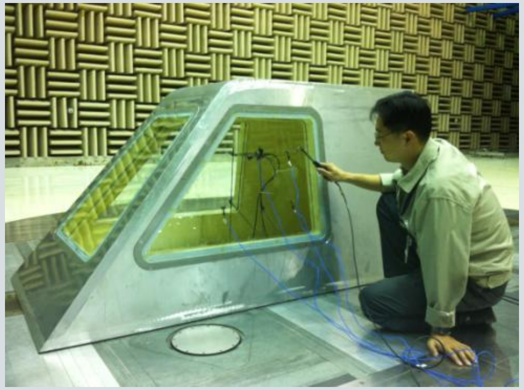
SIEMENS
Ingenuity for life

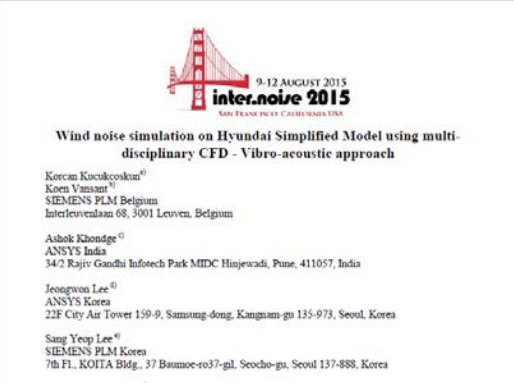
Aerodynamic field	Compute exterior aerodynamics accurately
Load Preparation	Prepare external loads smoothly for the vibro-acoustic model
Vibro-acoustic solution	**Efficient finite element computation using single coarse physical mesh for all frequencies of interest**

Validation

Hyundai Motor Company simplified model

Simplified cabin from literature	Vibro-acoustic solution with Simcenter 3D	Comparing pressure results with measurements





9-12 AUGUST 2015
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SAN FRANCISCO, CALIFORNIA USA

Wind noise simulation on Hyundai Simplified Model using multi-disciplinary CFD - Vibro-acoustic approach

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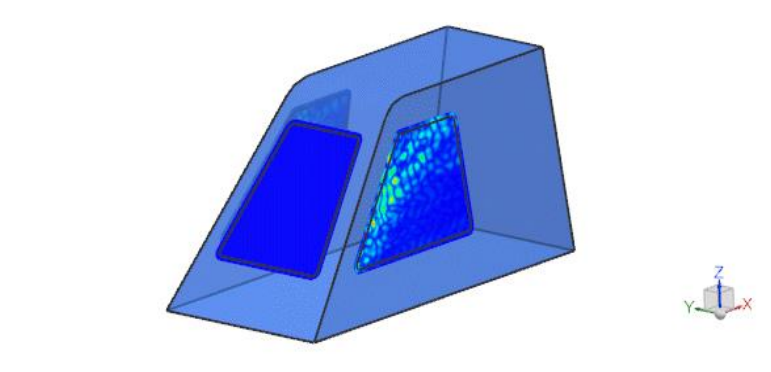
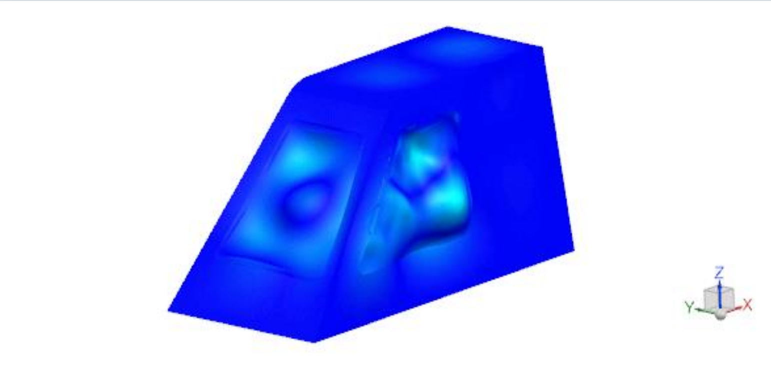
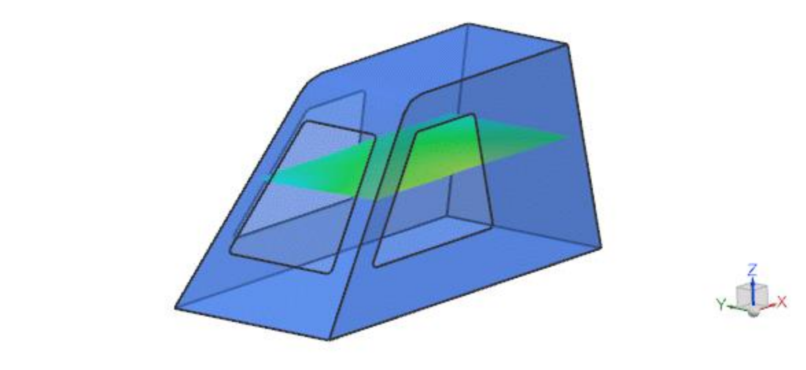
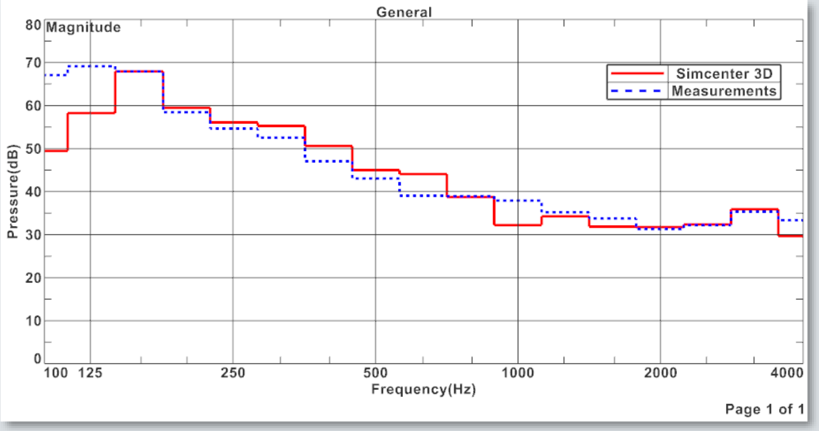
7th Fl., KOITA Bldg., 37 Baumoe-ro37-gil, Seocho-gu, Seoul 137-888, Korea









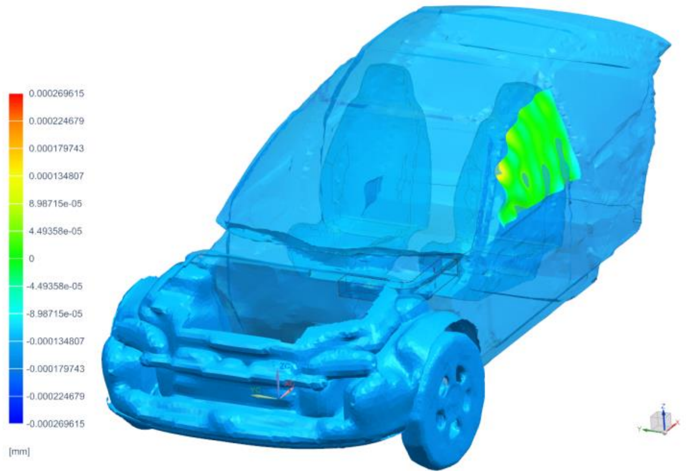
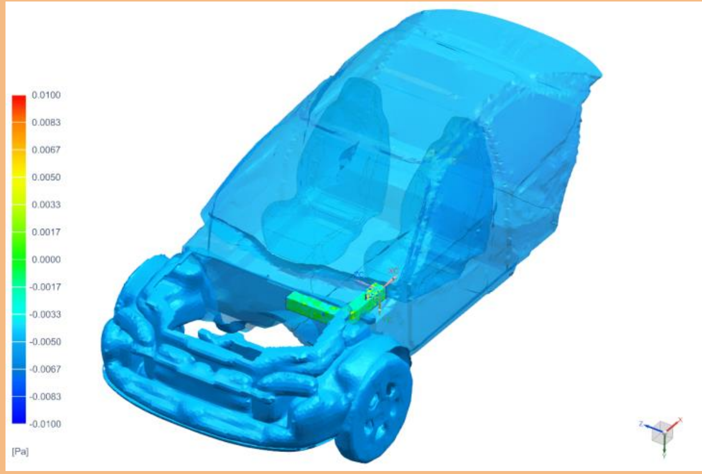
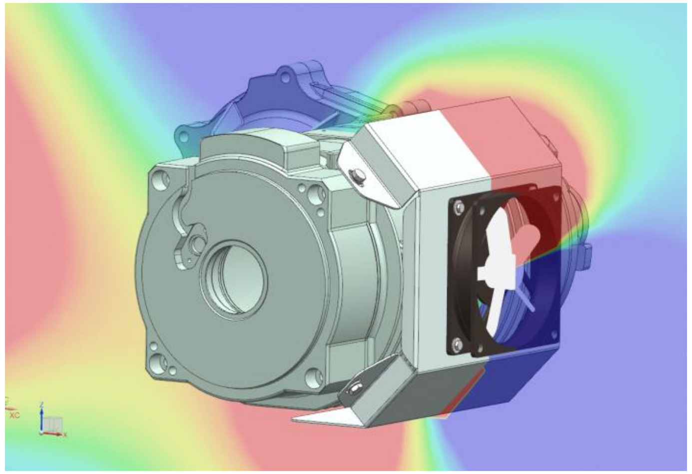
Windnoise simulation workflow

SIEMENS
Ingenuity for life

Aerodynamic field	Compute exterior aerodynamics accurately
Load Preparation	Prepare external loads smoothly for the vibro-acoustic model
Vibro-acoustic solution	Efficient finite element computation using single coarse physical mesh for all frequencies of interest

