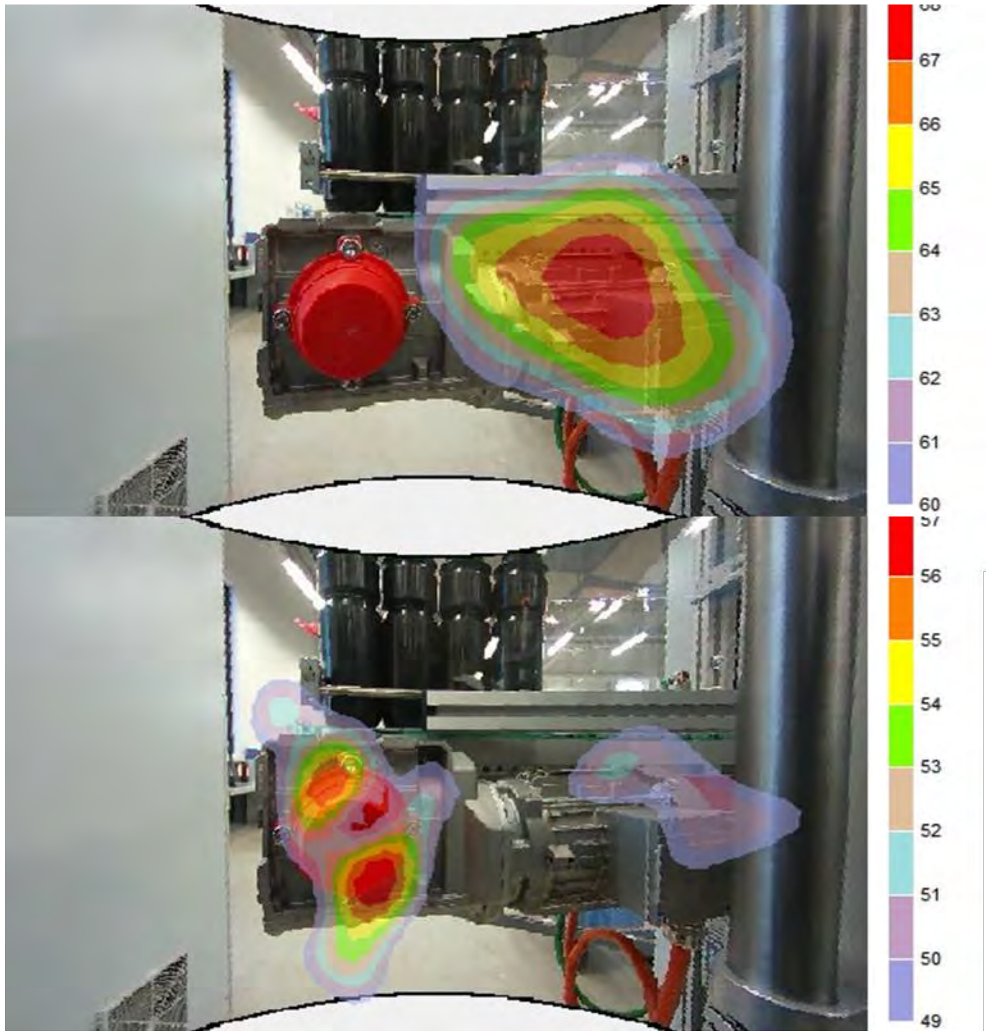
# Sound source localization techniques

# Agenda

SIEMENS
Ingenuity for life

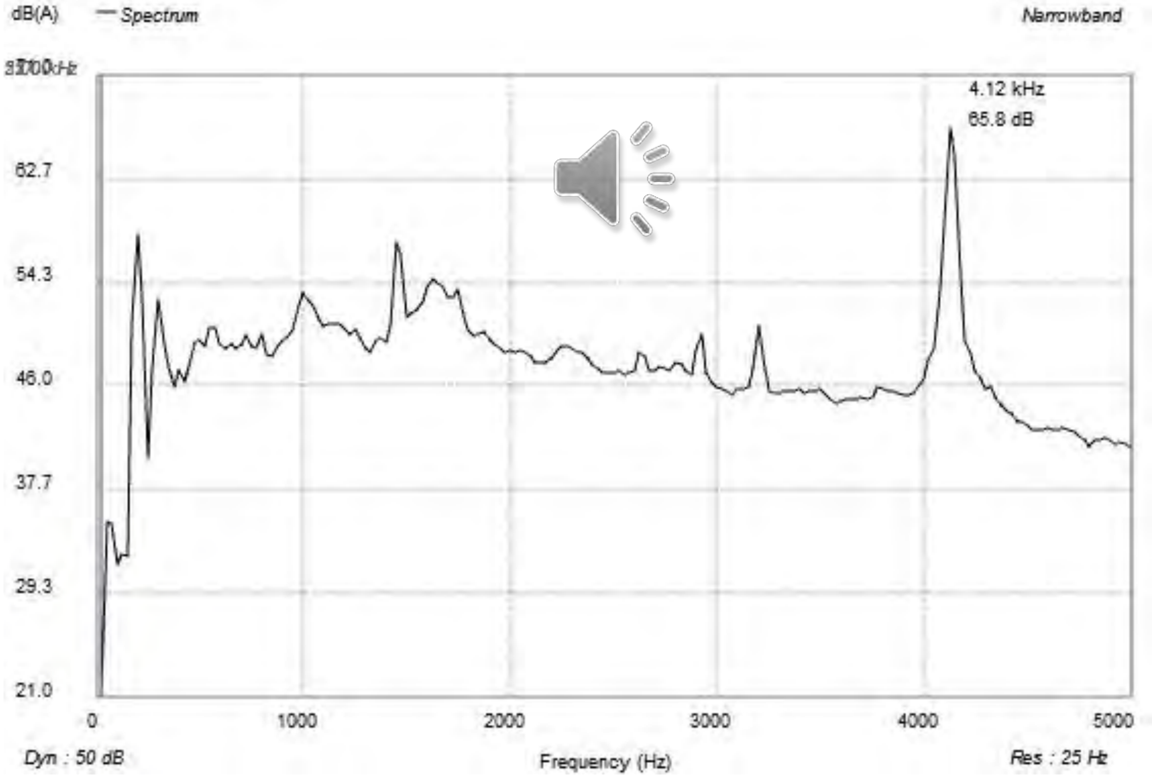



- **Sound source localization**
  - **Why do we need it?**
  - **How is it done?**
    - **Beamforming**
    - **Holography**
  - **Hungry for more?**
    - **Parallel data acquisition**
    - **Interior SSL**

# Sounds annoying, where is it coming from?

SIEMENS
Ingenuity for life

## Looks like it's the pump!




## Pump housing? Panel? Leakage?

# Sounds annoying, where is it coming from?

# When is Sound Source Localization applied?

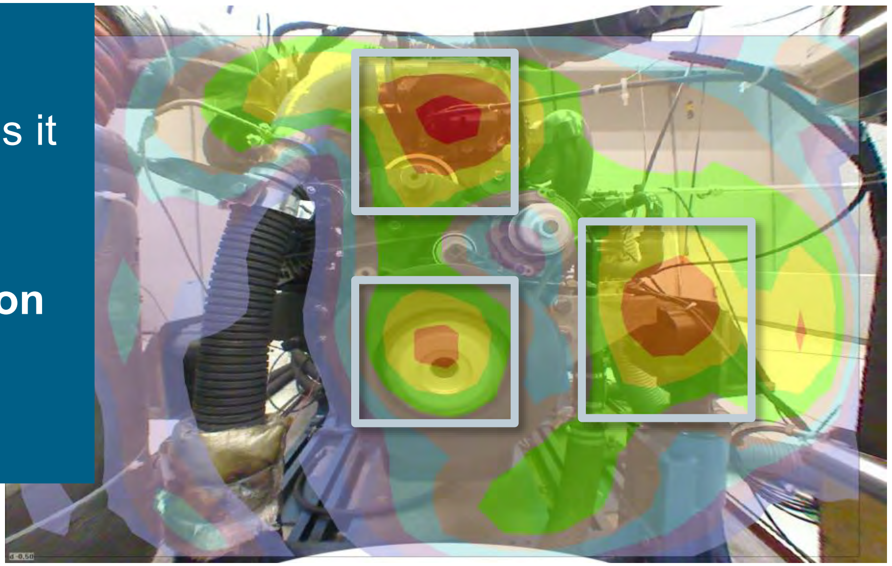
SIEMENS
Ingenuity for life

“What are the main contributors?”

**Estimate sound power for objective ranking**

“I hear something, but where does it come from?”

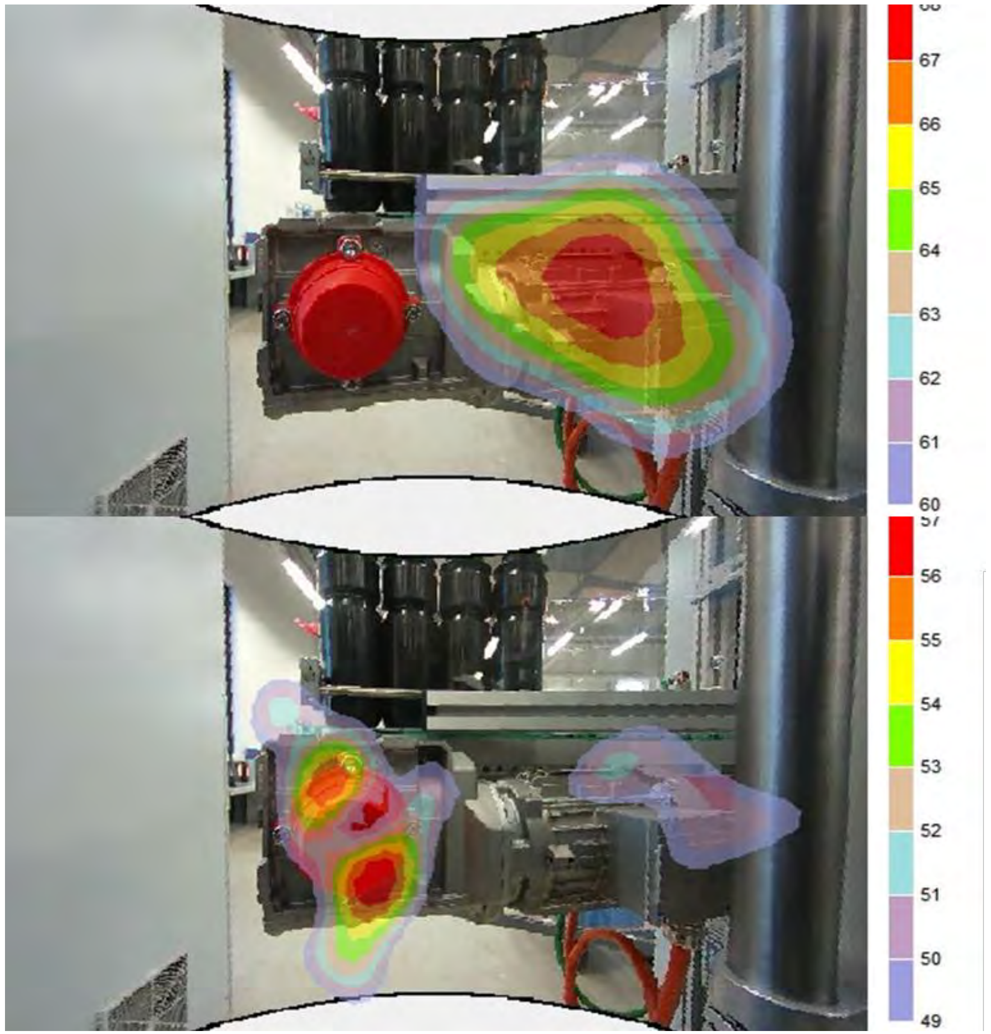
**Confirm that you are working on the right problem**



“How do other properties influence my acoustics?”

**Integrate into general purpose measurement systems**

# Agenda




**Sound source localization**

- Why do we need it?
- **How is it done?**
  - Beamforming
  - Holography
- Hungry for more?
  - Parallel data acquisition
  - Interior SSL

# How is Sound Source Localization performed?

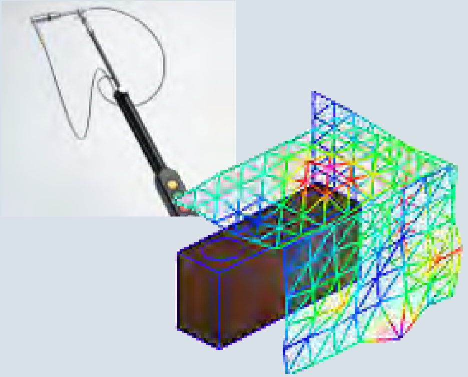
Simple → Advanced

## Stethoscope

- ❑ Limited hardware

- ❑ No reportable data
- ❑ Sound pressure only
- ❑ Stationary sources only

## Sound Intensity



- ❑ ISO sound power & partial sound power

- ❑ Time-consuming
- ❑ Limited frequency range
- ❑ Stationary sources only

## SoundBrush

- ❑ Fast results
- ❑ Limited hardware
- ❑ Directivity & sound power estimation

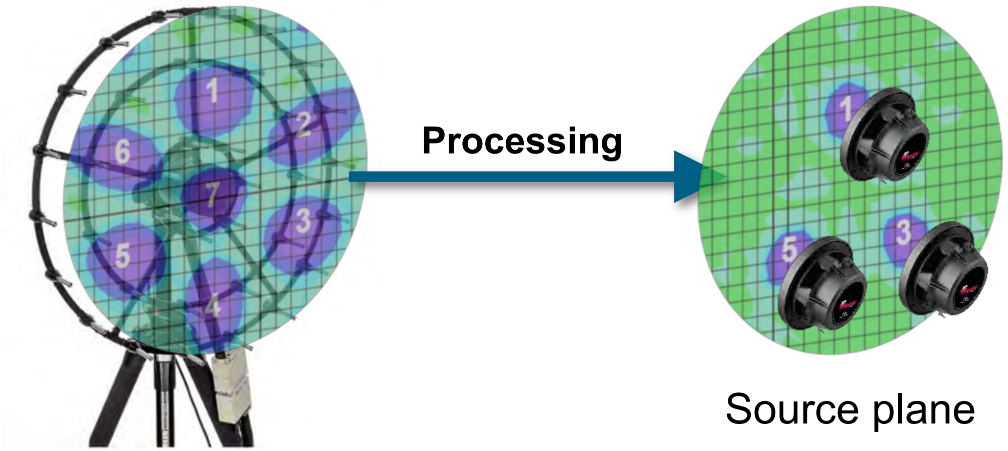
- ❑ Stationary sources only

## Sound Camera

# Why don’t we just measure sound pressure?

SIEMENS
Ingenuity for life

Measured
pressure field
(7 sources?)



