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
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

EV vs. ICE vehicles: NVH Challenges

Greg Goethius: Leading the Charge – The Future of Electric Vehicle Noise Control
Why simulating flow-induced-noise?

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.
Flow-induced-noise
Broadband characteristic of the acoustic response

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

Standard FEM → 1 single model for all frequencies

Standard FEM → several models for different frequency ranges

FEMAO → 1 single model for all frequencies
Simcenter 3D Acoustics – FEMAO

Benefits

- 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

Three flow-induced noise applications examples with FEMAO

Windnoise  HVAC noise  Fan noise
Acoustics: What happens in the presence of flow?

- **Turbulent Flow**
  - Structural vibrations
  - Structure-borne noise

Flow-induced vibrations $\rightarrow$ Vibro-acoustics

- **Flow fluctuations**
  - Flow-induced noise
  - Structure-borne noise

Flow-induced noise $\rightarrow$ Aero-acoustics

- **Turbulent Flow**
  - Flow fluctuations
  - Flow-induced noise

Flow-induced vibrations $\rightarrow$ Aero-vibro-acoustics
The supremacy of lean FE models to solve flow-induced noise

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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<tr>
<th>Low-frequency wind noise</th>
<th>High-frequency wind noise</th>
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<td>f &lt; 500 Hz</td>
<td>1000 Hz &lt; f &lt; 5000 Hz</td>
<td>500 Hz &lt; f</td>
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<tr>
<td>Underbody and green house</td>
<td>Side window and/or windshield</td>
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Structure: Simcenter Nastran FEM
Acoustics: Simcenter Nastran FEM/FEMAO

Virtual SEA+ / SEA+

Covered by FEM and FEMAO
Covered by SEA
Windnoise simulation workflow

**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

External aerodynamic field around the car

Aerodynamic field

Load Preparation

Vibro-acoustic solution

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

Export aerodynamic and acoustic pressure on side window in CGNS
Windnoise simulation workflow

Aerodynamic field

Load Preparation

Vibro-acoustic solution

Compute exterior aerodynamics accurately
Windnoise simulation workflow

Load preparation for the vibro-acoustic simulation

1. Imported Pressure Fluctuations (t) on CFD model
2. Mapped to Structural Model and converted to Forces (Hz)
3. 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

Aerodynamic field

Compute exterior aerodynamics accurately

Load Preparation

Prepare external loads smoothly for the vibro-acoustic model

Vibro-acoustic solution
Windnoise simulation workflow

Aerodynamic field

Load Preparation

Vibro-acoustic solution

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

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

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

For this SPL response point
At this frequency
Response for unit force loading is expressed on inputs
Windnoise simulation workflow

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
Windnoise simulation workflow

Aerodynamic field
Compute exterior aerodynamics accurately

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Three flow-induced noise applications examples with FEMAO

Windnoise

HVAC noise

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

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

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

Aerodynamic pressure loading on the HVAC components

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

Transform pressure to acoustic velocity boundary condition

Advanced aeroacoustic sources for HVAC duct components
Hybrid approach: Alternative Solutions

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

Low average Mach number (around $M=0.07$)
$D=0.150\text{m},\ d=0.116\text{m},\ \text{thickness}\ 0.008\text{m}$

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

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Stamats Ingemercuni Software, NC, 2000 London, Belgium

M. Sirilos, A. Trzeciak
Saint Petersburg Polytechnic University and New Technologies P. Services (NTS), Saint Petersburg, 199529, Russia

This paper presents the results of hybrid aeroacoustic computations of the sound induced by the turbulent flow inside ducts with single and tandem diaphragms at low Mach numbers. The aeroacoustic source is 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 condition, or on flow velocity fluctuations, which are used to define equivalent quasiperiodic sources. Several implementations of the source models are discussed in the context of a highorder finite element approach for radiation. 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.

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Single diaphragm

Tandem diaphragms (separation 2D)

Tandem diaphragms (separation 4D)
CFD: Snapshots of vorticity

- 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

Formulation can be applied to incompressible CFD input for similar low-Mach Number applications.
Tandem diaphragms: Acoustic prediction with dipole sources

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2D separation

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CFD

4D separation

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Hybrid

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Experimental

Dipole sources on downstream diaphragm surface (dominant source of sound)

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

Source region
HVAC Noise Simulations
Validation with academic model

Simplified HVAC from literature
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
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The supremacy of lean FE models to solve flow-induced noise

Three flow-induced noise applications examples with FEMAO

Windnoise

HVAC noise

Fan noise
Cooling Fan Noise
Component level simulation

- 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

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

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
### Aeroacoustics simulation workflow

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Questions?