The supremacy of lean FE models to solve flow-induced noise

Three flow-induced noise applications examples with FEMAO

Windnoise	**HVAC noise**	Fan noise
		

Simcenter STAR-CCM+
Acoustic Perturbation Equation (APE) Solution

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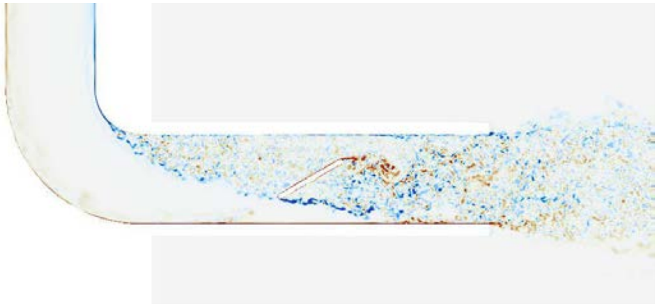
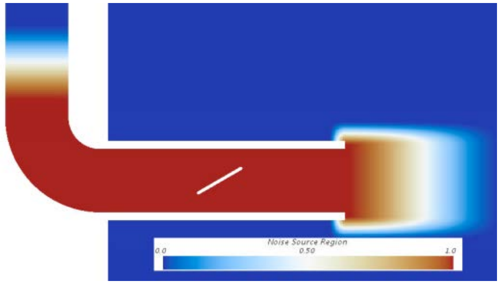
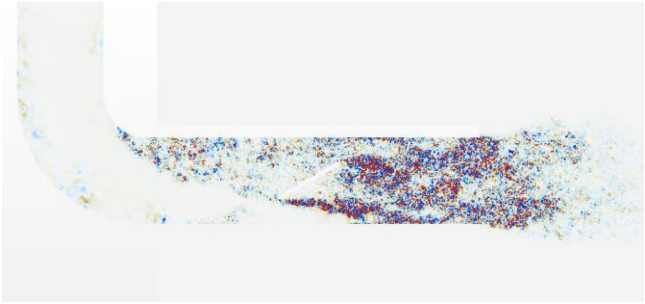
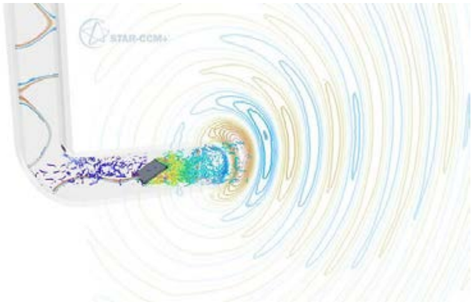


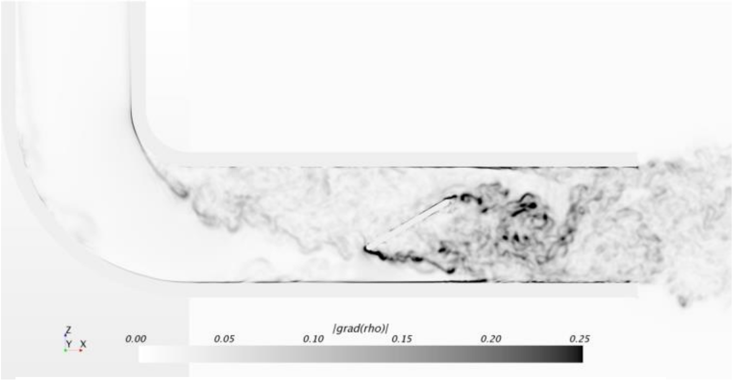




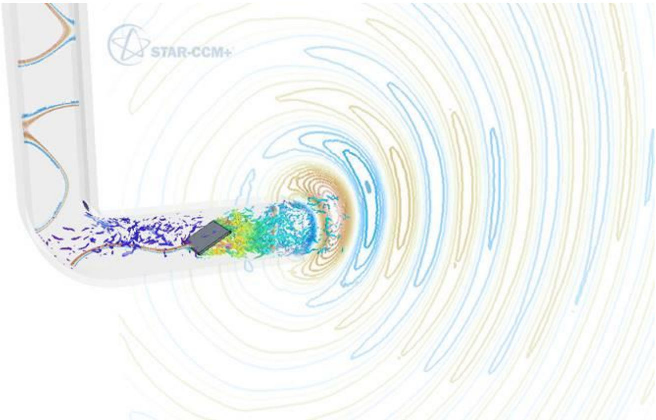


Calculate flow field → Specify a source region where noise sources are calculated → Calculate the noise sources → Use APE to calculate the sound waves

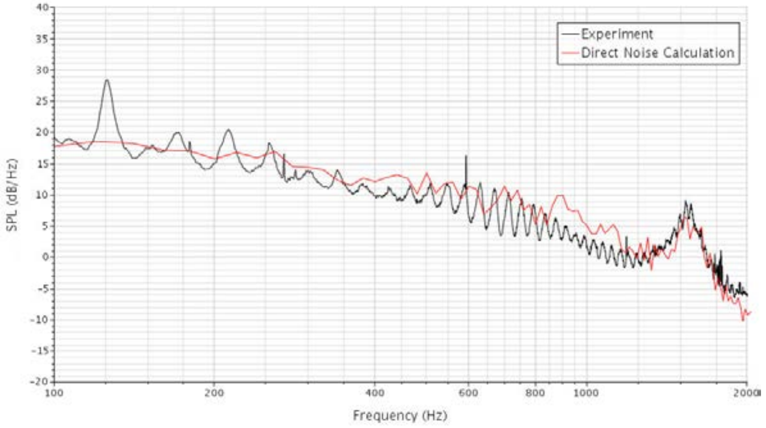
Simcenter STAR-CCM+ approaches
Duct Elbow

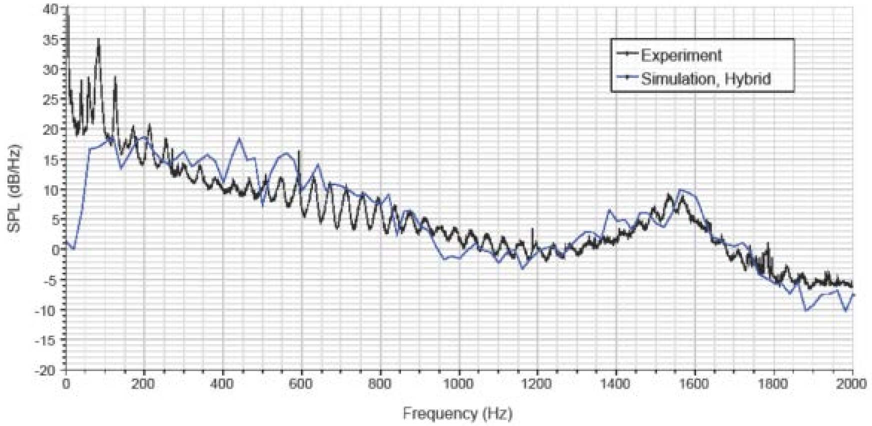


Direct Noise Calculation



Hybrid (Acoustic Perturbation Equation)

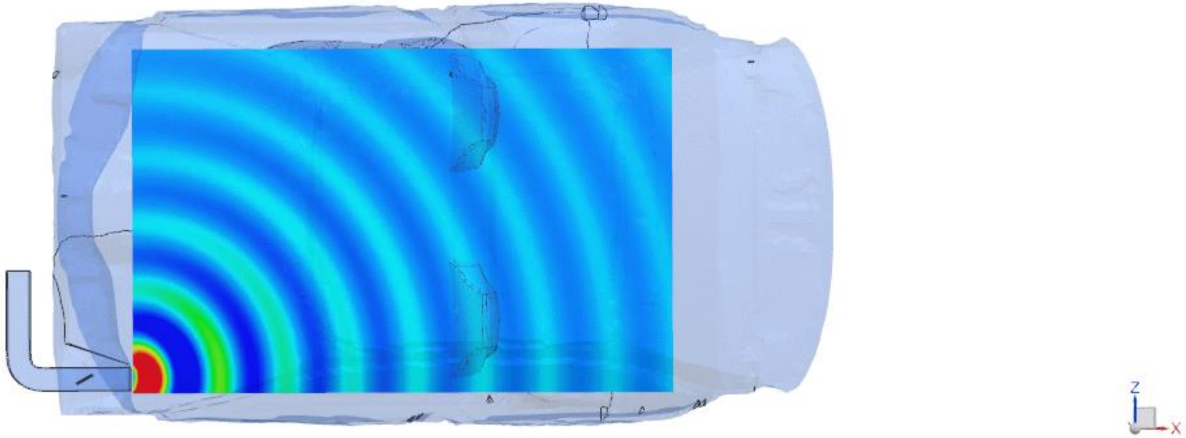




HVAC Noise Simulations

Component level free-field propagation

Acoustic wave propagation from HVAC outlet in free-field



Acoustic wave propagation from HVAC outlet inside cabin with absorbing surfaces such as seats, carpet and roof

?