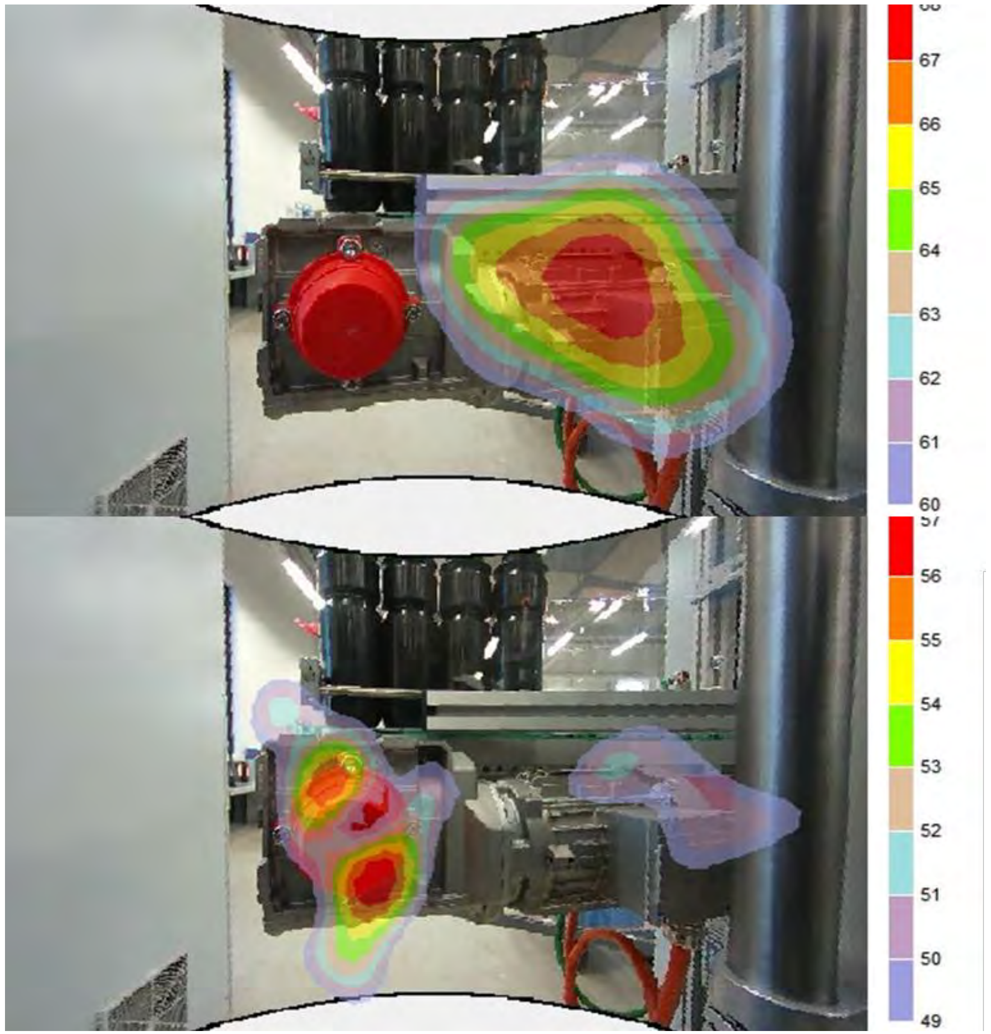

Propagated
pressure field
(3 sources)

Source plane

**How can we estimate the propagated pressure field from the measured one?**

# Agenda

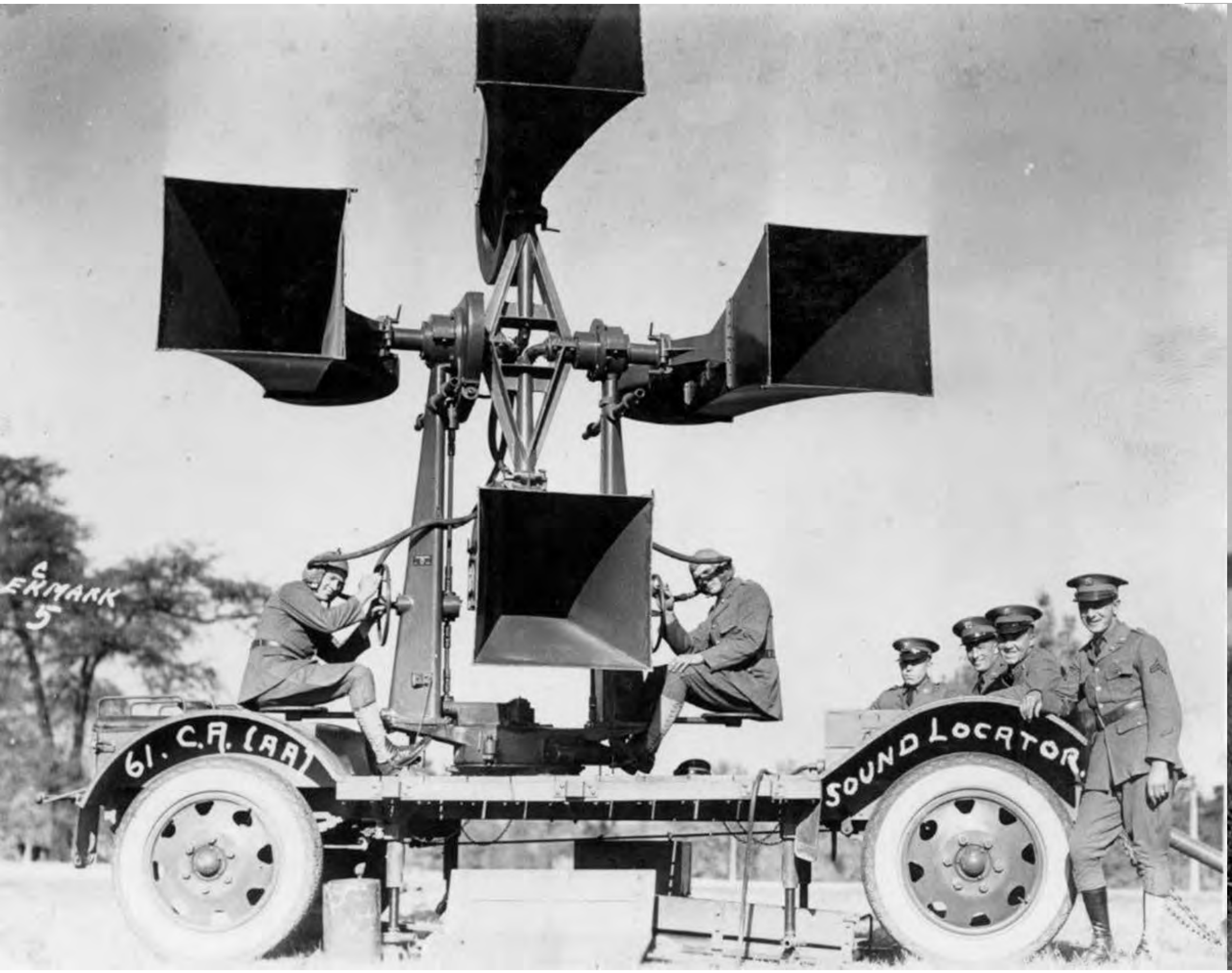
SIEMENS
Ingenuity for life




**Sound source localization**

- Why do we need it?
- **How is it done?**
  - **Beamforming**
  - Holography
- Hungry for more?
  - Parallel data acquisition
  - Interior SSL

# Beamforming
## A new method?

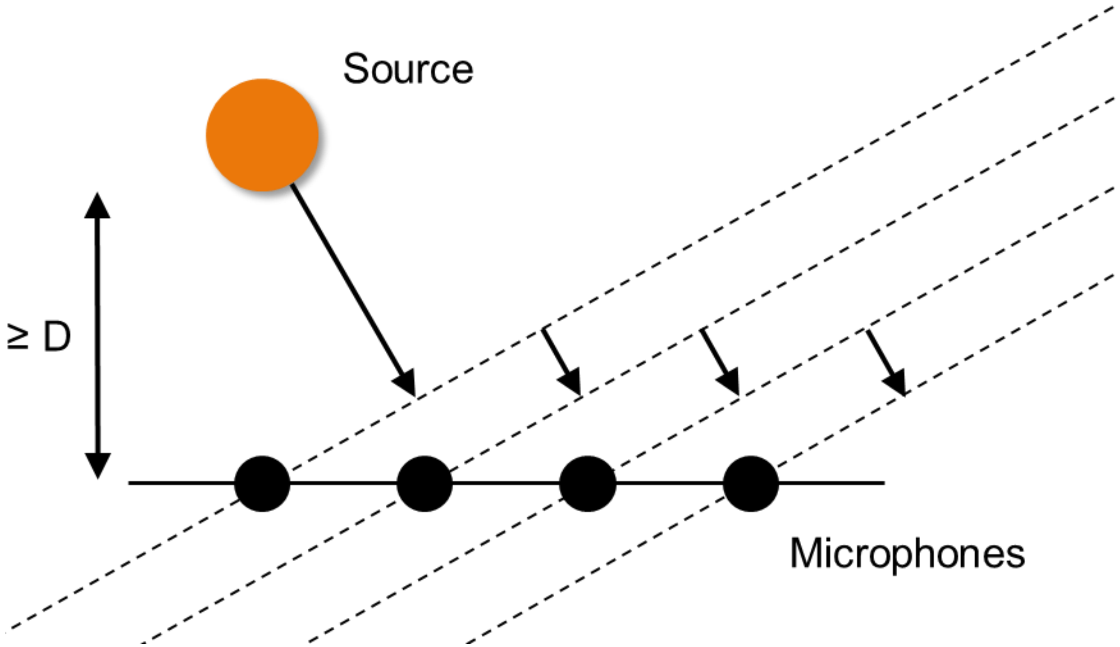



# Beamforming
## How does it work?

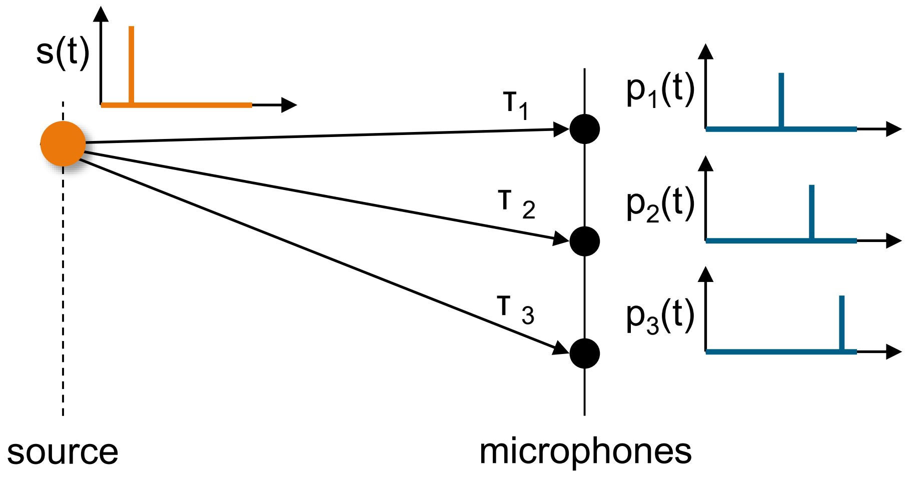
SIEMENS
Ingenuity for life

- Assume source emits **planar** pressure waves
- Assumption requires **far-field** measurement conditions
  → Distance to source ≥ array diameter D
- Microphone array consists of many microphones which record the sound pressure signal simultaneously
- Spatial distribution of sources causes a small time delay between the measured signals

**Beamforming core principle:**
**Sound source origin can be extracted from time delay (or phase delay) information between microphones**



# Beamforming
## Time-domain example

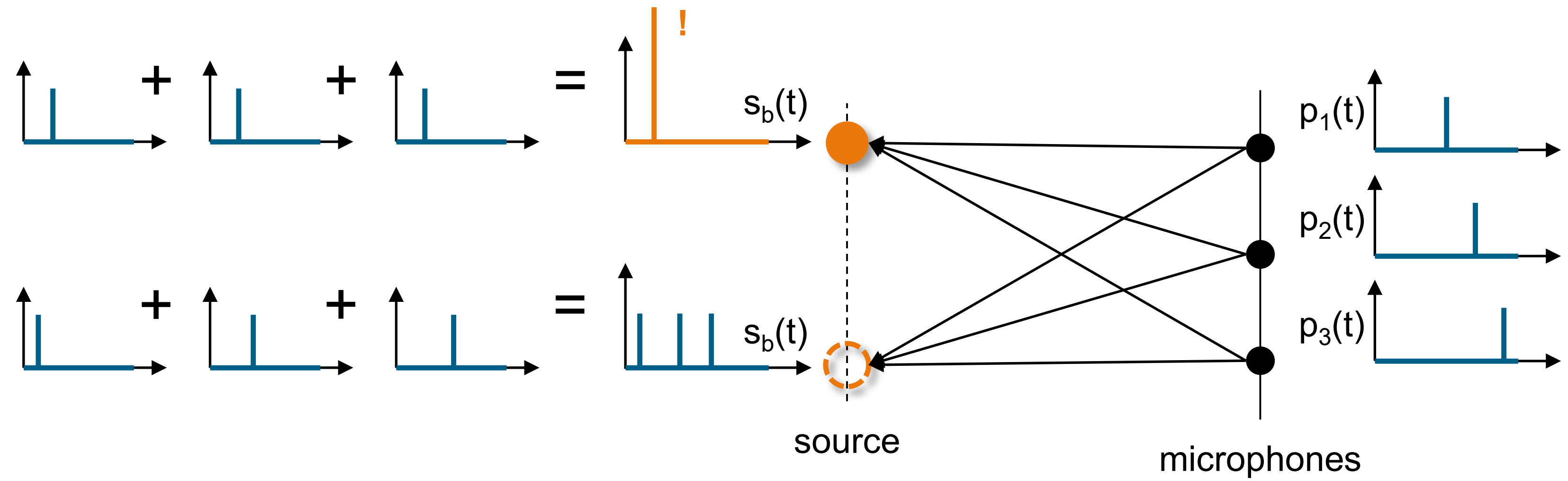



**Propagation of source signal:**

$$p_i(t) = s(t + \tau_i)$$

**Back-propagation:**

$$s_b(t) = \sum_i p_i(t - \tau_i)$$




**In practice:**

**Generalized 'filter-and-sum' method implemented in frequency domain**

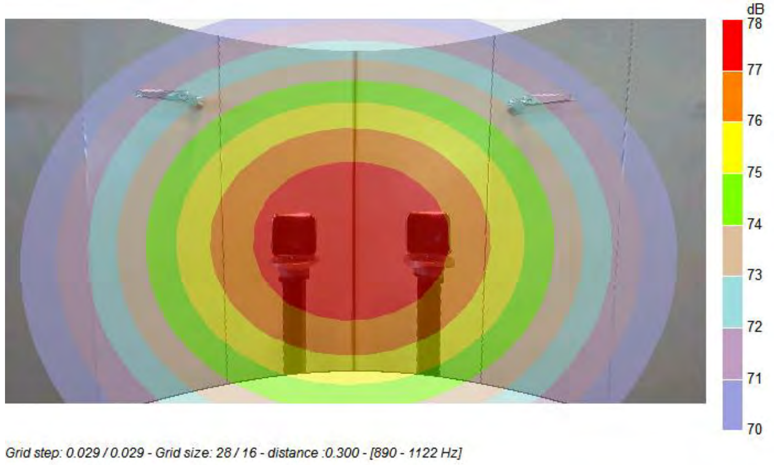
$$s(f) = \sum p_i(f) \cdot w(f) \cdot e^{-2\pi\tau j}$$

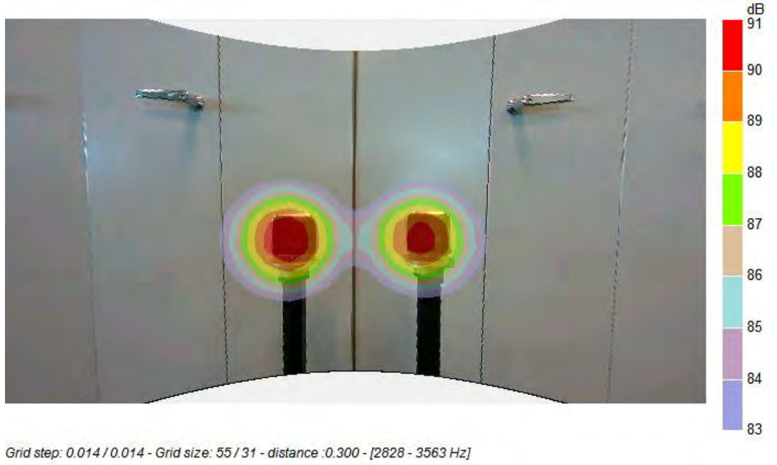
- **Source localization per frequency line possible**
- **Weighting function w(f) approximates physical source pressure level**

# Beamforming
## Quality indicators of a Sound Source Localization tool

**Spatial resolution:**
**"Where are my sources?"**

**Mainly ~ array <u>size</u>**




**Dynamic range:**
**"Am I getting the full picture?"**

**Mainly ~ array <u>design</u>**


# Demo

# Beamforming
## Array diameter comparison

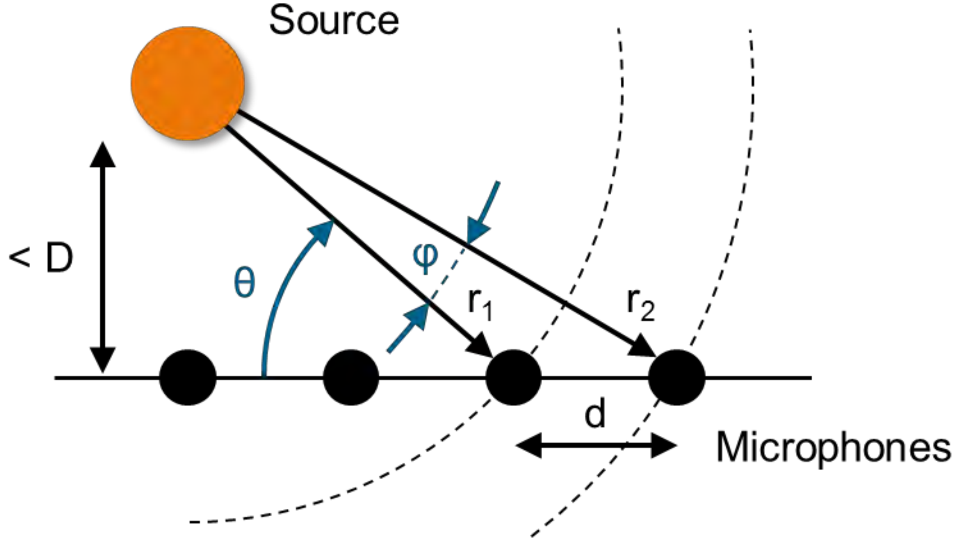
| | 840 Hz @ 75 cm | 1800 Hz @ 75 cm |
|---|---|---|
|  |   |   |
|  |   |   |

# Focalization
## A variant to Beamforming

- Planar pressure wave assumption not valid in **near-field**
- When distance to source < array diameter D, pressure waves are better approximated as **spherical** waves
- Time delay between microphones can be expressed as:

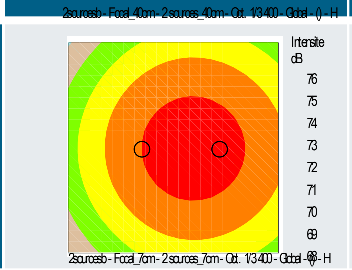
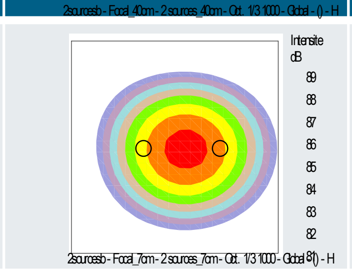
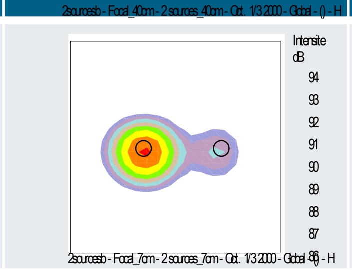
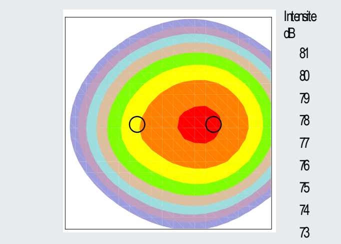
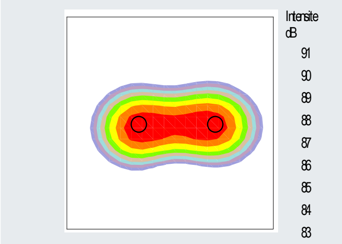
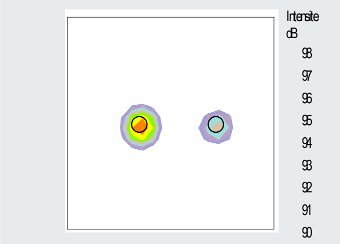
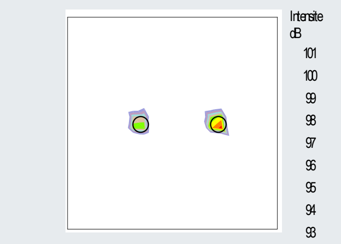
$$\tau = \frac{r_2 - r_1}{c} = \frac{d \cdot \cos(\theta) \cdot \left(\cos\left(\frac{\varphi}{2}\right) + \sin\left(\frac{\varphi}{2}\right) \cdot \tan\left(90 - \frac{\varphi}{2}\right)\right)}{c}$$

**Practical benefit:**
**Spatial resolution improves by factor ~2**



# Beamforming vs. Focalization

## Synergy

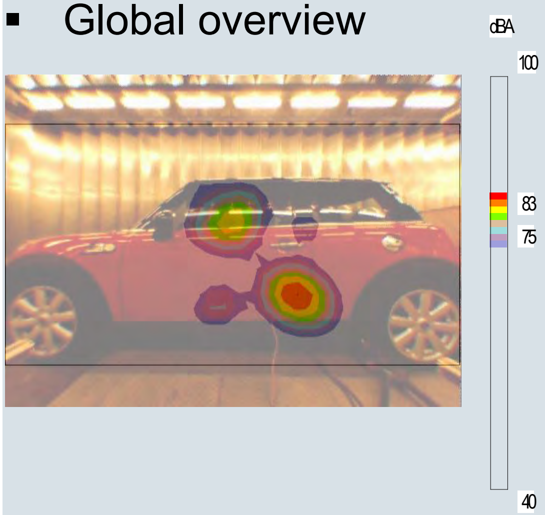
| Two monopoles with 20 cm separation | λ = 86 cm<br>**400 Hz** | λ = 34 cm<br>**1000 Hz** | λ = 17 cm<br>**2000 Hz** | λ = 8,5 cm<br>**4000 Hz** |
|---|---|---|---|---|
| **Beamforming (@ 40 cm)** |  |  |  |  |
| **Focalization (@ 7 cm)** |  |  |  |  |

# Beamforming vs. Focalization
## Synergy

**Where does wind noise leak into this vehicle?**

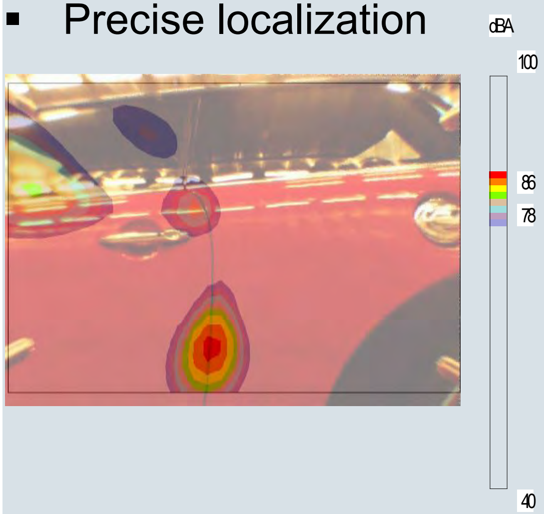

### 1. Beamforming

- Far-field technique
- Low resolution
- Global overview



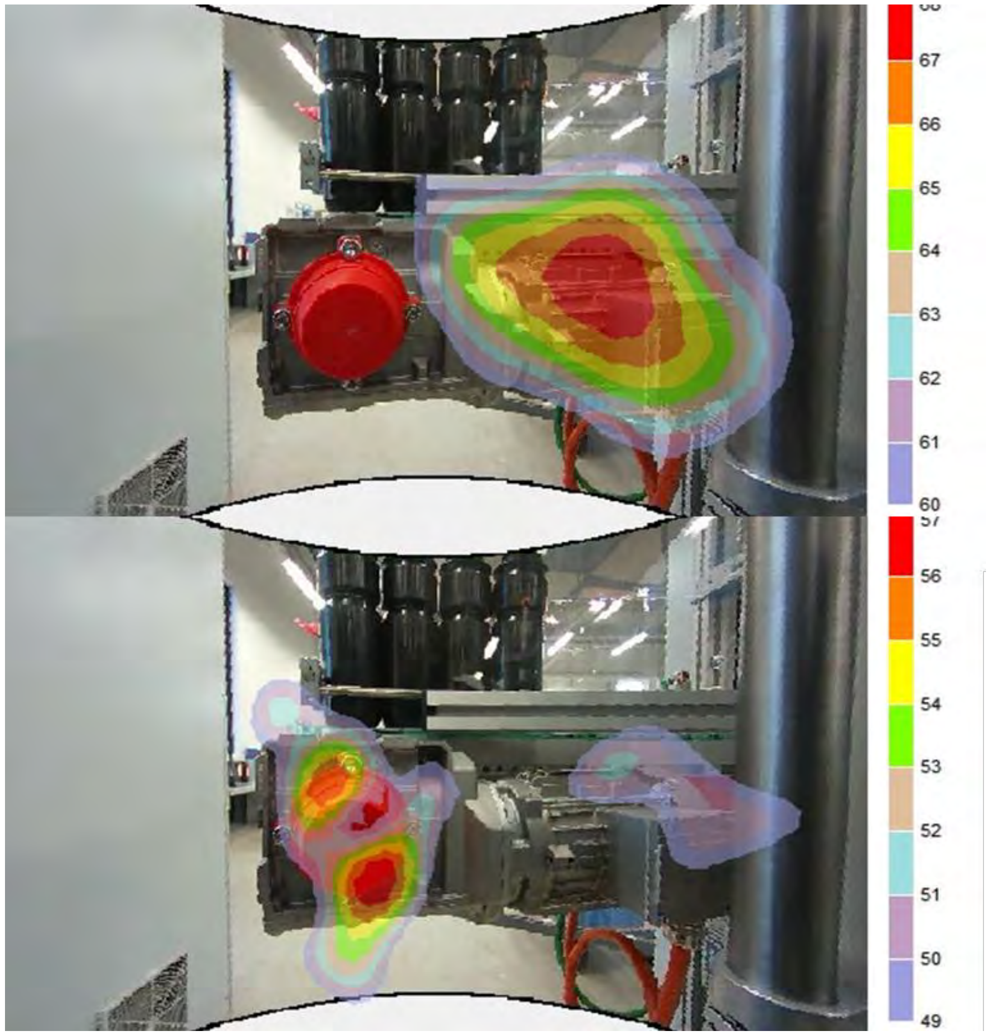

### 2. Focalization

- Near-field technique
- High resolution
- Precise localization



# Agenda

SIEMENS
Ingenuity for life



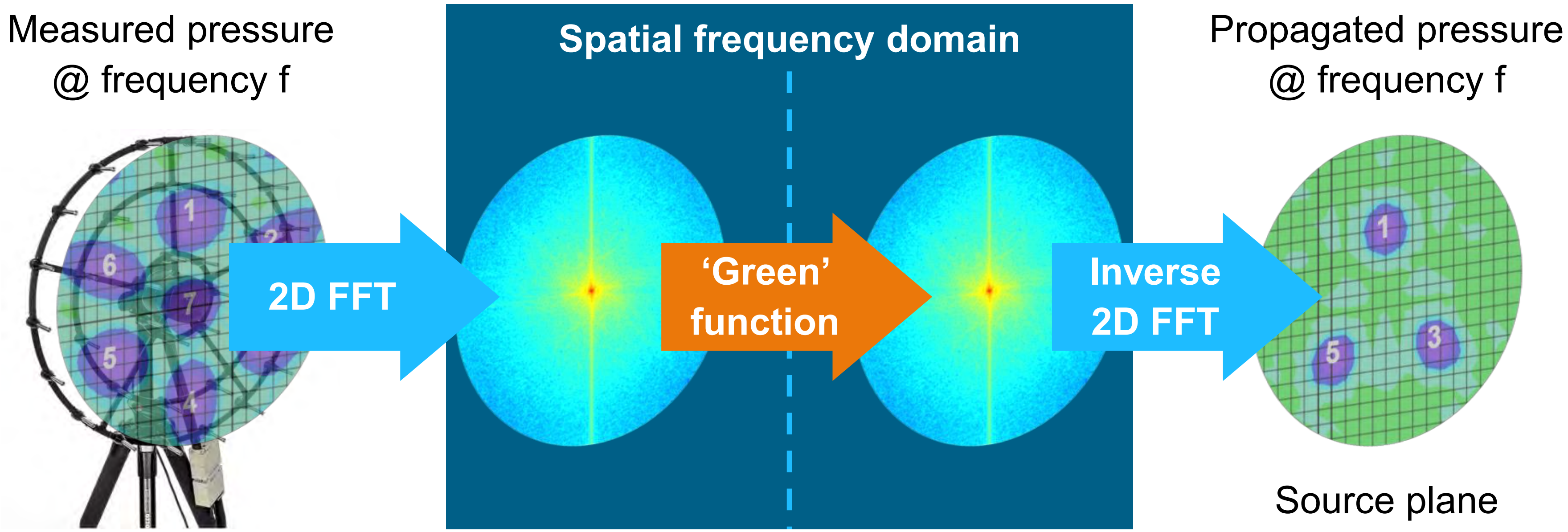

**Sound source localization**

- Why do we need it?
- **How is it done?**
  - Beamforming
  - **Holography**
- Hungry for more?
  - Parallel data acquisition
  - Interior SSL

# Near-field Acoustic Holography
## How does it work?

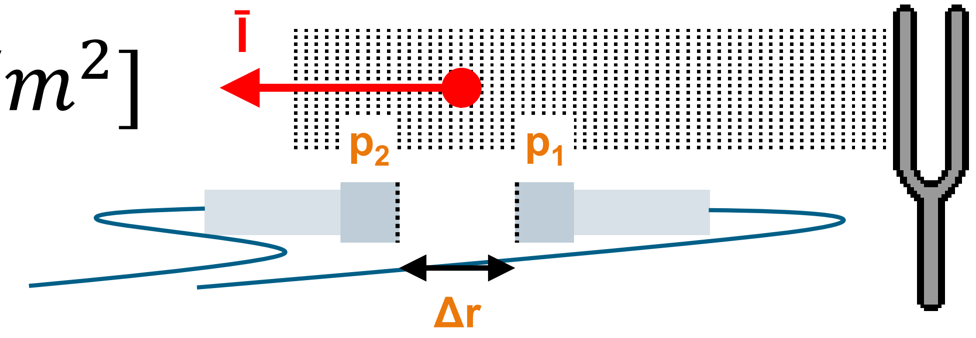
**Localization principle**

- Estimate real pressure field at source based on measured pressure field
- Calculated in spatial frequency domain for parallel plane propagation (‘Green’ function)
- <u>Quantitative</u> estimation of pressures on source plane with identical dimensions



# Near-field Acoustic Holography
## Sound power estimation

$$\vec{I} = \overline{p(t) \cdot \vec{v}(t)}\ [W/m^2]$$



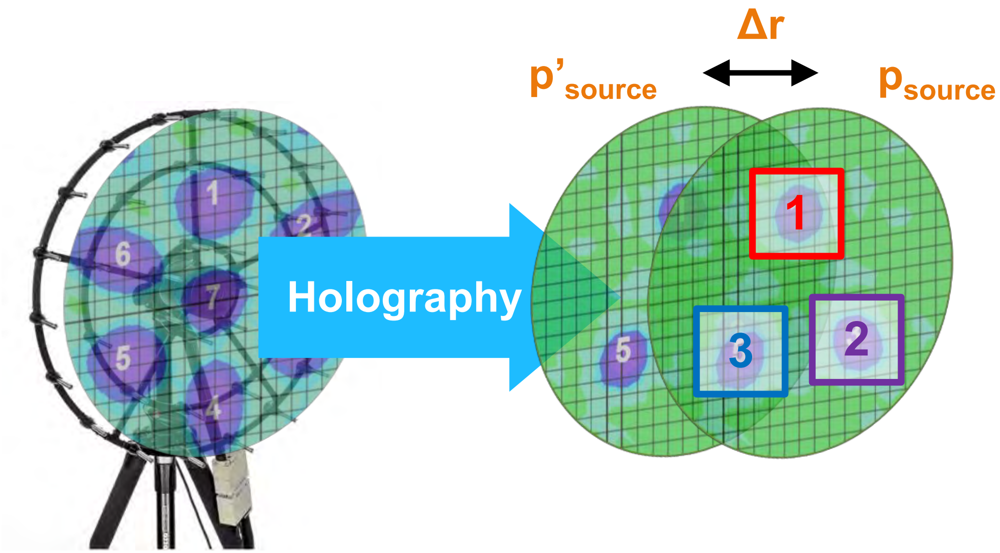

**Sound Intensity probe:**

- p(t) → average of $p_1$ and $p_2$
- v(t) → estimate from pressure gradient ($p_1 - p_2$ over Δr)