Aeroacoustics hybrid simulation workflow

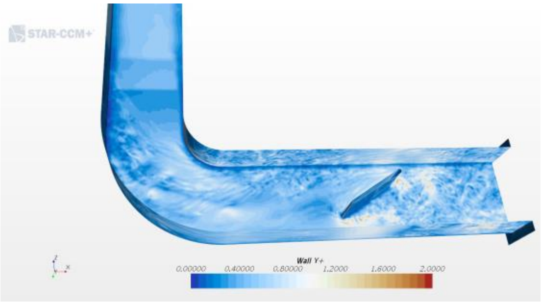
SIEMENS
Ingenuity for life

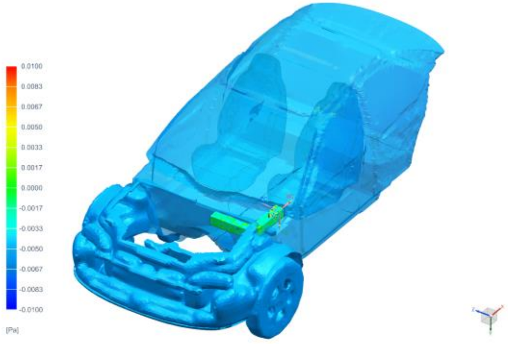
Aerodynamic load preparation

Aeroacoustic source modeling

Acoustic propagation

From CFD output files to propagation towards driver's ear





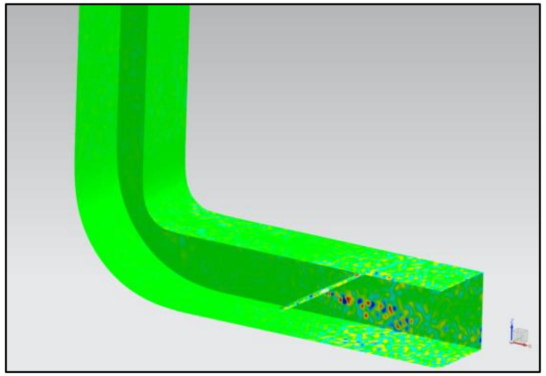
Turbulent flow field in the duct with Simcenter STAR-CCM+

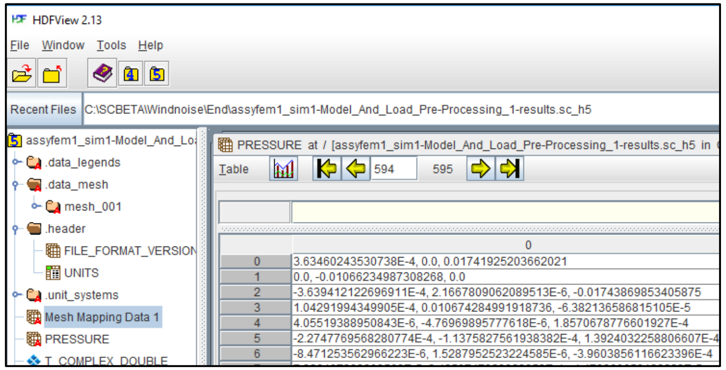
Load and Source Preparation for aeroacoustics simulation with Simcenter 3D

Solution of the acoustics field in the car cabin with Simcenter Nastran

Aeroacoustics
Hybrid simulation workflow

Generation of advanced aeroacoustics sources





Transform pressure to acoustic velocity boundary condition

Aerodynamic pressure loading on the HVAC components

Easy link to the hdf5 load file to be picked up by Simcenter Nastran ACSPO2

Advanced aeroacoustic sources for HVAC duct components

Hybrid approach: Alternative Solutions

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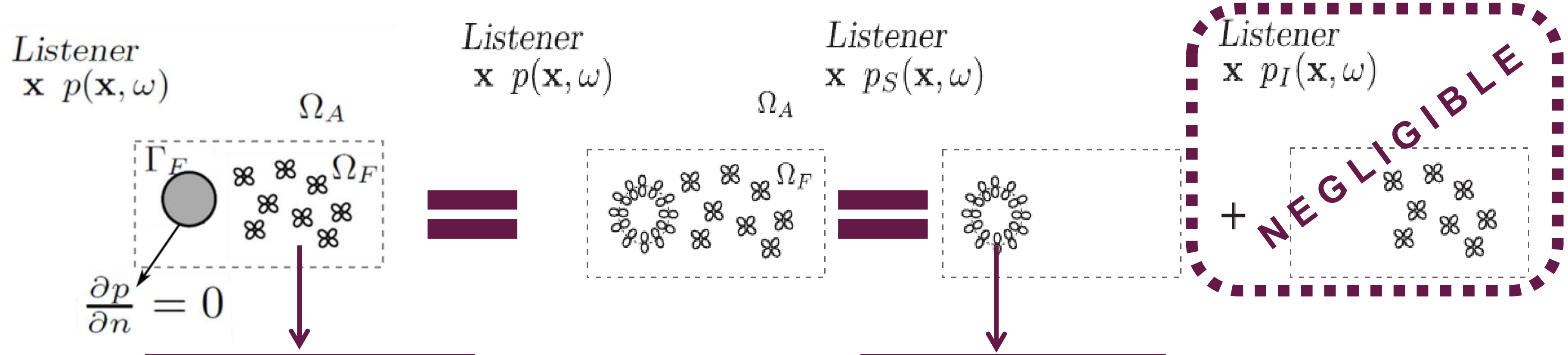
Scattered field of Quadrupole sources by the surfaces is equivalent to Dipole radiation for low-Mach Number flows

Quadrupole problem	Surface Sources: Dipoles



Flow velocities

Wall pressure

Transform pressure to acoustic velocity boundary condition

Benefit: Lean models with reduced load file size

Cases description

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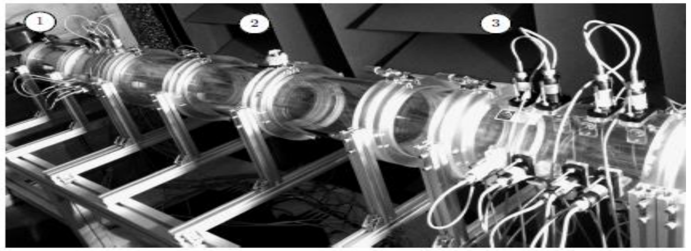
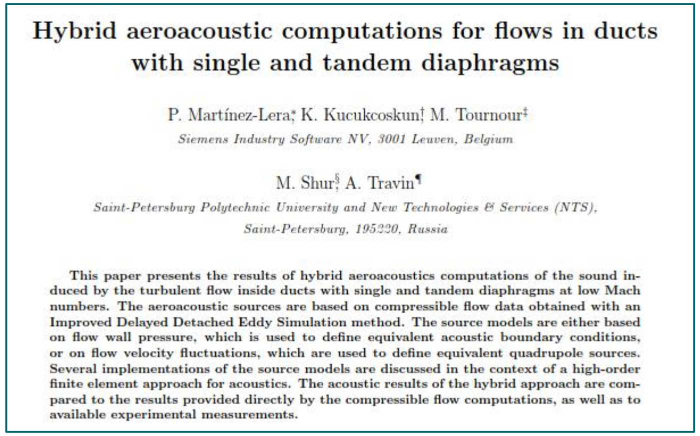


AIAA 2016-2796



Hybrid aeroacoustic computations for flows in ducts with single and tandem diaphragms

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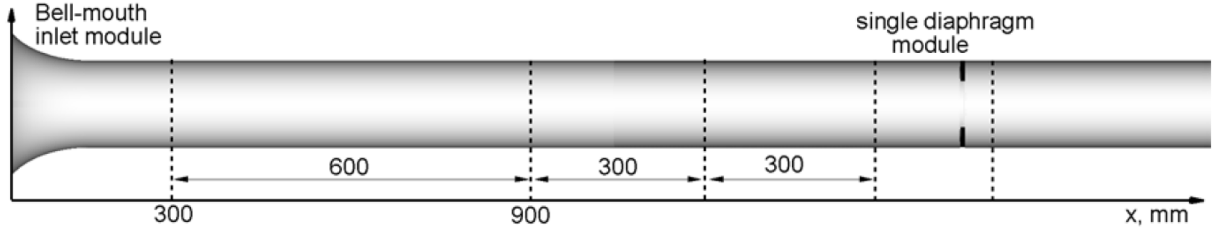
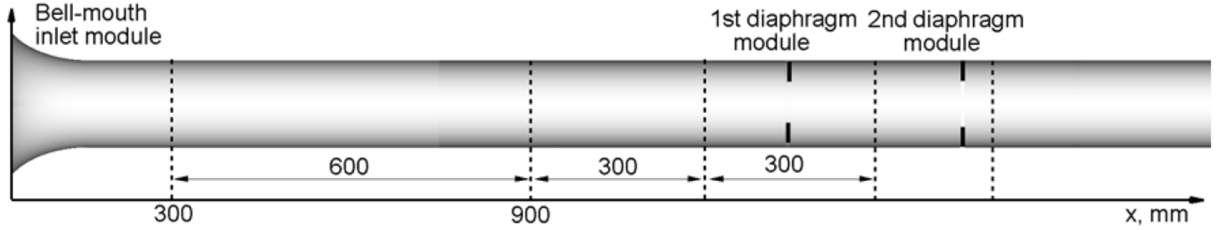
This paper presents the results of hybrid aeroacoustics computations of the sound induced by the turbulent flow inside ducts with single and tandem diaphragms at low Mach numbers. The aeroacoustic sources are based on compressible flow data obtained with an Improved Delayed Detached Eddy Simulation method. The source models are either based on flow wall pressure, which is used to define equivalent acoustic boundary conditions, or on flow velocity fluctuations, which are used to define equivalent quadrupole sources. Several implementations of the source models are discussed in the context of a high-order finite element approach for acoustics. The acoustic results of the hybrid approach are compared to the results provided directly by the compressible flow computations, as well as to available experimental measurements.

Low average Mach number (around M=0.07)
D=0.150m, d=0.116m, thickness 0.008m

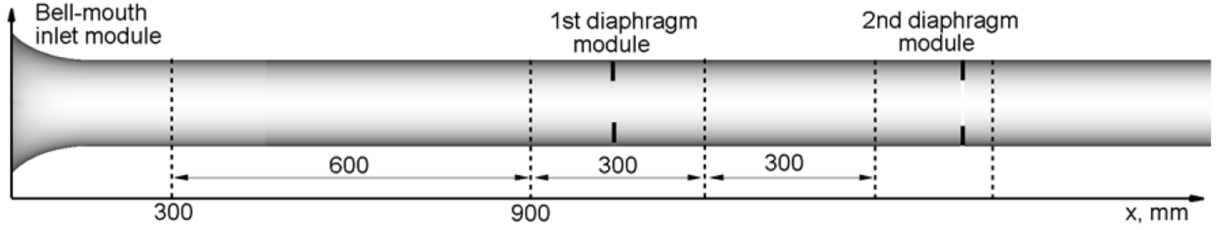
Single diaphragm



Tandem diaphragms (separation 2D)



Tandem diaphragms (separation 4D)