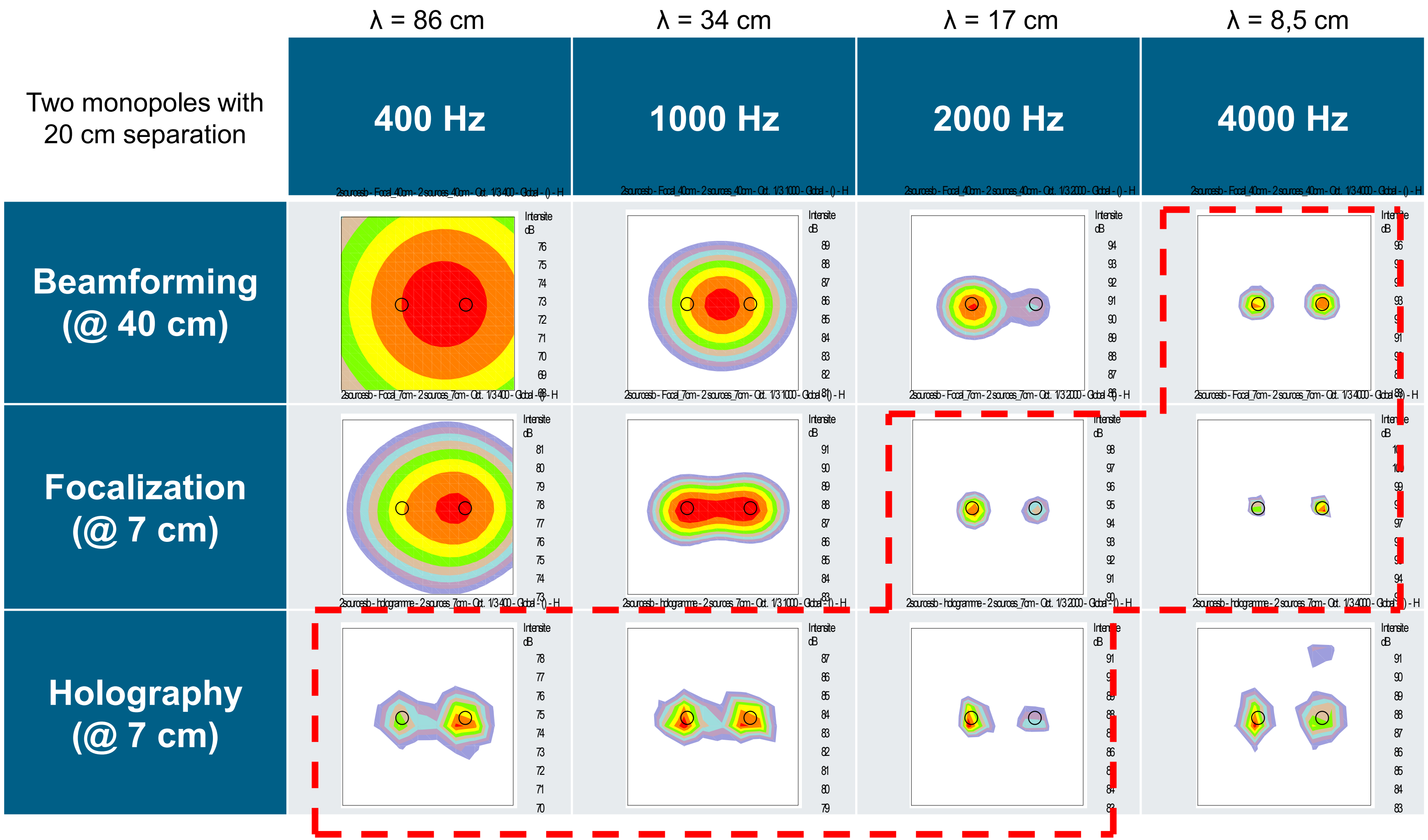
**Acoustic camera:**

- p(t) → pressure field at source calculated using Holography
- v(t) → estimate from pressure gradient ($p'_{source} - p_{source}$ over Δr)

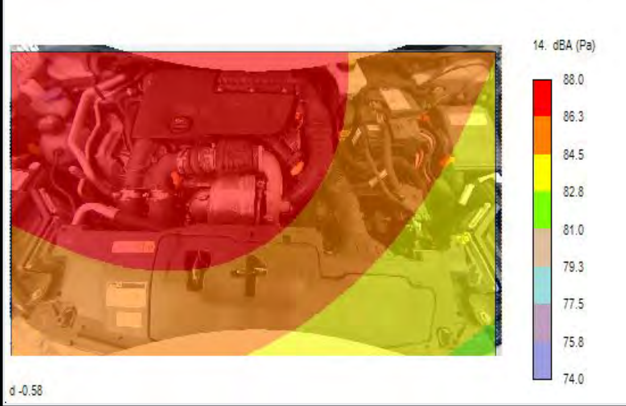
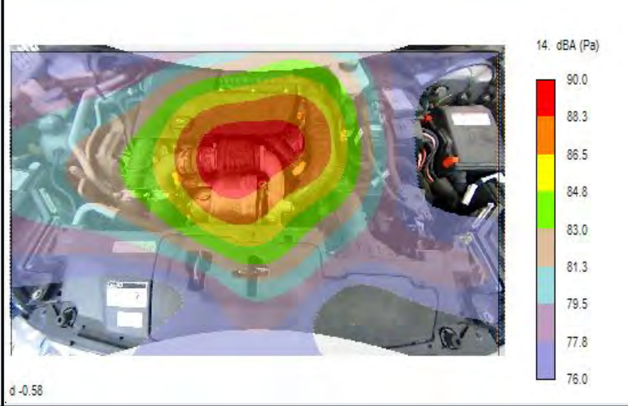
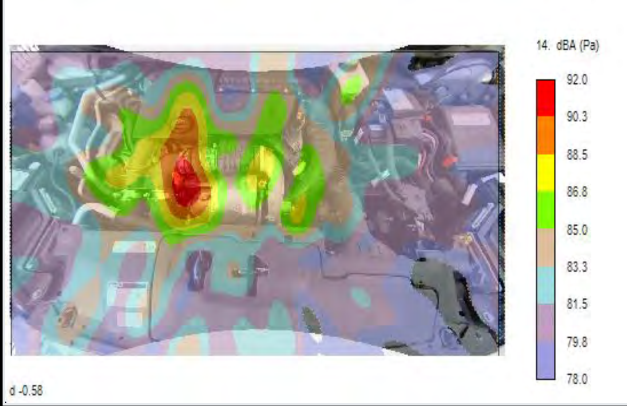
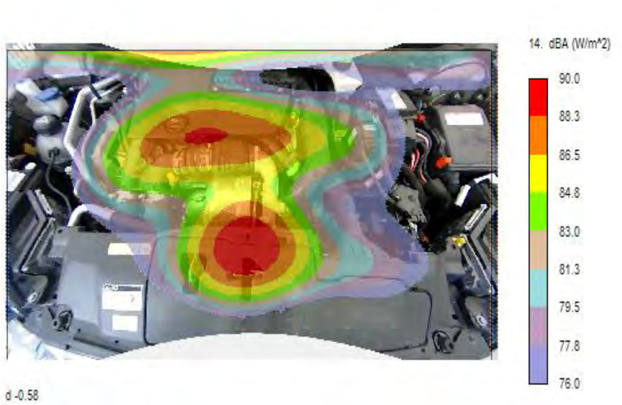
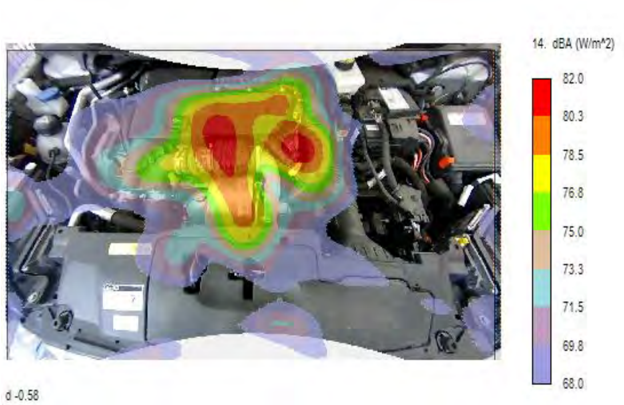
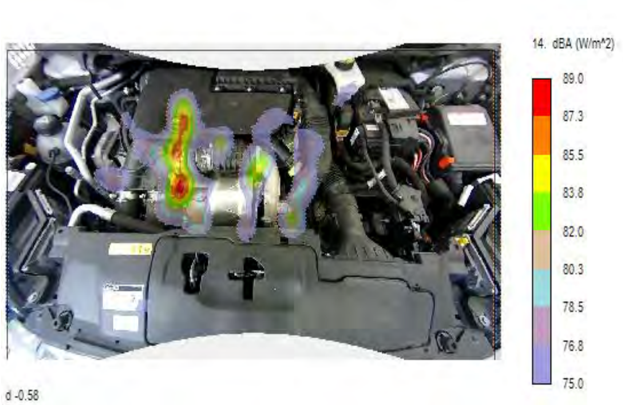
**Sound intensity & power**
**→ Objective source ranking!**



# Holography vs. Beamforming & Focalization
## Synergy

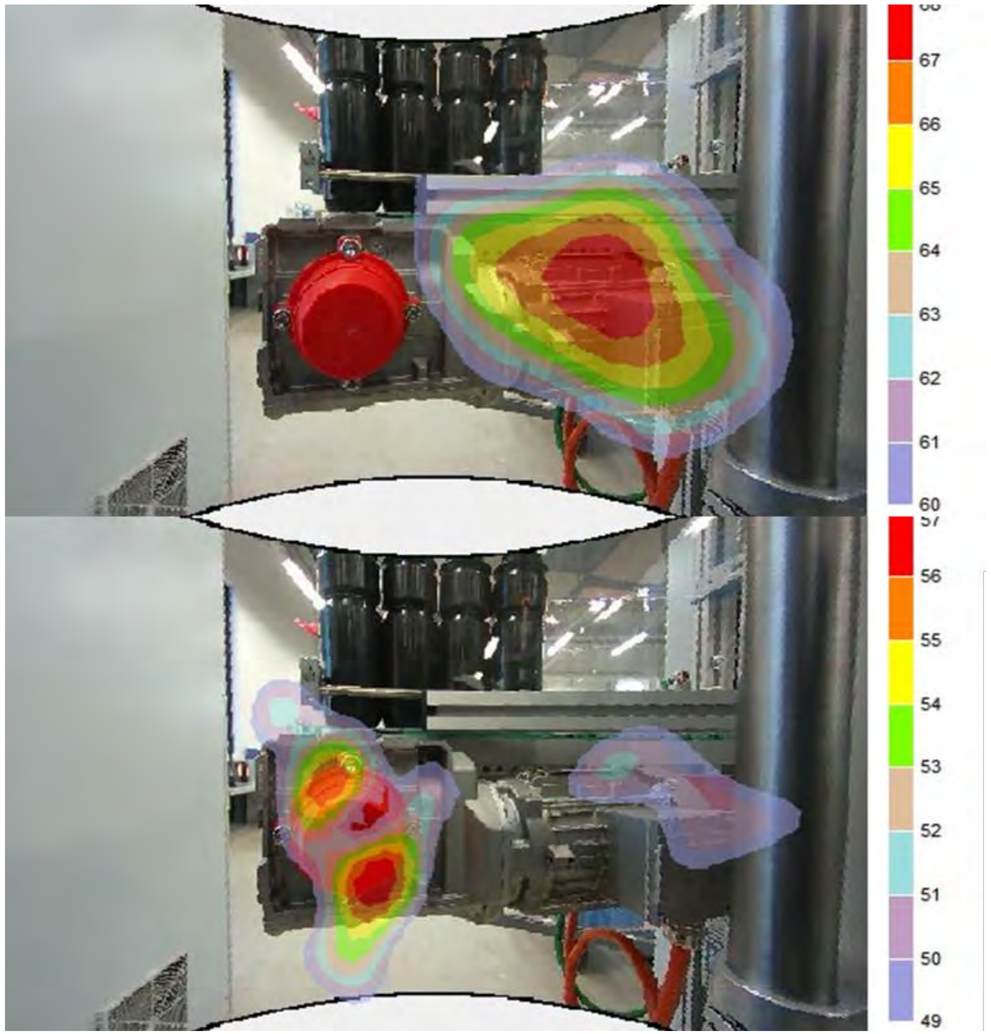


# Holography vs. Beamforming & Focalization
## Synergy

| | 400 Hz | 2000 Hz | 4000 Hz |
|---|---|---|---|
| **Beamforming** |  |  |  |
| **Holography** |  |  |  |

# Agenda

SIEMENS
Ingenuity for life



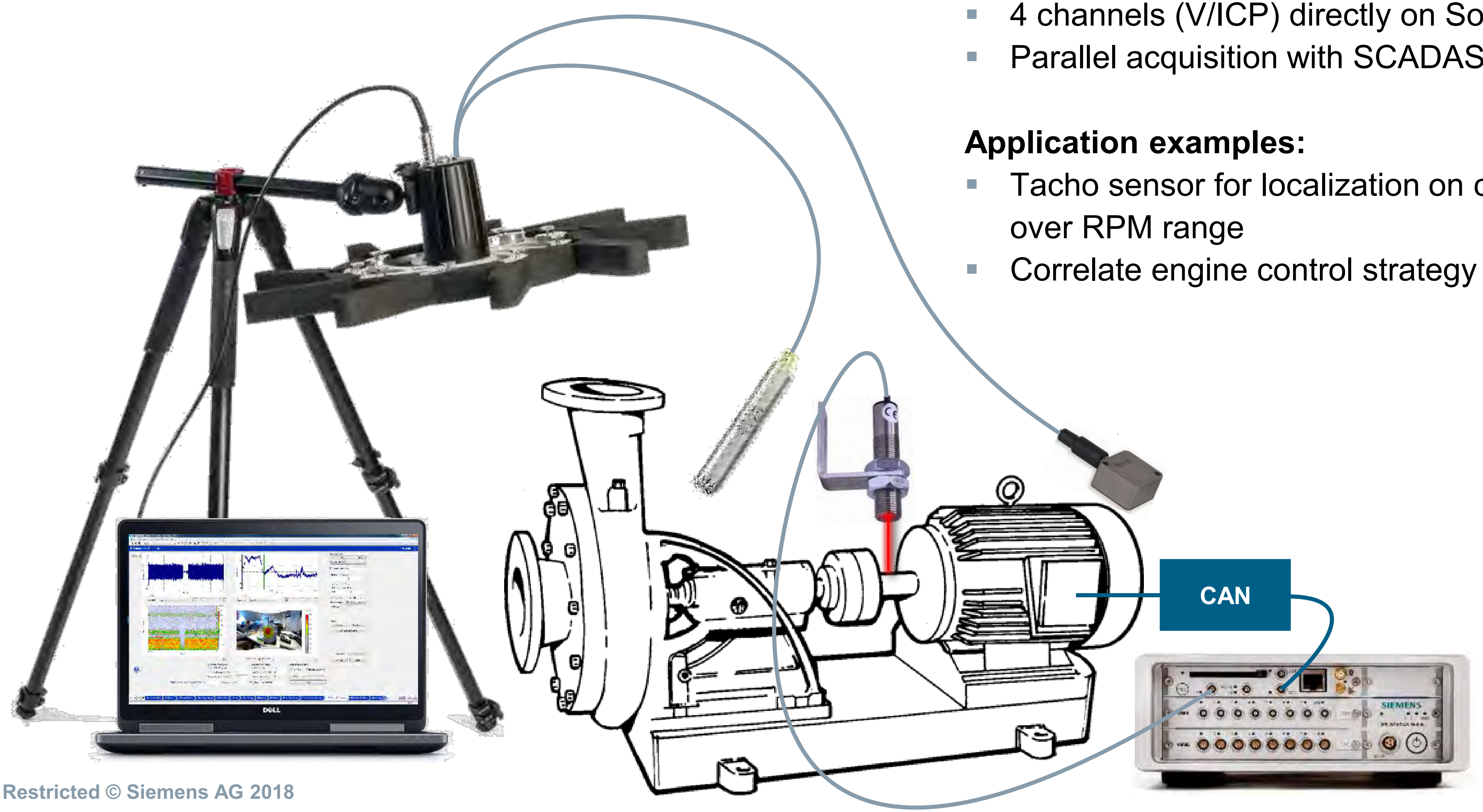

**Sound source localization**

- Why do we need it?
- How is it done?
  - Beamforming
  - Holography
- **Hungry for more?**
  - **Parallel data acquisition**
  - Interior SSL

# Sound sources don't just make noise
## Deeper understanding through parallel data acquisition

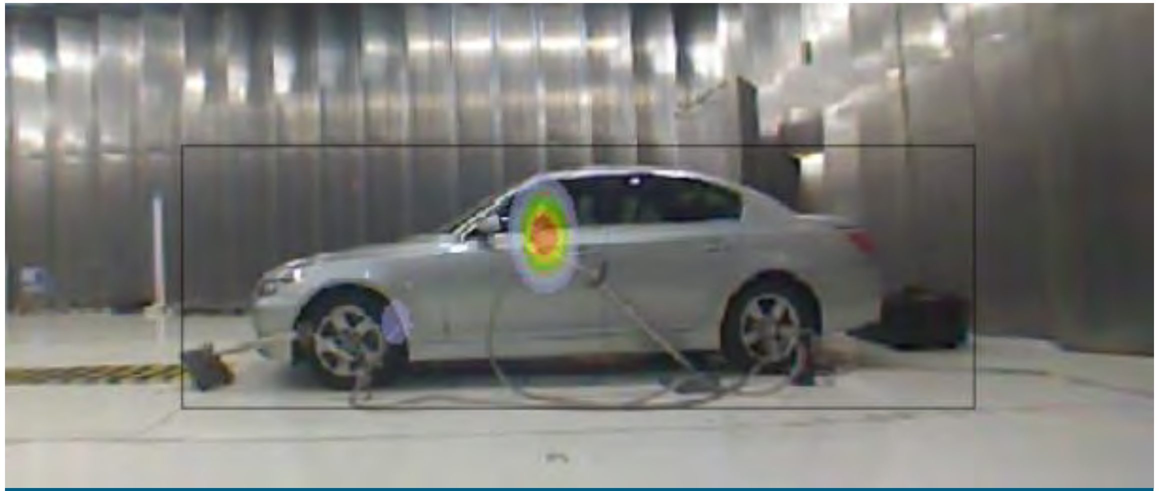
- 4 channels (V/ICP) directly on Sound Camera
- Parallel acquisition with SCADAS front-end