CFD: Snapshots of vorticity

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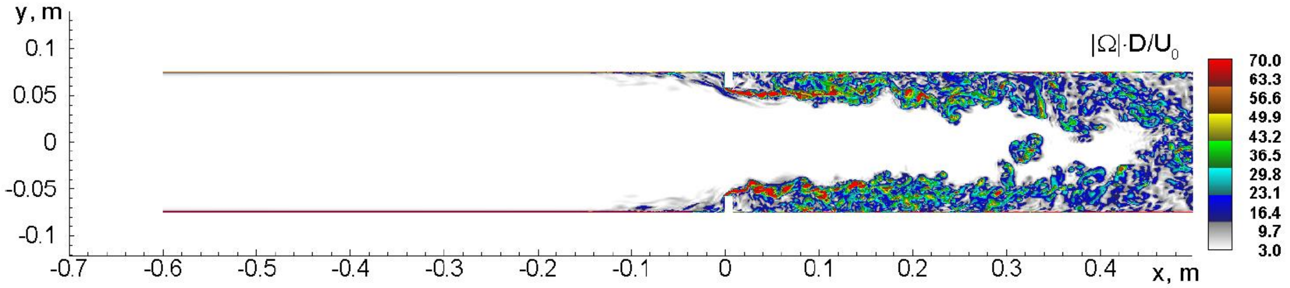
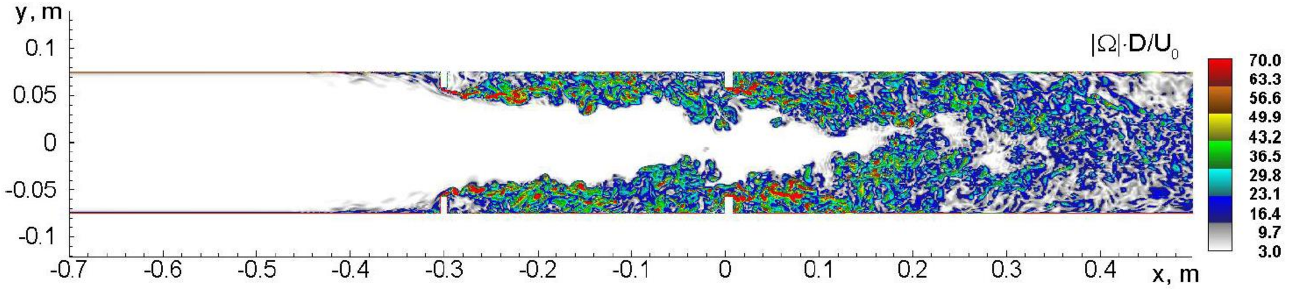
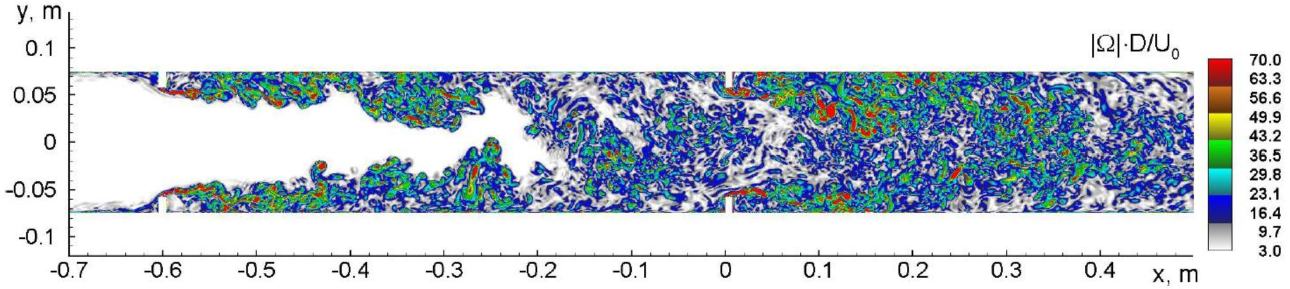
Single diaphragm



Tandem diaphragms 2D separation



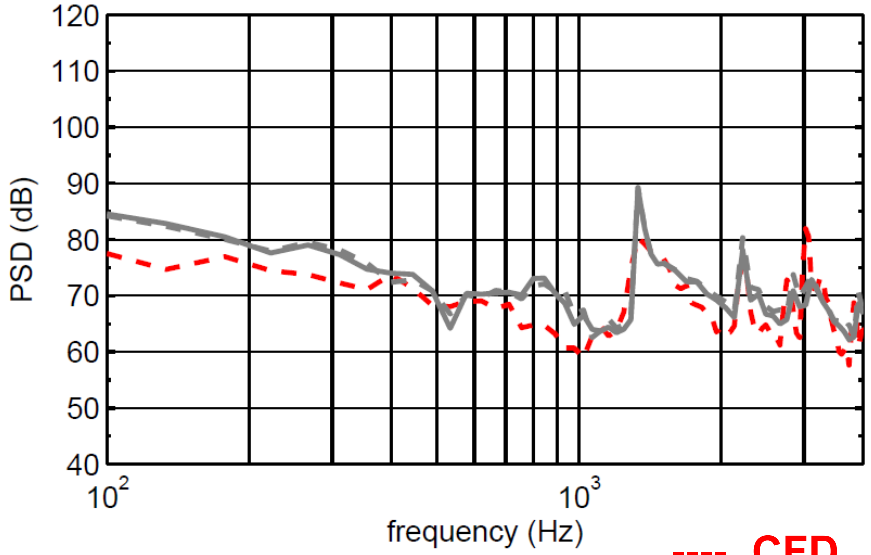
Tandem diaphragms 4D separation



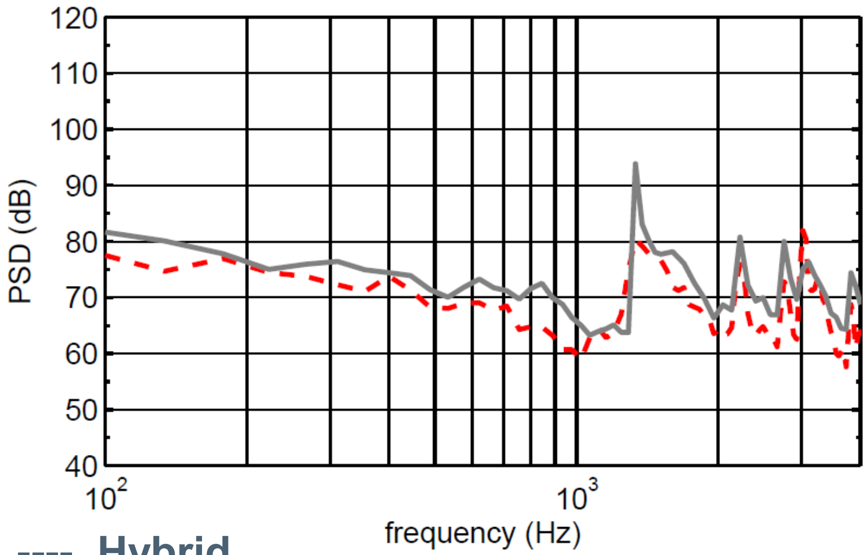
Single diaphragm:

Acoustic prediction with quadrupole sources

Lighthill's analogy (no mean flow)



Vortex sound theory (mean flow)