**Application examples:**
- Tacho sensor for localization on complete orders over RPM range
- Correlate engine control strategy to sound generation



# Sound sources don't just make noise
## Deeper understanding through parallel data acquisition

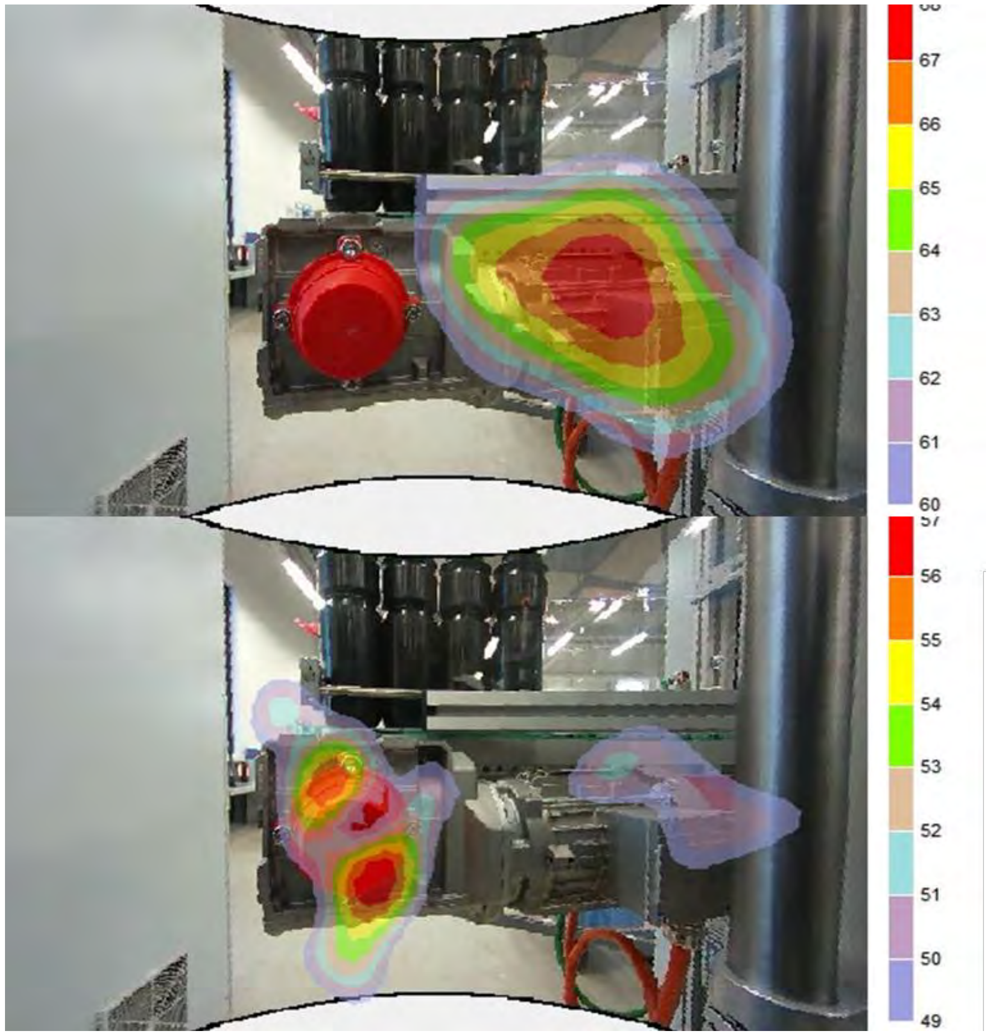
SIEMENS
Ingenuity for life



| Raw exterior acoustics | Referenced exterior acoustics |
|---|---|
| What does the pedestrian hear? | What does the driver hear? |

**Which components are dominant? Structure-borne vs. airborne? Secondary sources?**

# Agenda




**Sound source localization**

- Why do we need it?
- How is it done?
  - Beamforming
  - Holography
- **Hungry for more?**
  - Parallel data acquisition
  - **Interior SSL**

# Interior sound source localization
## Why can't we use standard microphone arrays?

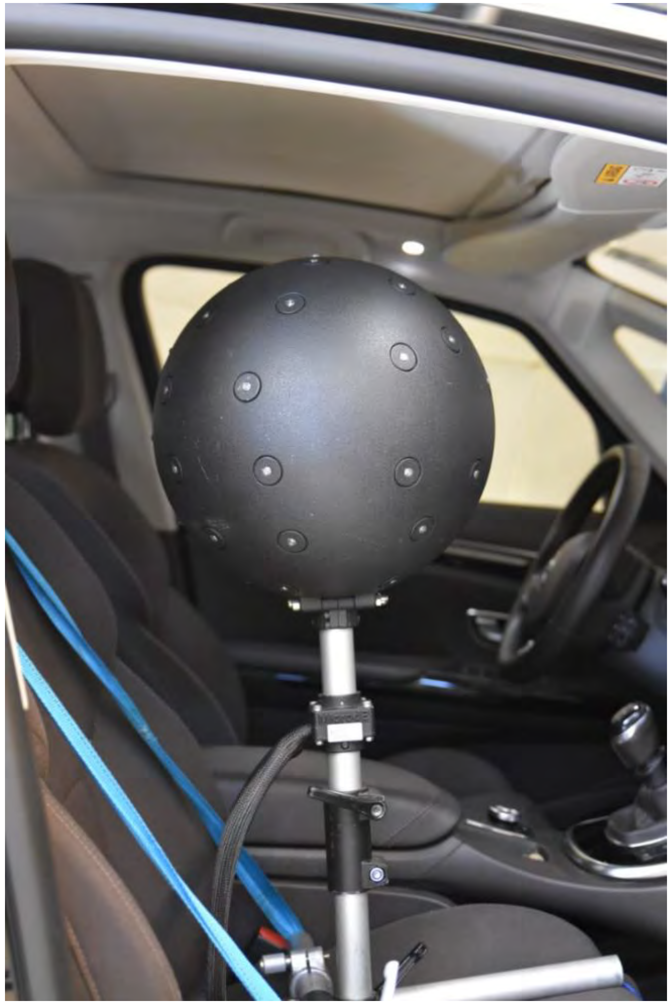
SIEMENS
Ingenuity for life

| Challenges |
| --- |
| Compact interior cavity |
| Sources from any direction, including behind the camera |
| Propagation towards complex, non-flat geometry |

| Solution |
| --- |
| Solid sphere array with optimized microphone placement |
| Geometry scanner creates accurate 3D model of interior |

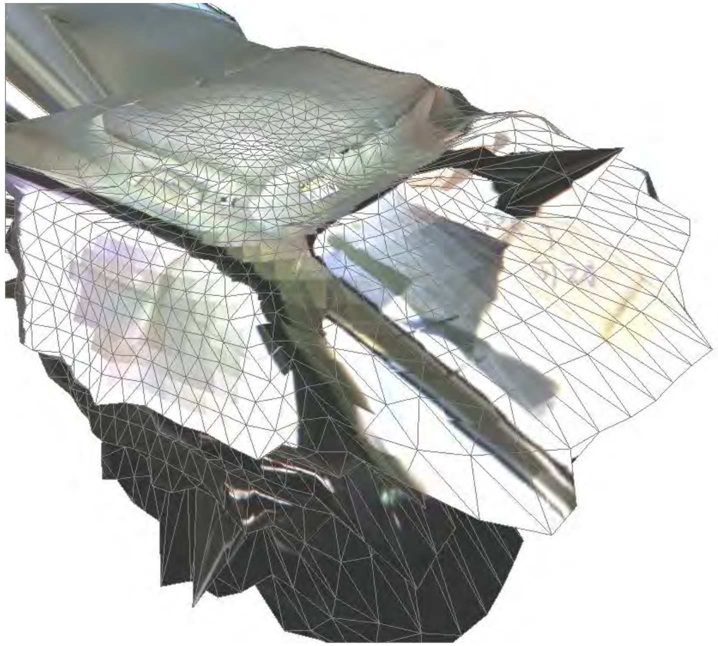
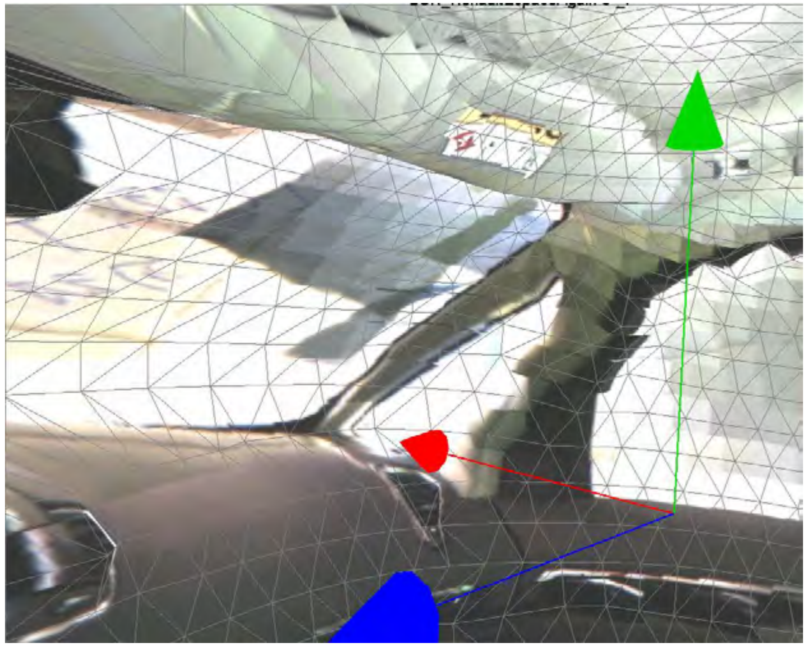
# Interior sound source localization
## Rattle noise localization example

- **Goal:** identify rattle noise source subjectively located above sun shield (yellow)
- Rattle noise audible at 1100 – 1200 RPM and 2000 – 2200 RPM, 2nd and 3rd gear
- Interior geometry used for propagation:



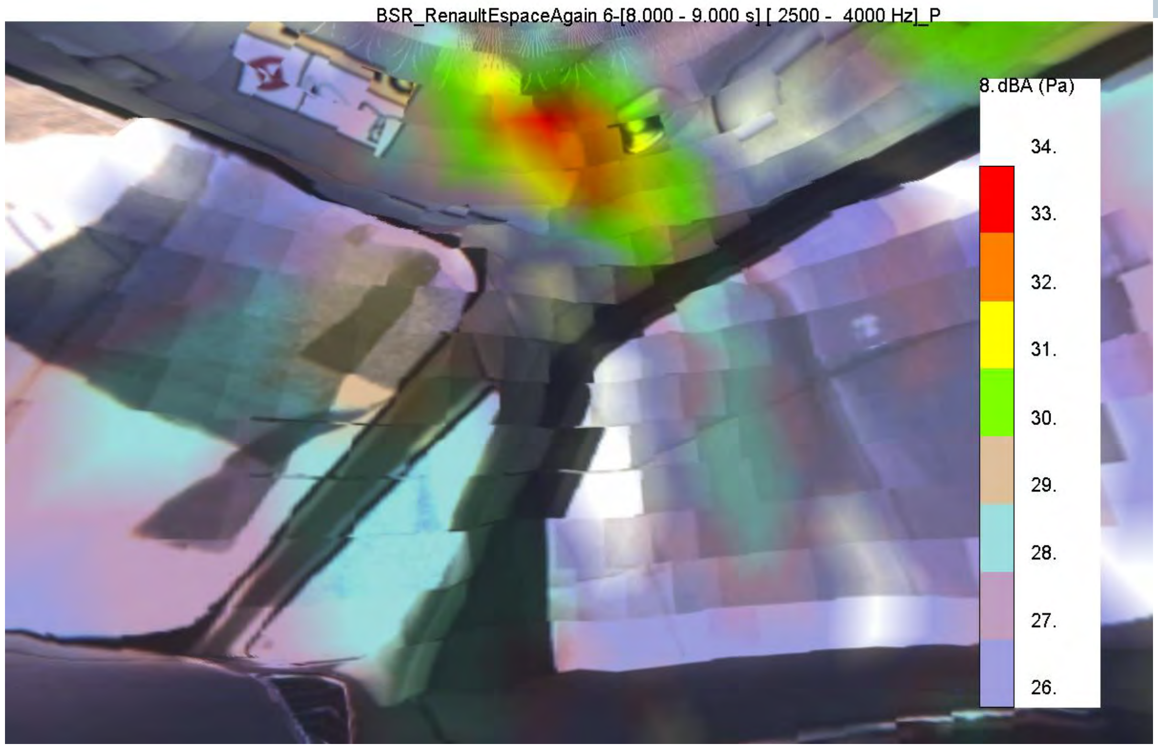
# Interior sound source localization
## Rattle noise localization example

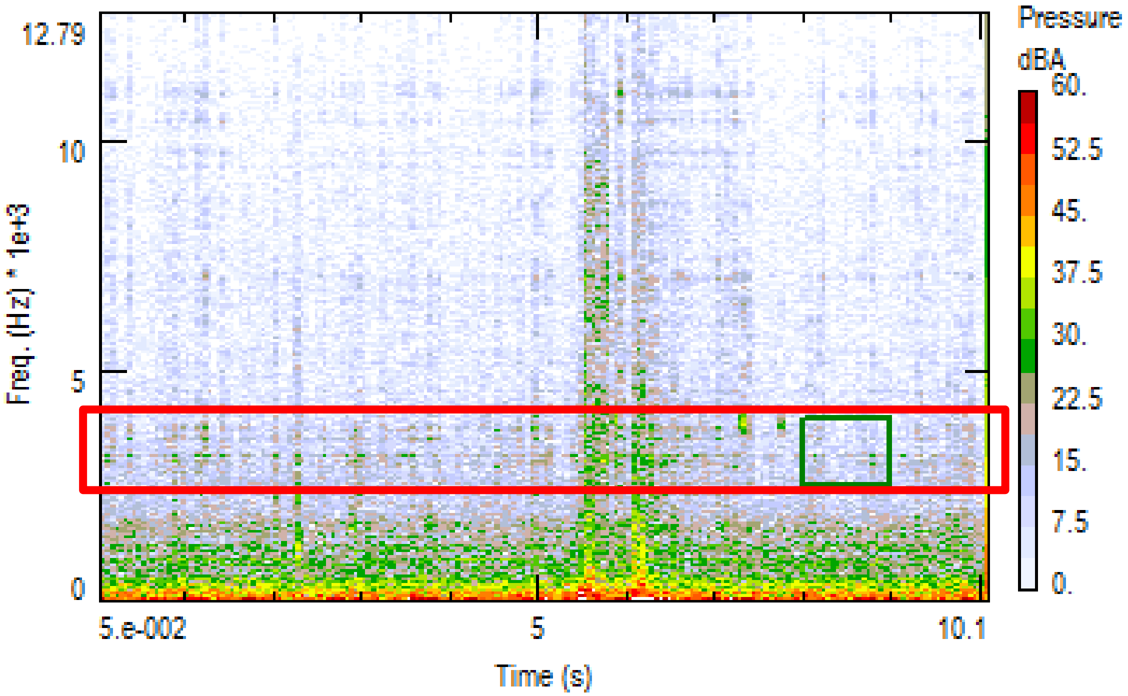
- Simcenter Geometry Scanner creates 3D mesh of vehicle interior
- 1500 grid points, ~10 cm element size


# Interior sound source localization
## Rattle noise localization example

- Rattle origin confirmed on sun shield
- Verified by fixing the top hatch, blocks rattle transfer




- Rattle phenomenon visible between 2500 – 4000 Hz
- Selection of time-frequency range allows localization on transient noise sources

# Introduction to sound source localization

## Overview of current techniques

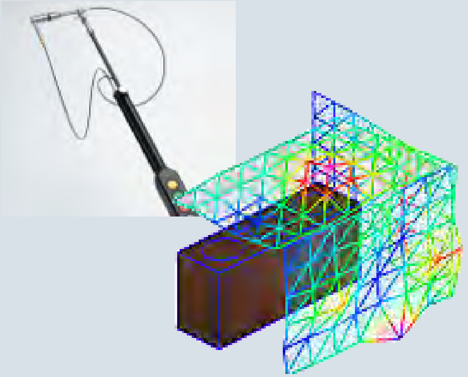
SIEMENS
*Ingenuity for life*

**Simple** → **Advanced**

### Stethoscope

- ❑ Limited hardware
- ❑ No reportable data
- ❑ Sound pressure only
- ❑ Stationary sources only