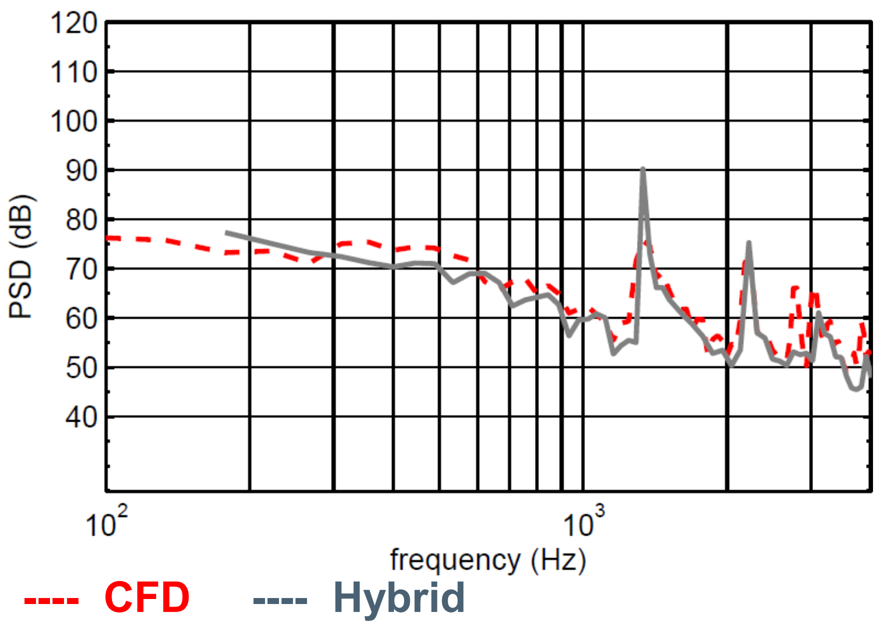


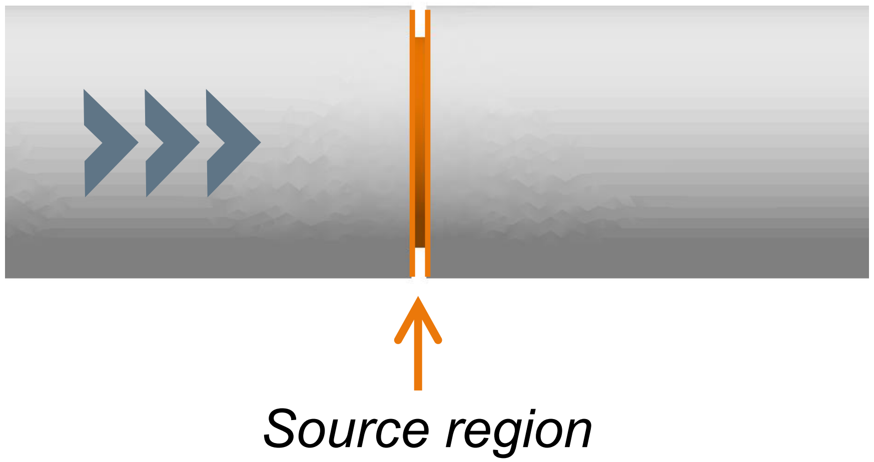
---- CFD ---- Hybrid

Source region

Single diaphragm:
Acoustic prediction with dipole sources

Dipole Sources

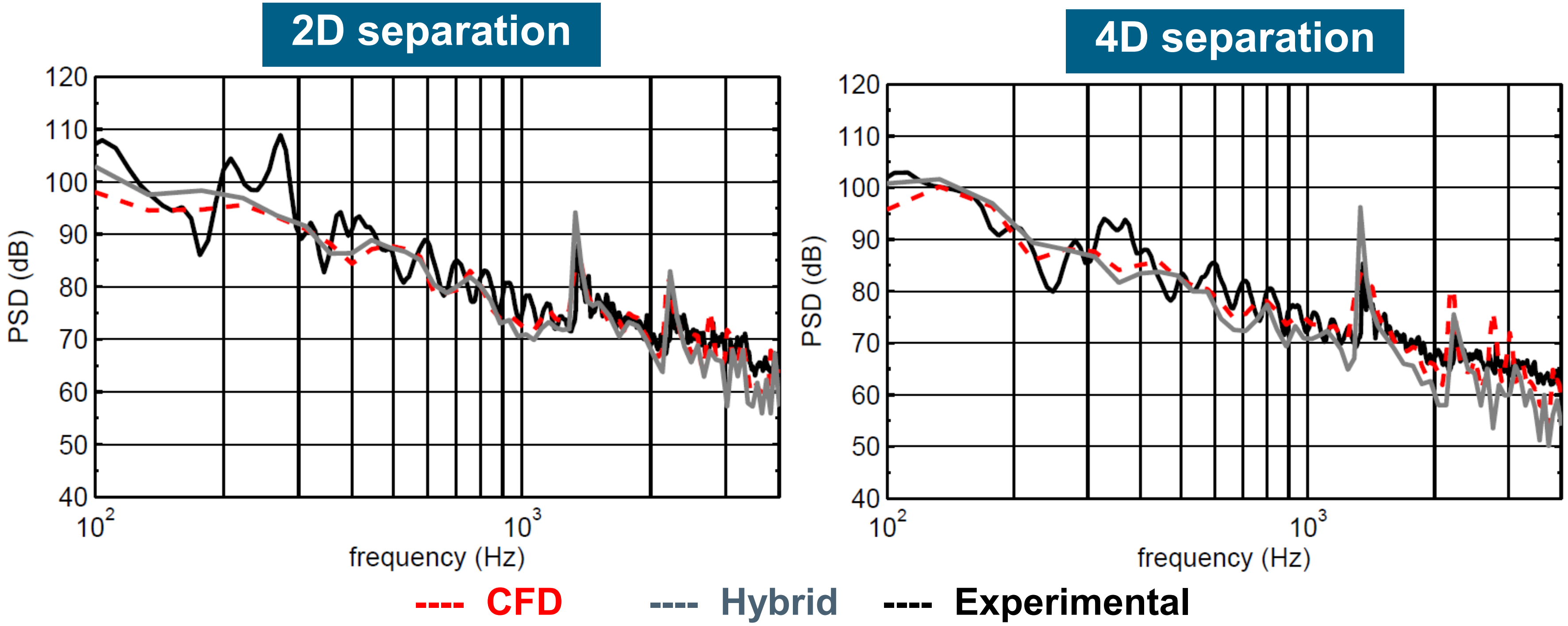




Dipole sources on diaphragm surface (dominant source of sound)

Formulation can be applied to incompressible CFD input for similar low-Mach Number applications

Tandem diaphragms:
Acoustic prediction with dipole sources



Dipole sources on <u>downstream</u> diaphragm surface (dominant source of sound)

Formulation can be applied to incompressible CFD input for similar low-Mach Number applications

HVAC Noise Simulations
Validation with academic model

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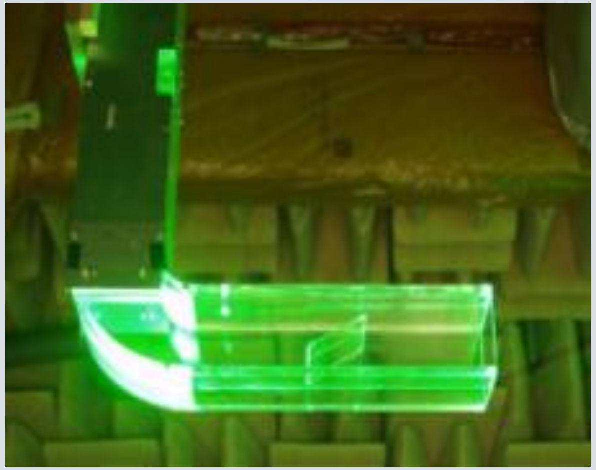
Simplified HVAC from literature



2008-2902

29th AIAA Aeroacoustics Conference, May 5-7 2008, Vancouver B.C.

Numerical and Experimental Investigations of the Noise Generated by a Flap in a Simplified HVAC Duct

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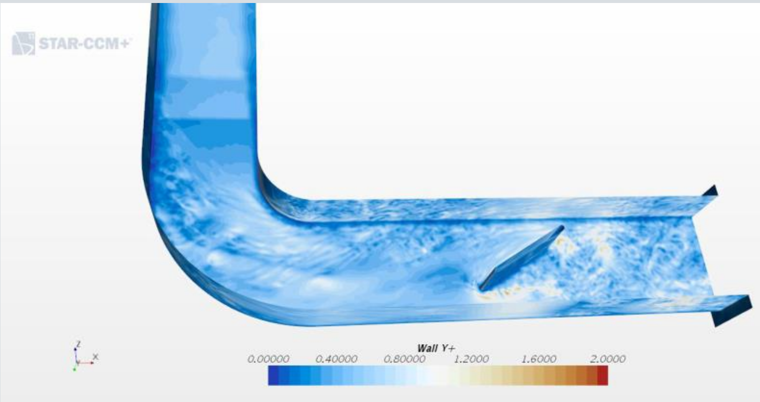
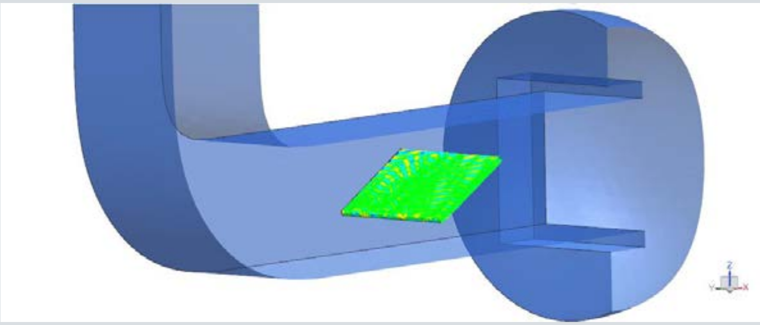
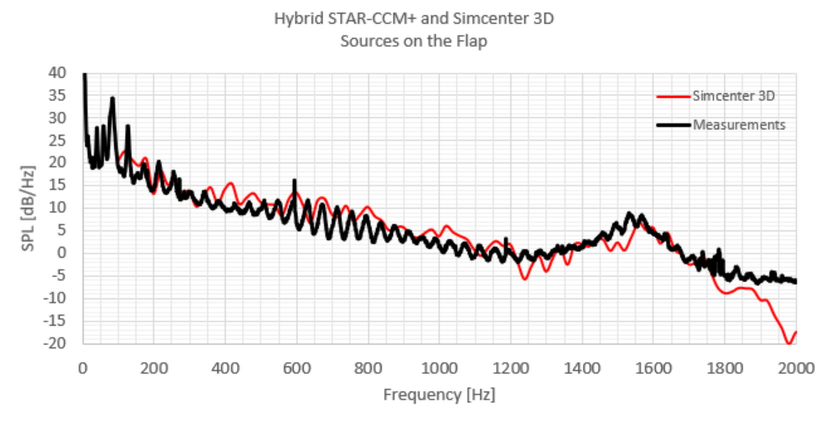
[8] EADS Deutschland GmbH, Innovation Works, D-81663 Munich, Germany

Coupling Simcenter STAR-CCM+ with Simcenter 3D





Comparison of simulation results with measurements

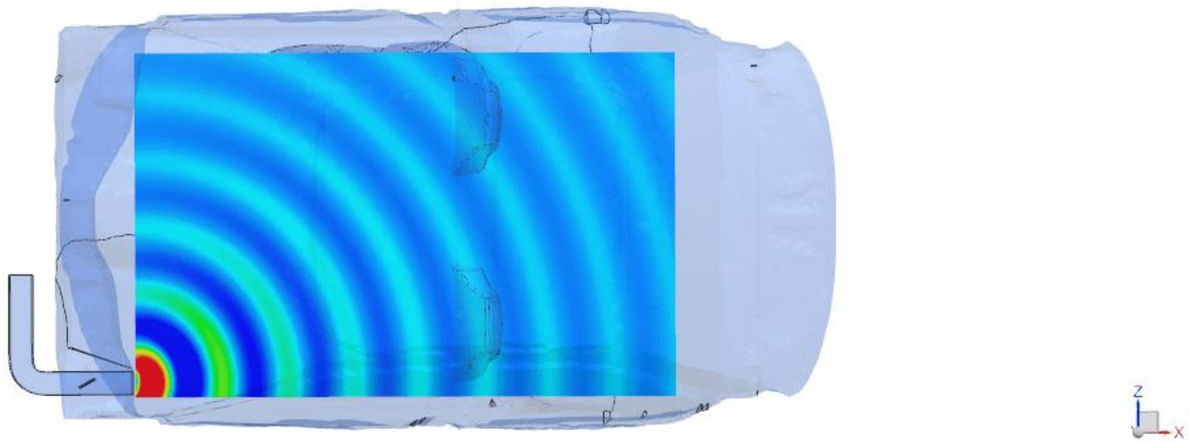


Dipole sources on flap surface (dominant source of sound)