### Sound Intensity



- ❑ ISO sound power & partial sound power
- ❑ Time-consuming
- ❑ Limited frequency range
- ❑ Stationary sources only

### SoundBrush

- ❑ Fast results
- ❑ Limited hardware
- ❑ Directivity & sound power estimation
- ❑ Stationary sources only

### Sound Camera

- ❑ Real-time results
- ❑ Stationary and transient sources
- ❑ Requires more advanced knowledge to operate

# Agenda:

Acoustic simulation: application view

Acoustic simulation: different methods/technology

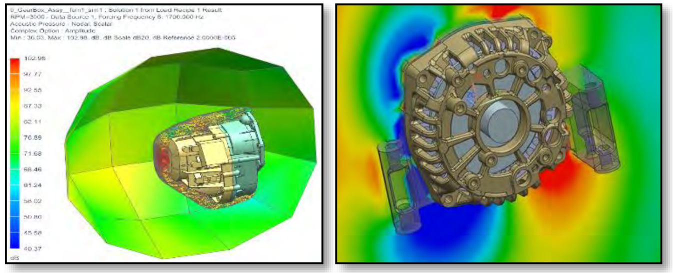
General workflow

Some more examples…

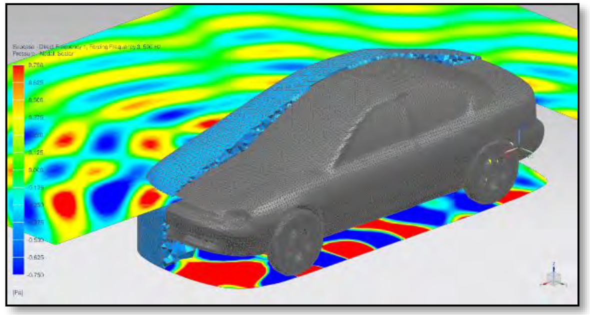
# Simcenter 3D Acoustics
# Application View

SIEMENS
Ingenuity for life

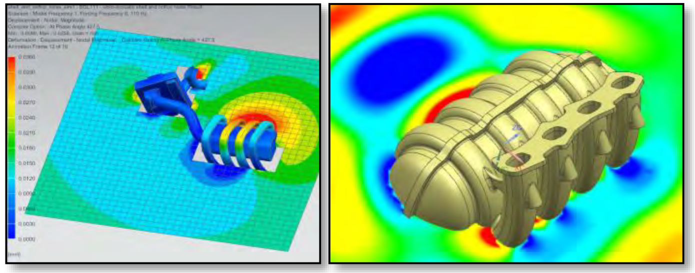
## Machinery noise radiation
engine, E-motor, compressor, pump..



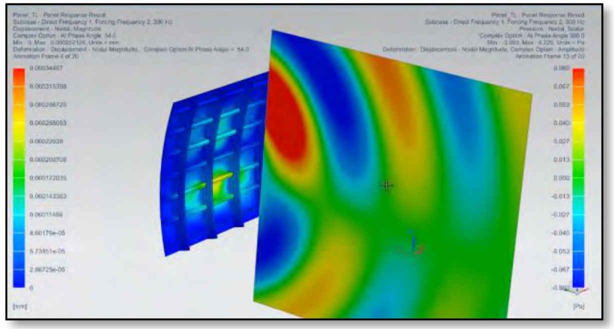
## Full Vehicle Radiation/ Scattering
Pass-by Noise, pedestrian safety, submarine scattering



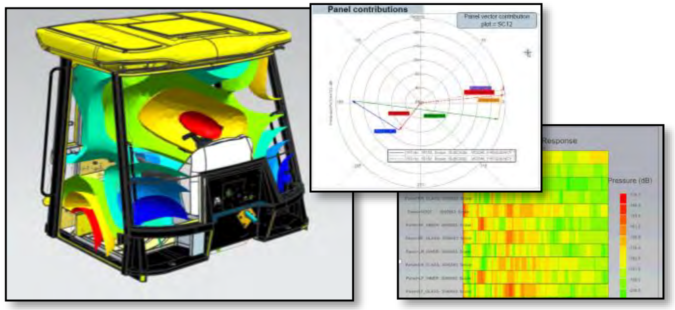
## Duct (Vibro)Acoustics
Intake/ exhaust/ muffler Transmission Loss, orifice noise and shell noise



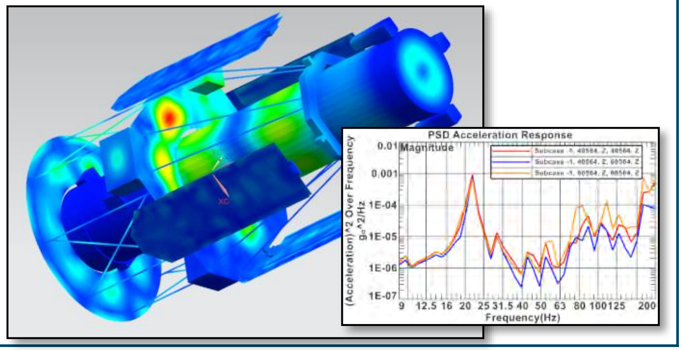
## Enclosure / Panel Design
Panel Transmission Loss, Insertion Loss



## Cabin Acoustics
Cars, tractors, excavators

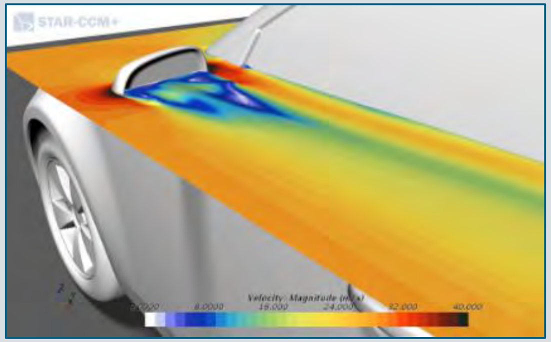
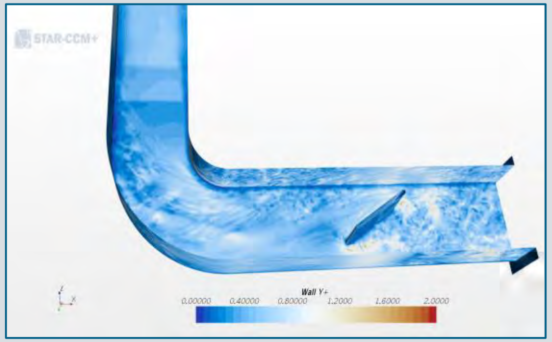
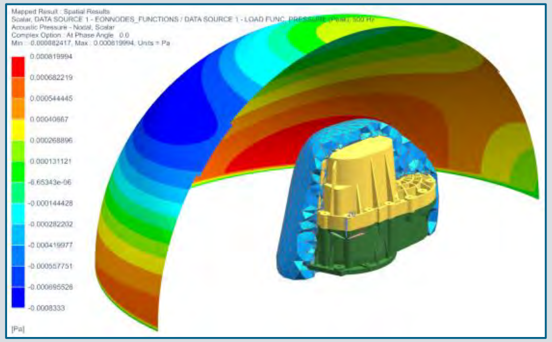
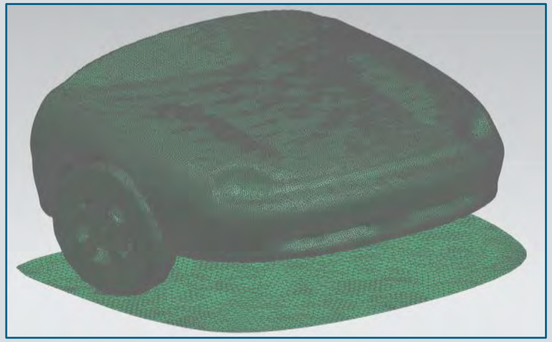
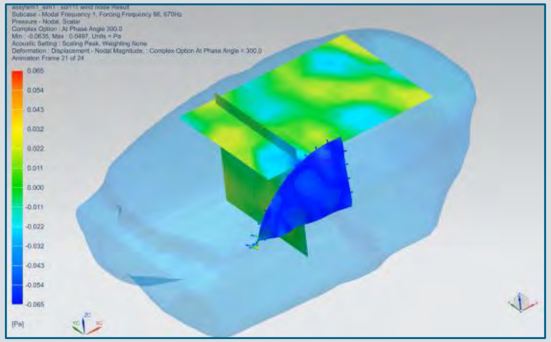
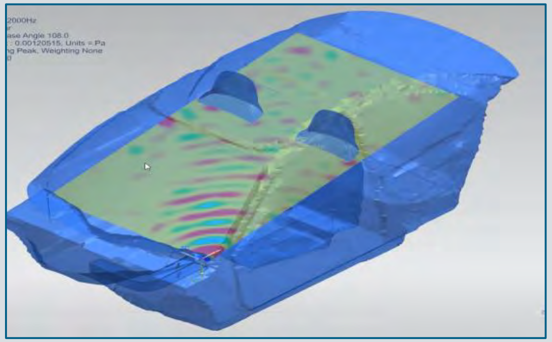
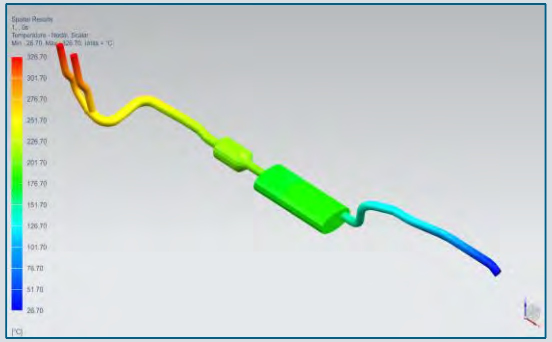
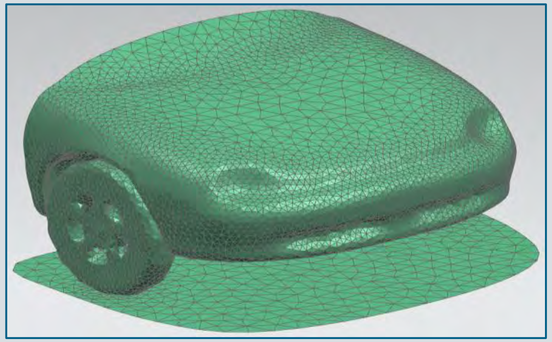



## Random Vibro-Acoustics
Spacecraft Mission De-risking



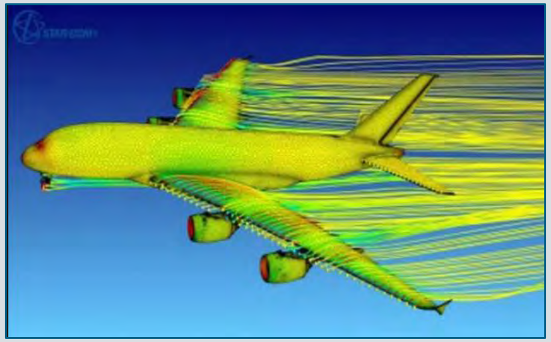
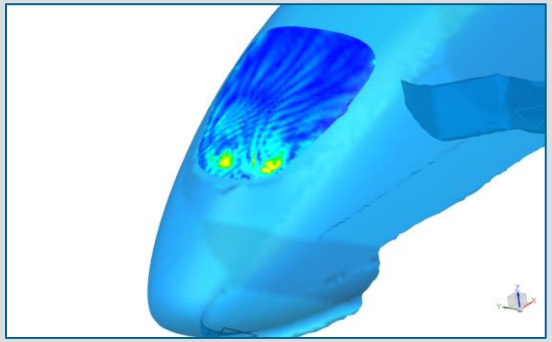
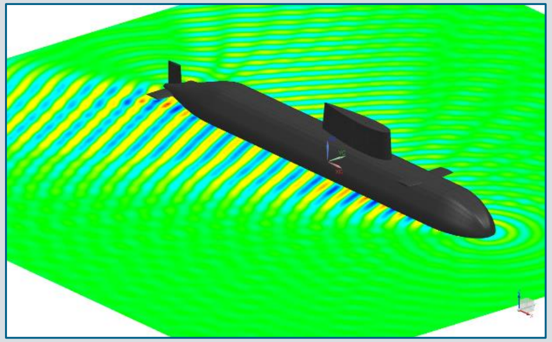
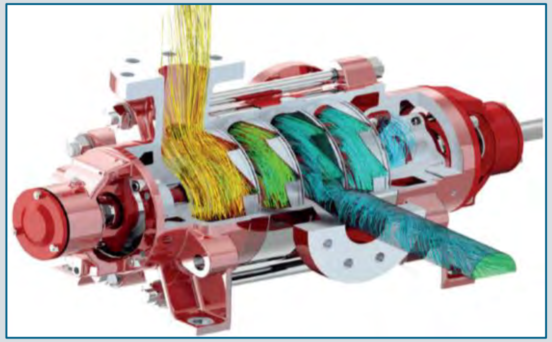
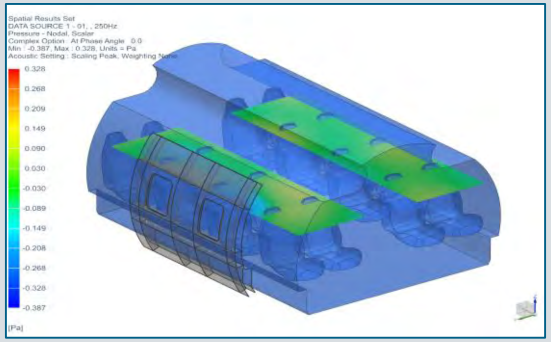
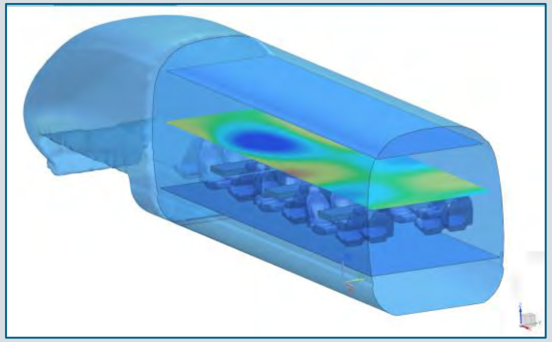
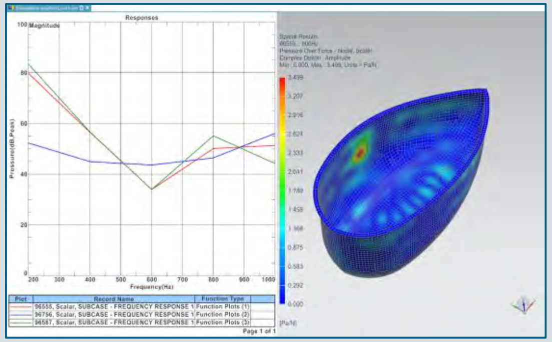
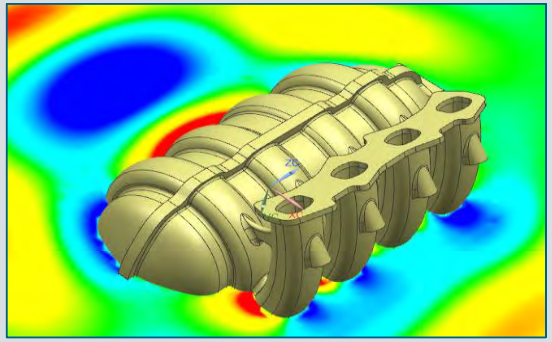
# Simcenter 3D Acoustics
## Key Applications

SIEMENS
Ingenuity for life

| **Aero-Vibro-Acoustics**<br>Wind Noise | **Aero-Acoustics**<br>HVAC Noise / Fan Noise | **Vibro-Acoustics**<br>Powertrain Acoustics | **All-Round**<br>Meshing Improvements |
|---|---|---|---|
|  |  |  |  |
|  |  |  |  |

# Some Aero-Vibro-Acoustic Applications

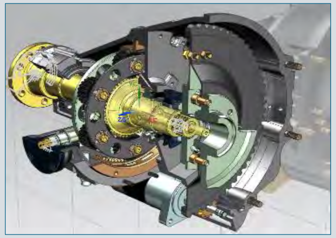
SIEMENS
Ingenuity for life

| **Aircraft** Flow Induced Noise | **Train** Flow Induced Noise | **Sonar Self Noise** | **Pump Noise** |
|---|---|---|---|
|  |  |  |  |
|  |  |  |  |