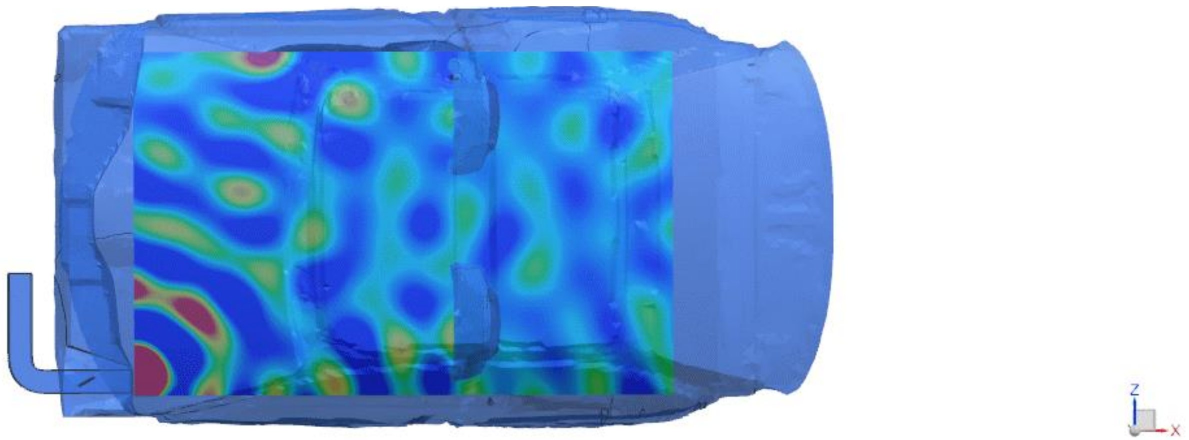
Formulation applied to incompressible CFD input

HVAC Noise Simulations
Propagation with cabin

Acoustic wave propagation from HVAC outlet in free-field



Acoustic wave propagation from HVAC outlet inside cabin with absorbing surfaces such as seats, carpet and roof



Aeroacoustics simulation workflow

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Aerodynamic load preparation	Prepare aerodynamic loads smoothly for the aeroacoustic problem
Aeroacoustic source modeling	Computation of the advanced aeroacoustics sources for stationary components
Acoustic propagation	Efficient finite element computation using single coarse physical mesh for all frequencies of interest

The supremacy of lean FE models to solve flow-induced noise

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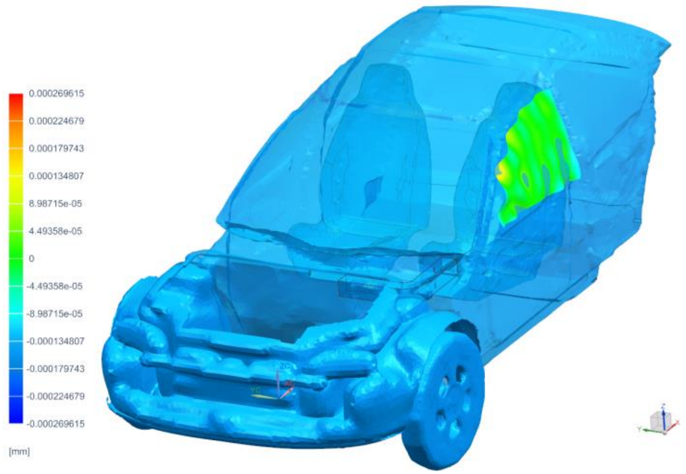
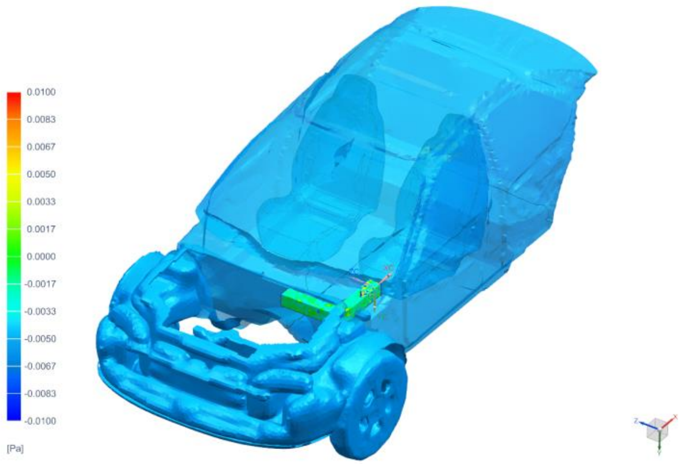
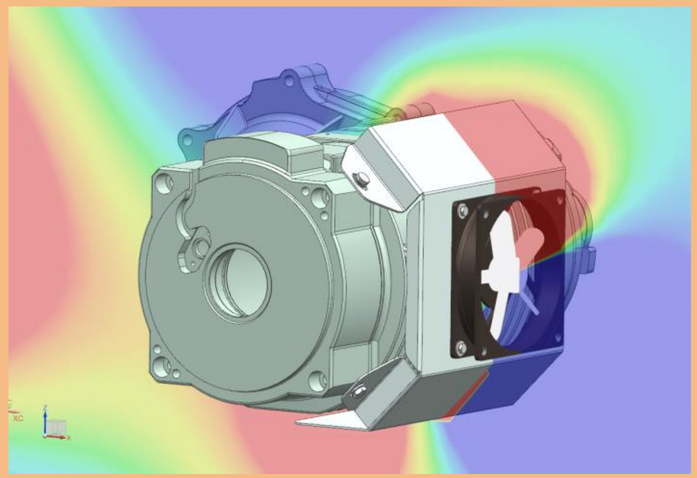
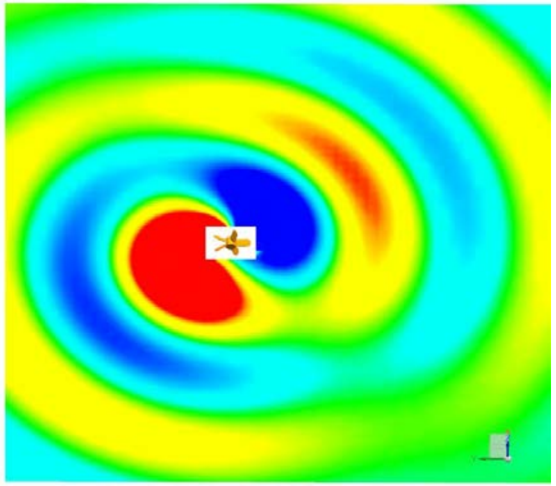
Three flow-induced noise applications examples with FEMAO

Windnoise	HVAC noise	**Fan noise**
		

Cooling Fan Noise
Component level simulation



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Compute unsteady flow field around source region with Simcenter STAR-CCM+

Compute free-field acoustic propagation accurately

Installation effects, reflective/absorbing surface, infinite plates, porous volumes in propagation

Aeroacoustics hybrid simulation workflow

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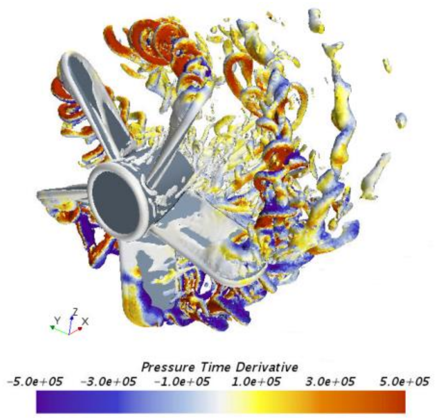
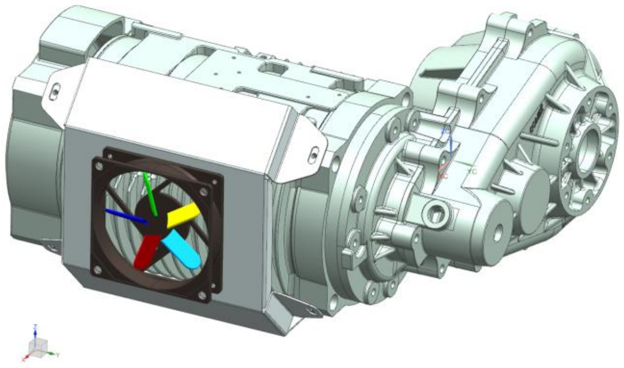
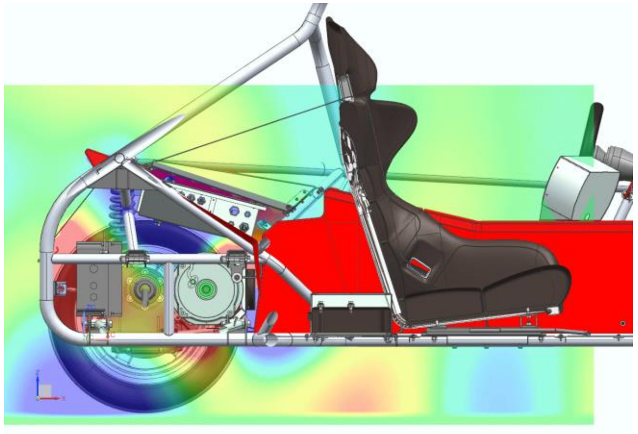
From CFD output files to propagation towards driver's ear







Turbulent flow field around the fan with Simcenter STAR-CCM+

Load and Source Preparation for aeroacoustics simulation with Simcenter 3D

Solution of the acoustic field towards the driver with Simcenter Nastran

Cooling Fan Noise Simulations in free-field
with Simcenter STAR-CCM+ and Simcenter 3D

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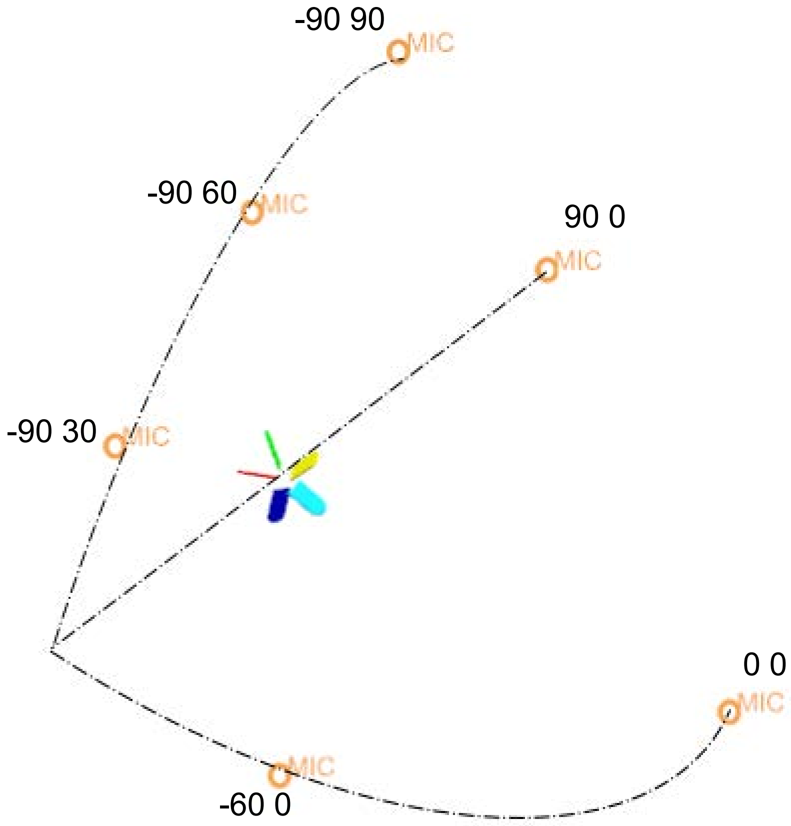
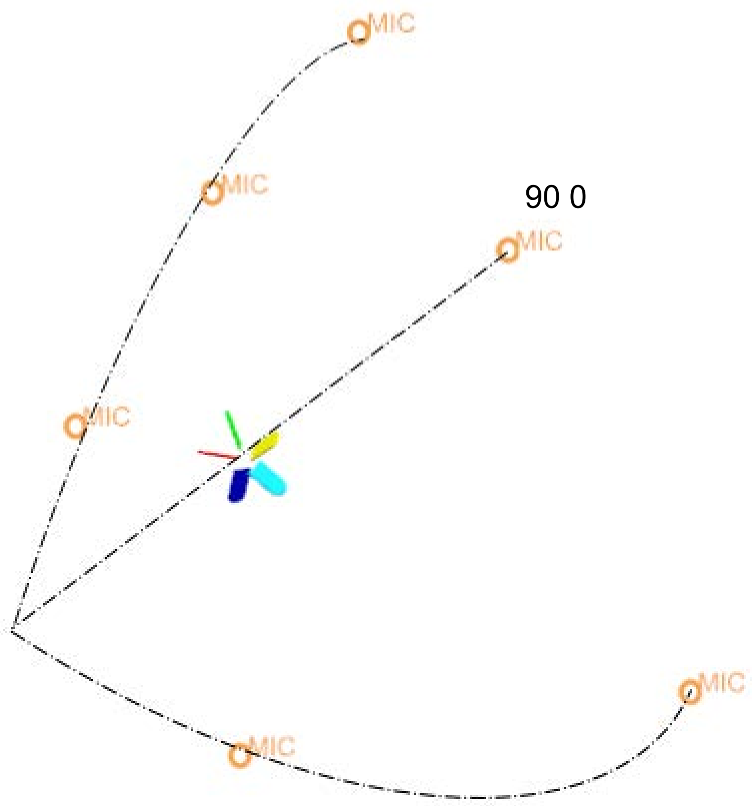
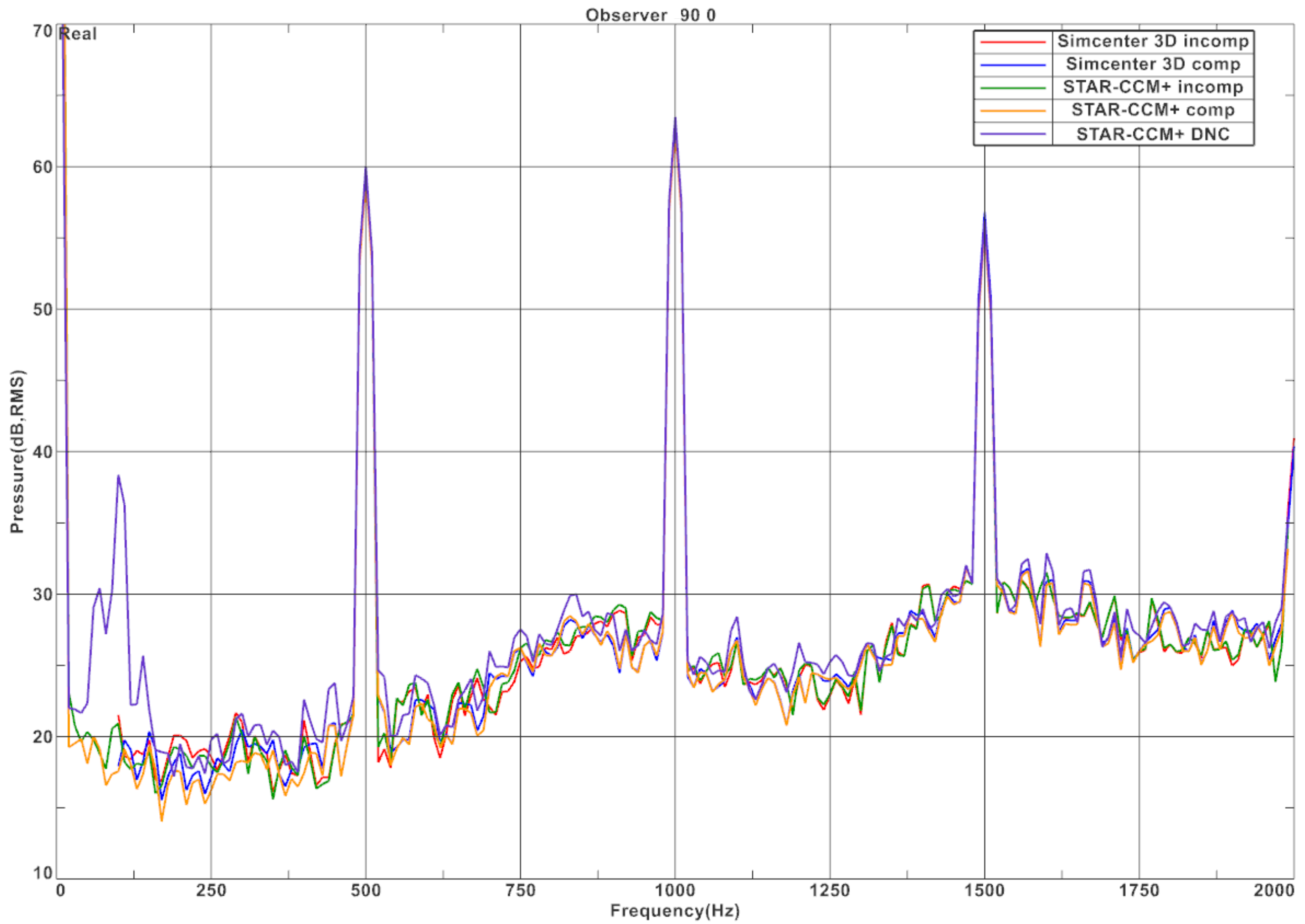


Two separate CFD inputs are considered
- **With incompressible CFD input**
  to compare hybrid and FWH approaches
- **With compressible CFD input**
  to compare hybrid, FWH and DNC approaches)

The goal of this comparison is to have
- same sound levels at Blade Passing Frequency (BPF) and harmonics
- similar broadband levels
- DNC solution is assumed to be the reference solution

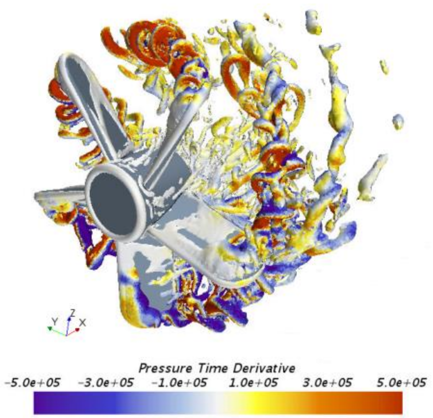
Cooling Fan Noise Simulations
with Simcenter STAR-CCM+ and Simcenter 3D

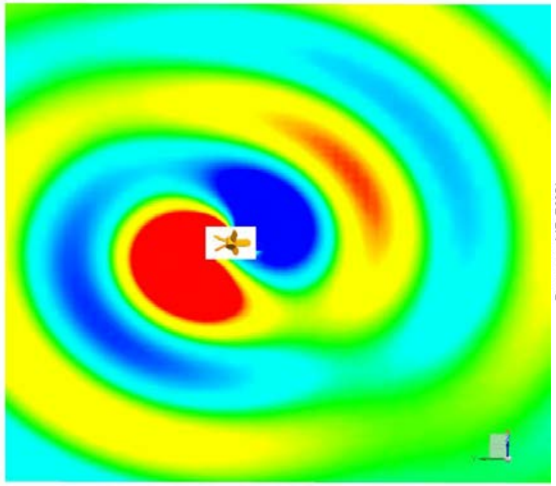


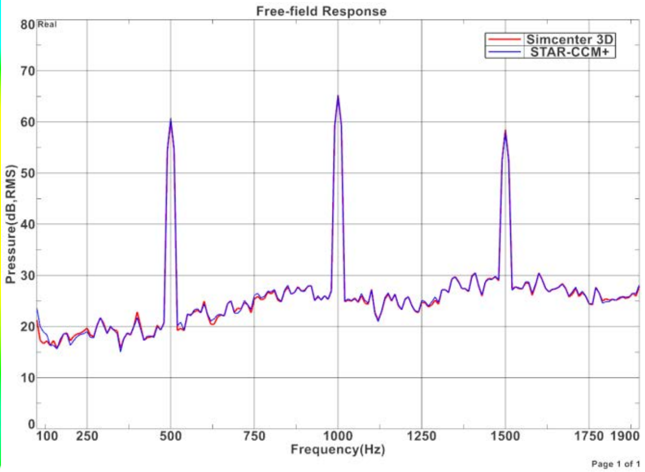


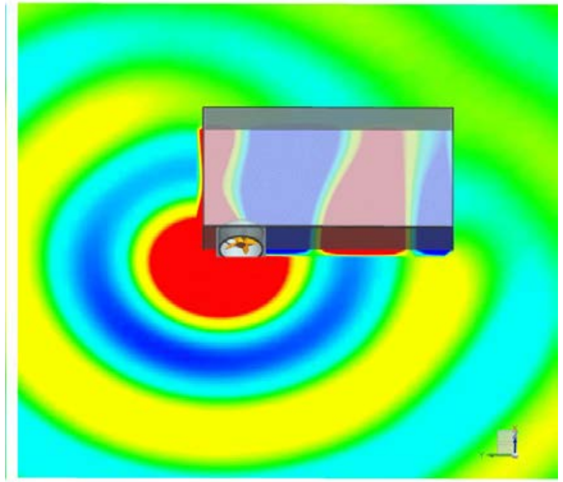
All 5 methods provide similar SPL results for both tones and broadband frequencies