# Simcenter 3D Acoustics
## Engineering View: Source – System Transfer – Receiver

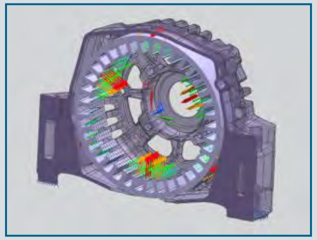
## Source

### Mechanical

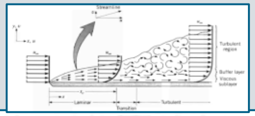


### CFD

### Electromagnetic



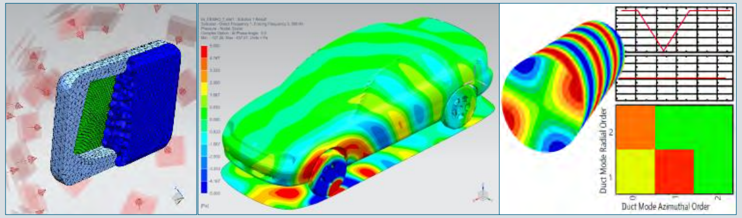
### Analytical TBL



$$S_{pp}(x_1,x_2,\omega)=\overline{S_{pp}}(\omega)\Gamma(x_1,x_2,\omega)$$

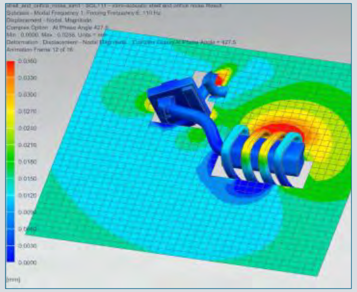
$$\Gamma(x_1,x_2,\omega)=e^{-\alpha\frac{\omega|\xi|}{U_c}}.e^{-\beta\frac{\omega|\eta|}{U_c}}.e^{-i\frac{\omega\xi}{U_c}}$$

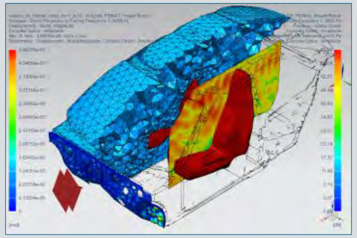
### Acoustic
### Diffuse Field / Blocked Pressure / Duct Modes



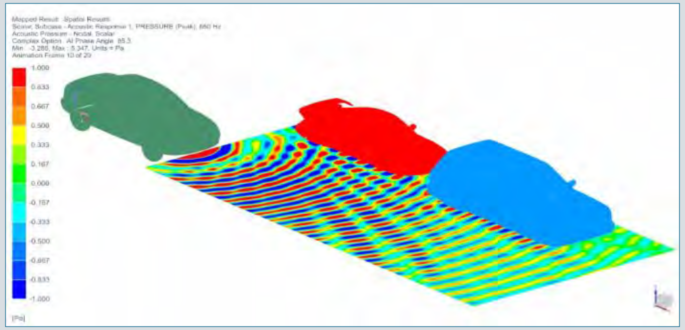

## System Transfer

### FEM Vibro-Acoustics
### Simcenter Nastran
### FEM AML / FEMAO / ATV / VATV



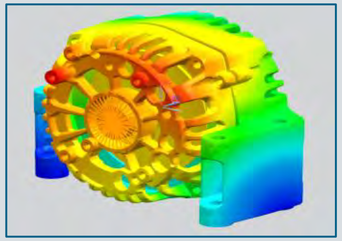


### BEM Vibro-Acoustics
### Simcenter 3D Acoustics BEM
### FMBEM / H-Matrix BEM

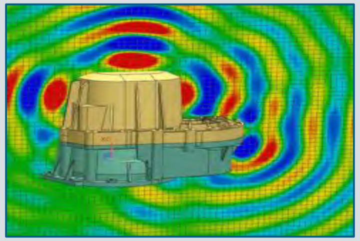


## Receiver

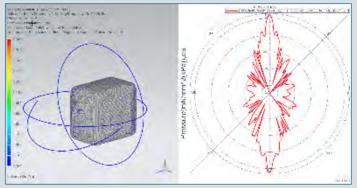
### Vibration/Force/Stress



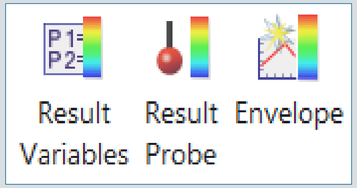
### Acoustics



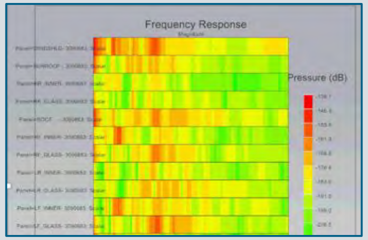
### Directivity



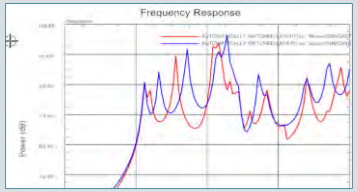
### Sensors




### Contributions



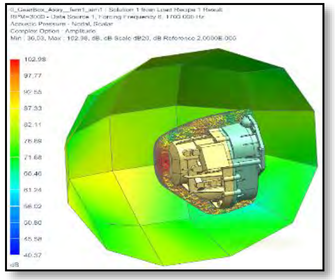

### Functions

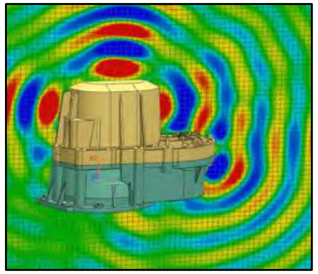


# Simcenter 3D Acoustics
# Technology View

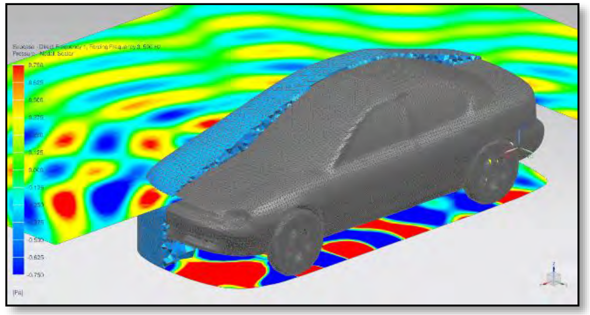
SIEMENS
Ingenuity for life

## FEM AML

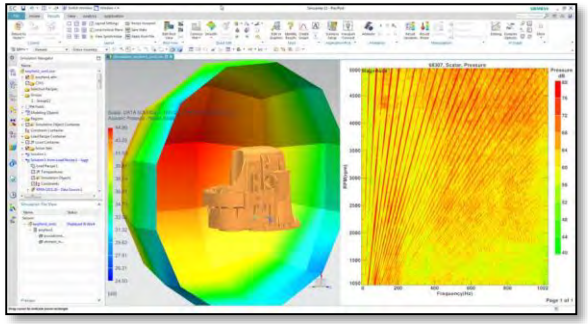




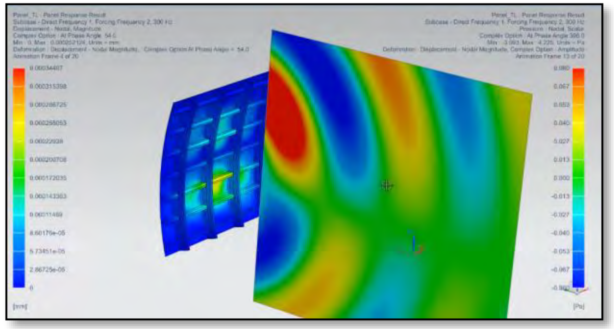
## FEMAO



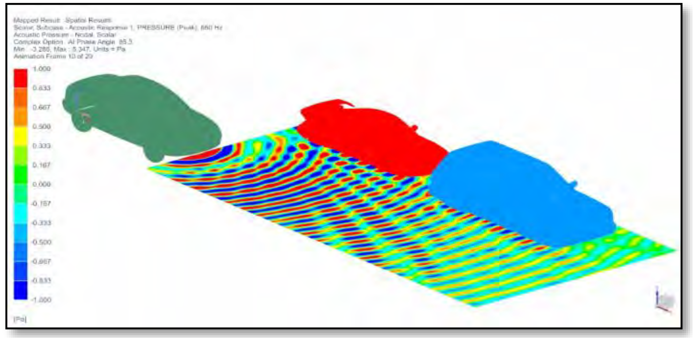
## ATV



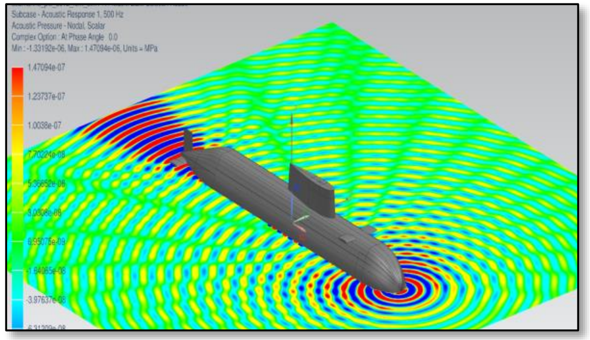
## Random Vibro-Acoustics



## Fast Multipole BEM

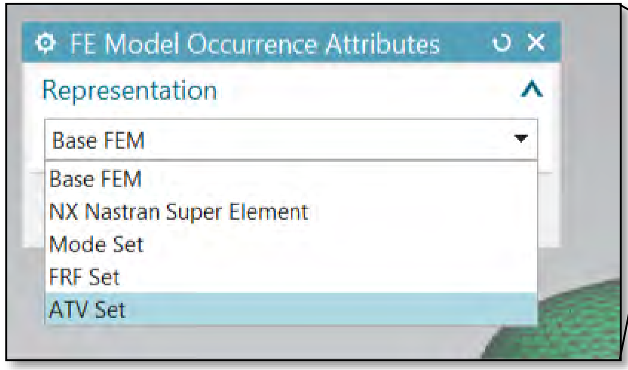


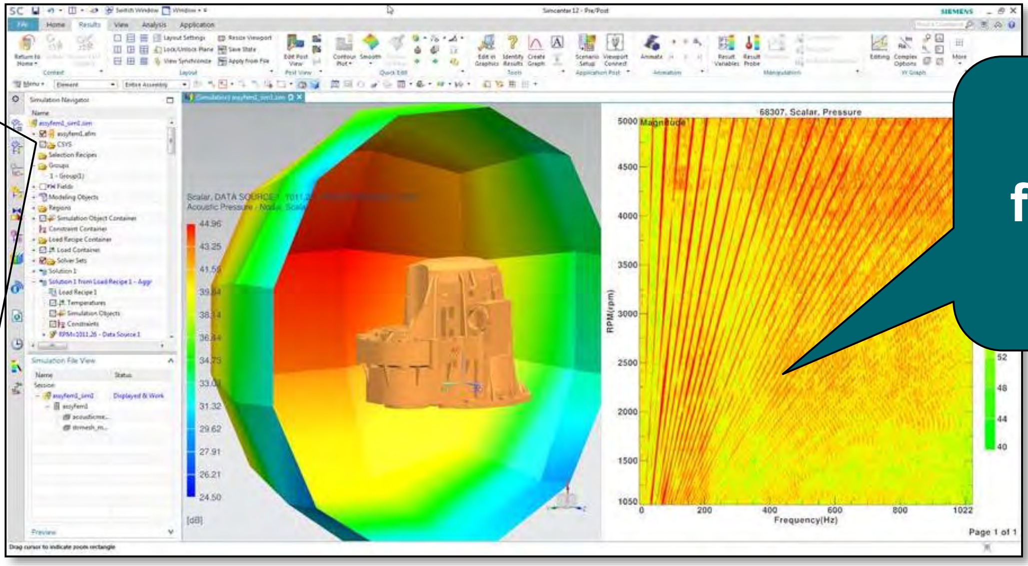
## H-Matrix BEM



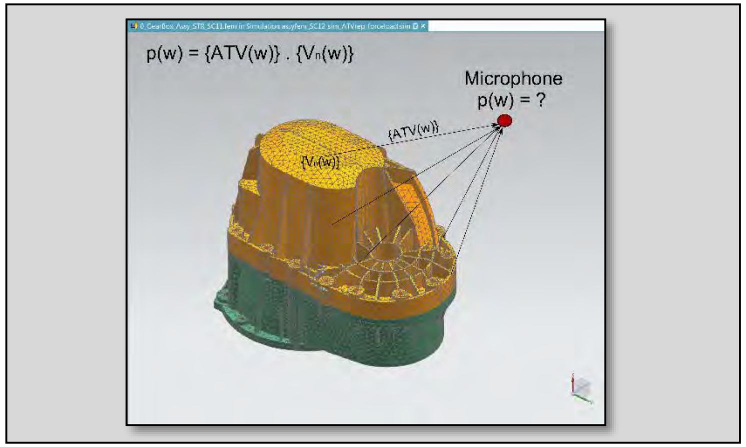
# Simcenter Acoustics – ATV (Acoustic Transfer Vector) Set

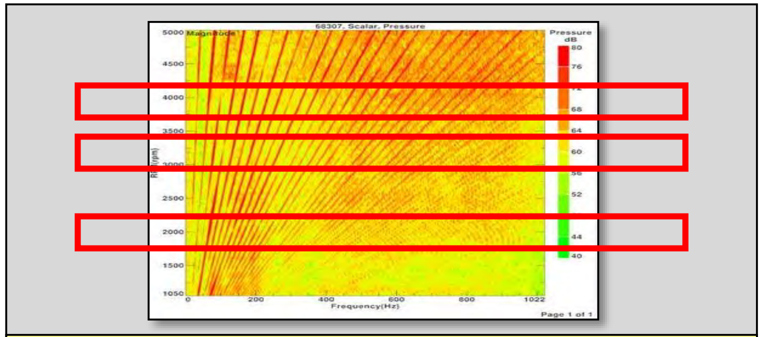
SIEMENS
Ingenuity for life



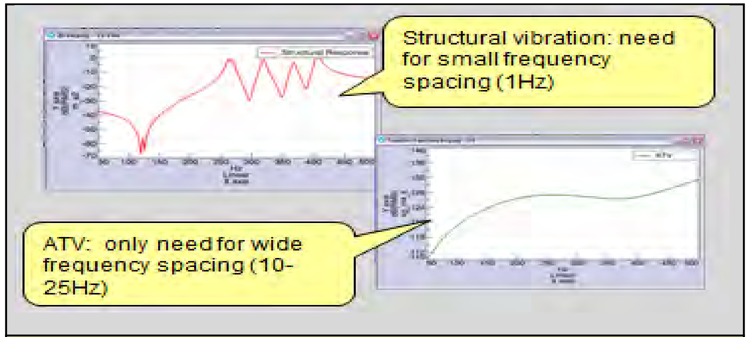




**ATV enables fast multi-rpm acoustic analysis**



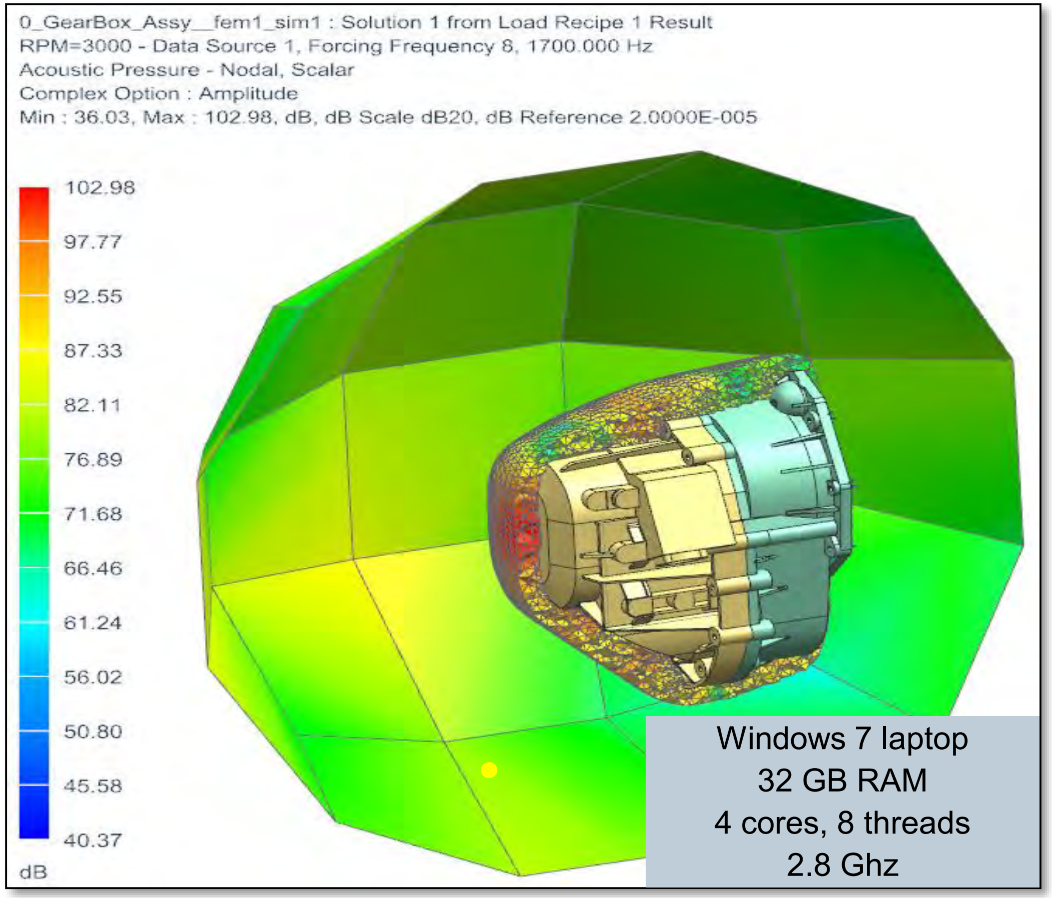




ATVs are INDEPENDENT from load conditions (rpm, order…)