Cooling Fan Noise Simulations
with Simcenter STAR-CCM+ and Simcenter 3D









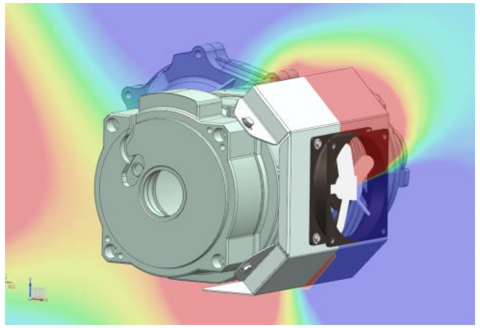
Compute unsteady flow field around source region with Simcenter STAR-CCM+

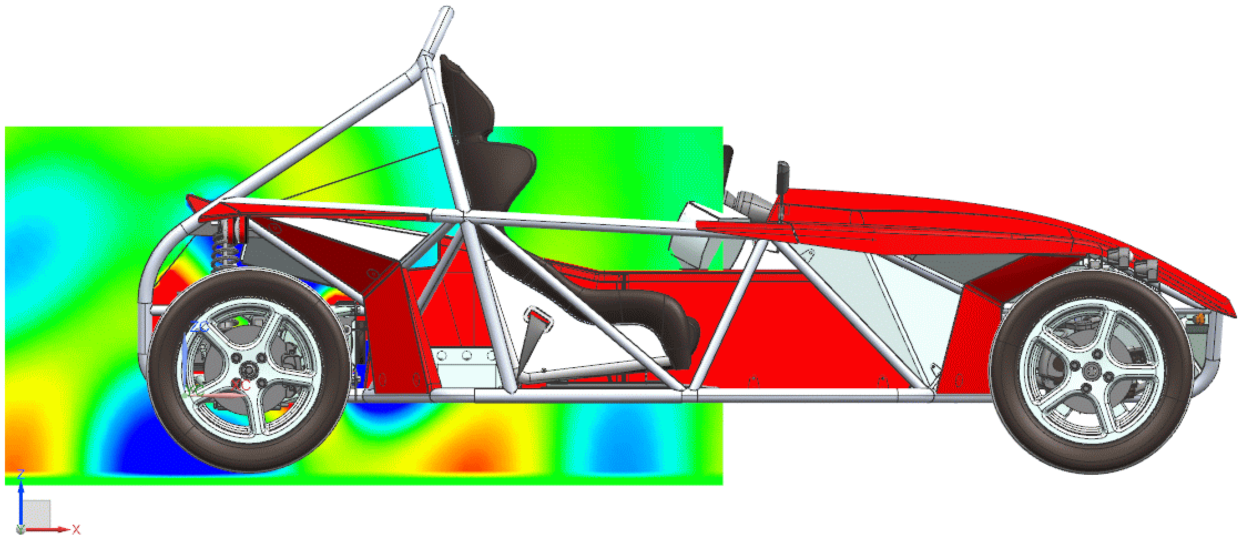
Using the transient blade pressure, compute free-field acoustic propagation with STAR-CCM+ FW-H or Simcenter 3D

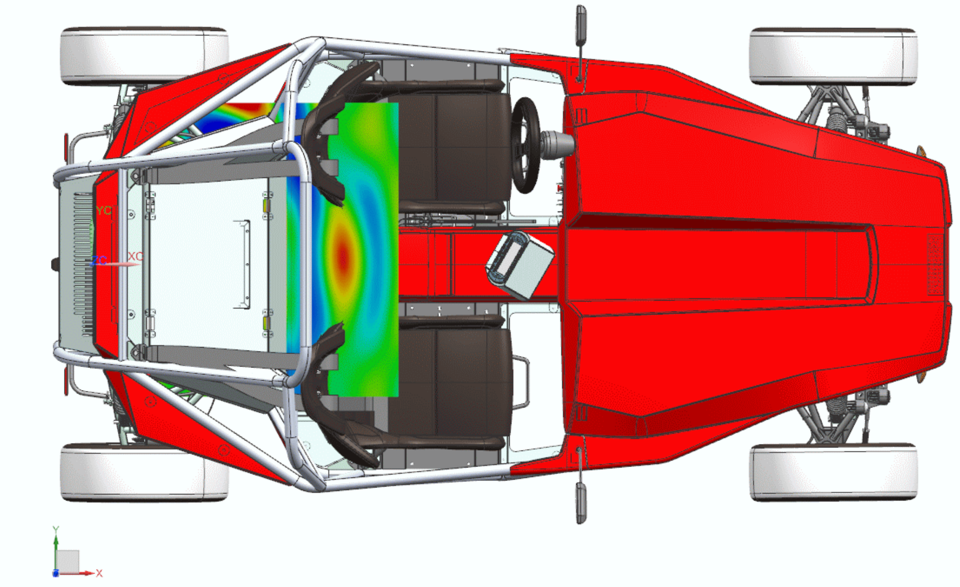
Add installation effects, reflective/absorbing surface, infinite plates, porous volumes in Simcenter 3D

EM Cooling Fan Noise Simulations
with absorbing and reflective surfaces

Acoustic wave propagation from cooling fan from engine bay towards driver's ear with absorbing surfaces such as panels and seats







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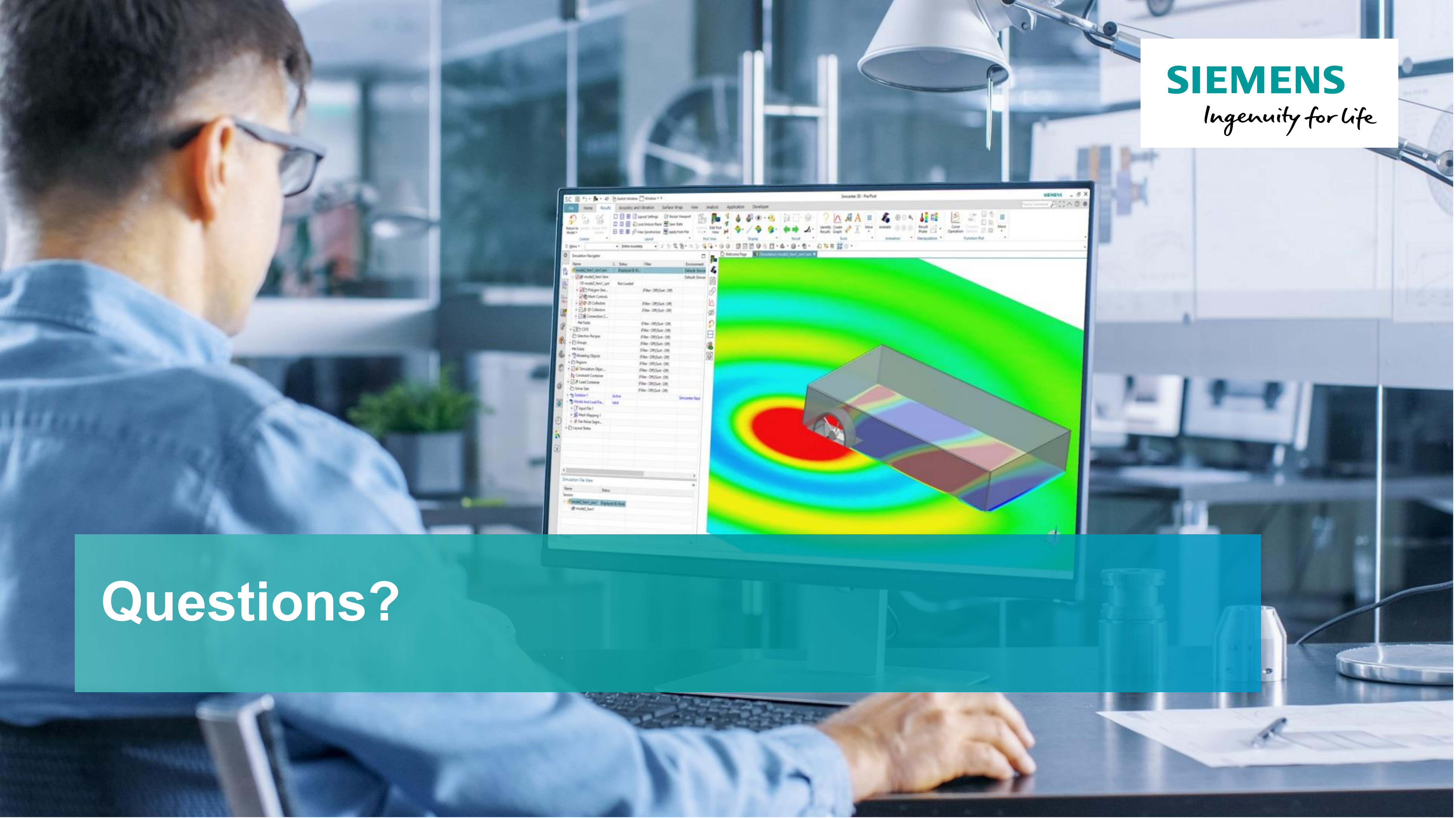
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Questions?