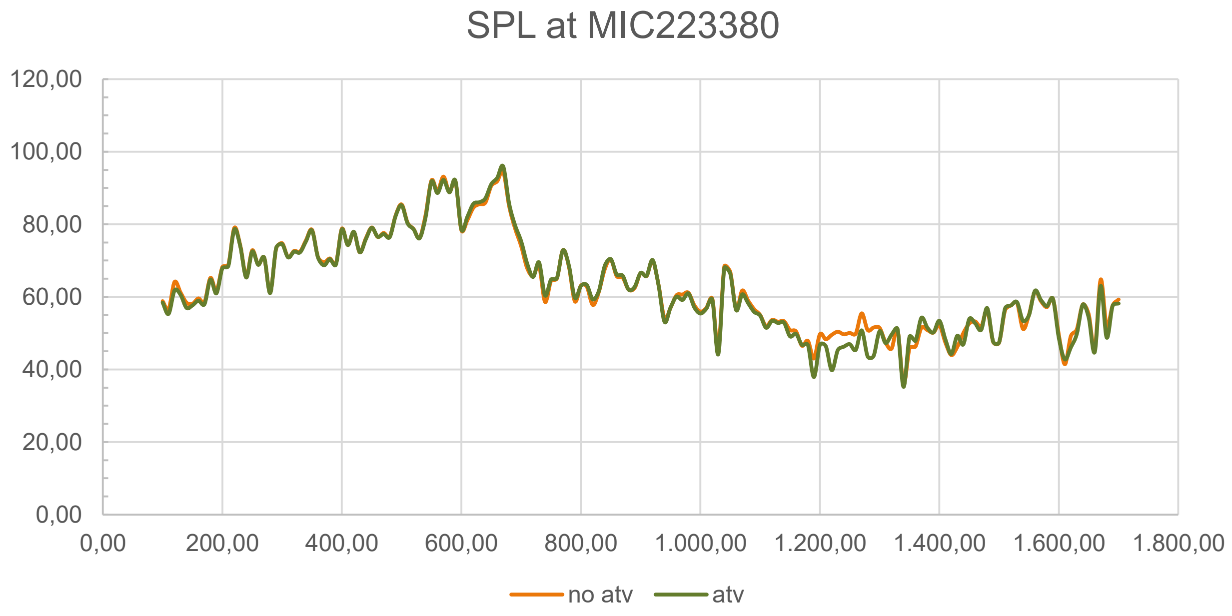



For exterior radiation, ATVs are SMOOTH functions (f), which can be interpolated

# ATV example
# Radiation of a gearbox

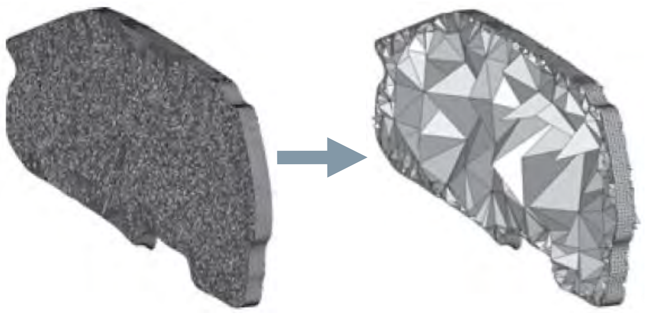



| 1 node, smp=4 | SOL111 Response | SOL111 ATV Response |
|---|---|---|
| freqs | 100-1700 Hz | 100-1700 Hz |
| Time | **22 min** | **3 min** |

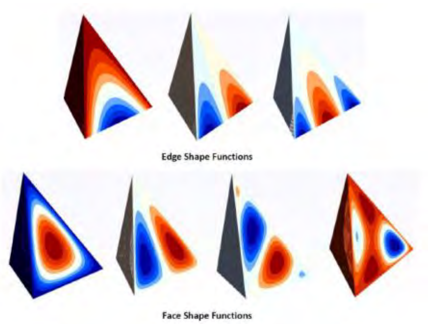


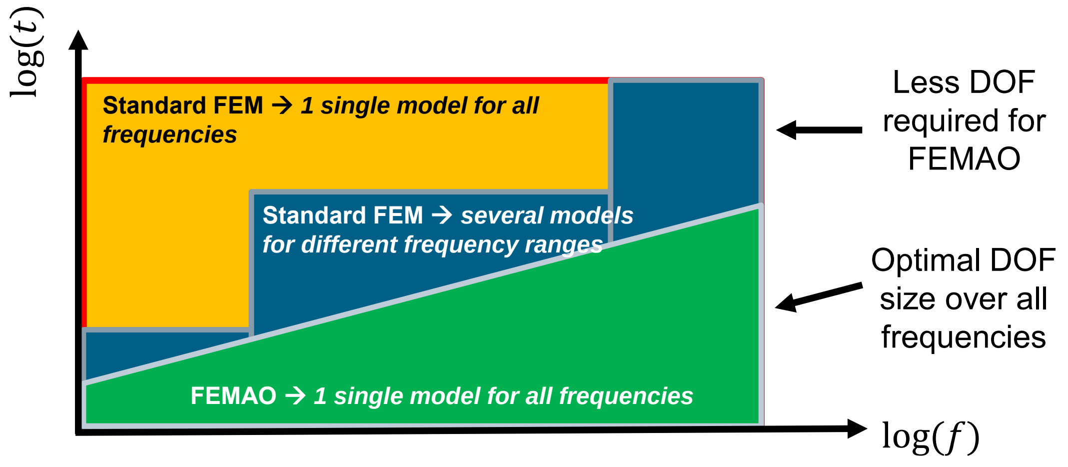
# SC Acoustics – FEMAO

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

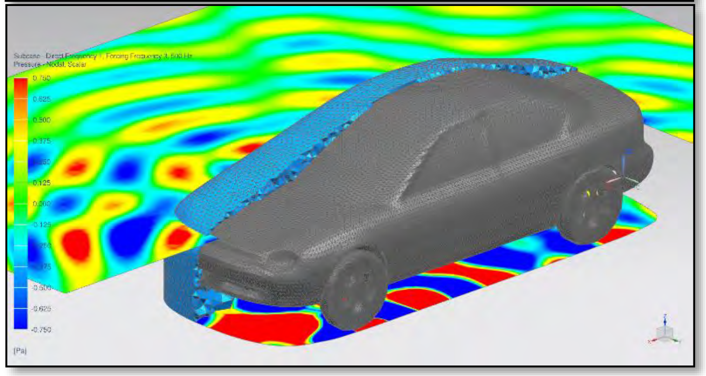


*FEM mesh* *FEMAO mesh*

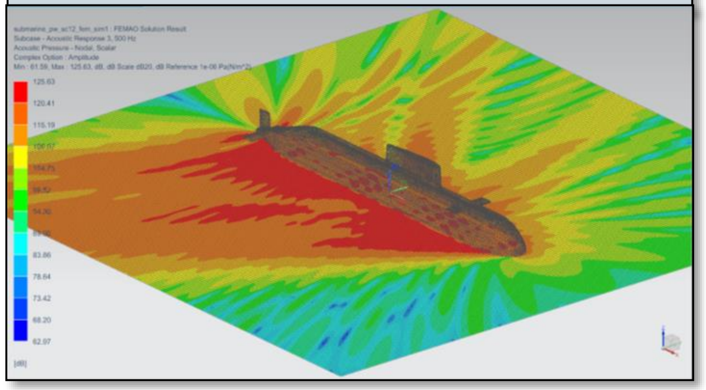



**Full vehicle exterior acoustics**
**Panel loading due to tire / tailpipe noise**



**Submarine sonar scattering**

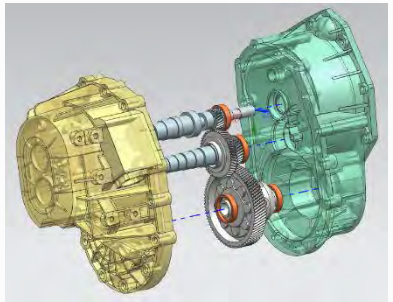


# Simcenter Acoustics for Machine Noise Radiation
# Process View

SIEMENS
Ingenuity for life

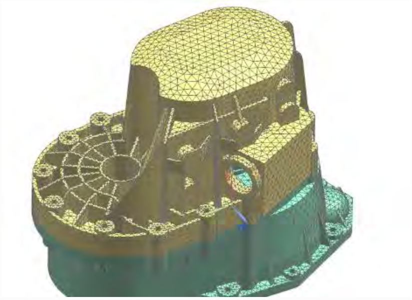
### Geometry preparation

Closing holes, removing blends, parts, ...



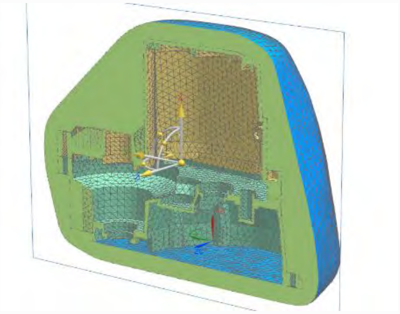
### Meshing and Assembly

Mesh mating, bolt pre-stress, acoustic meshing



### Structural-Acoustics Pre

Load recipe for loading, Output requests, FSI

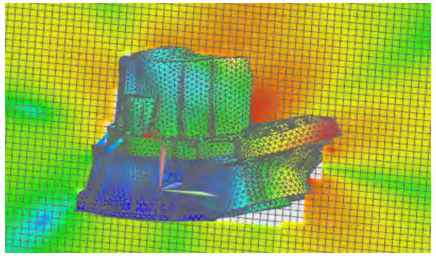


### Solving

NX Nastran Vibro-Acoustics FEM
AML / FEMAO / ATV
SC Acoustics BEM

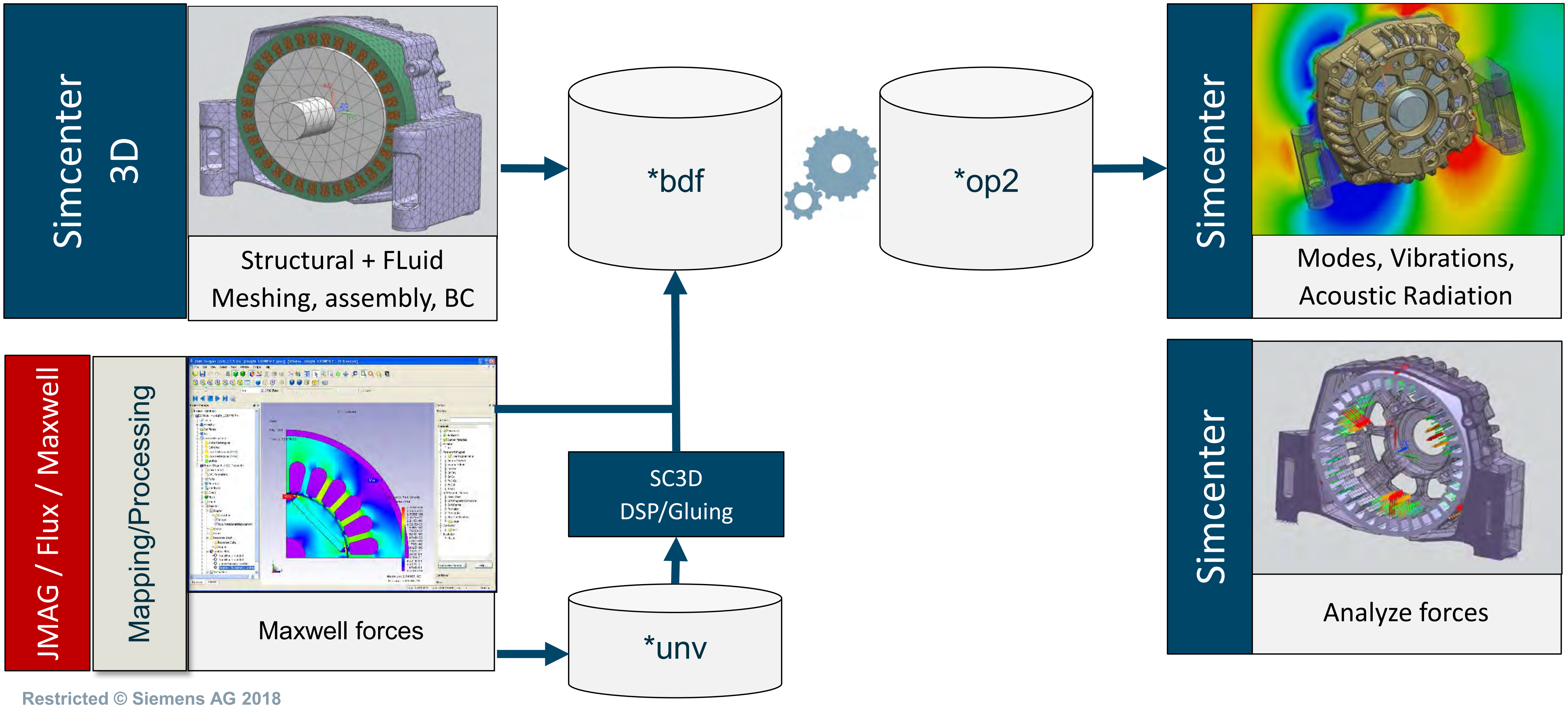
### Post-processing

Both Vibrations and acoustics.
Contribution analysis



What-if, optimization, feedback to designer

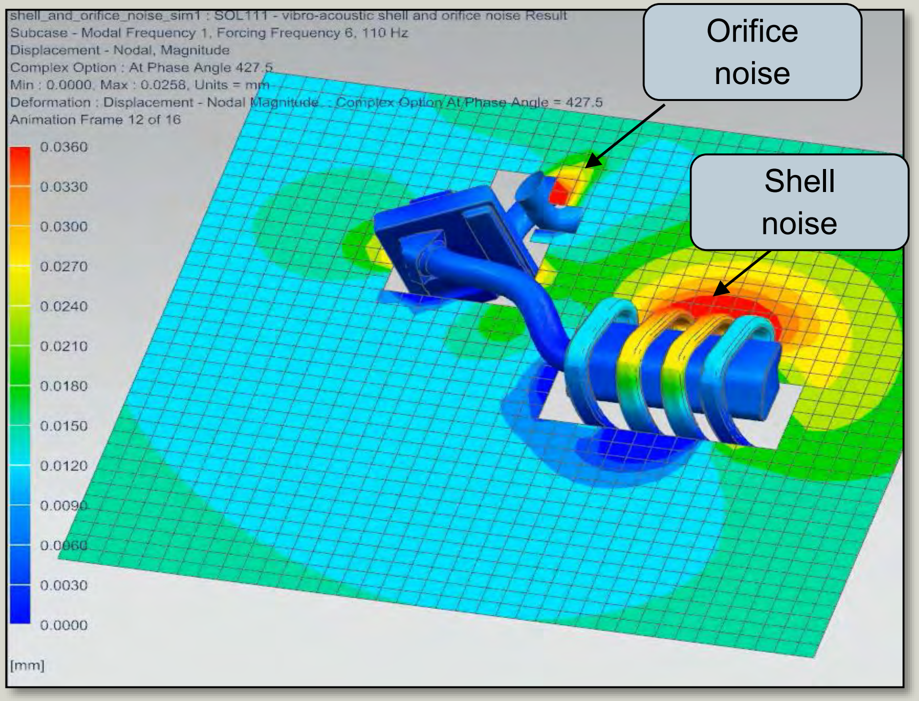
# Simcenter Acoustics for Machine Noise Radiation
## Process View on an Electric Motor model



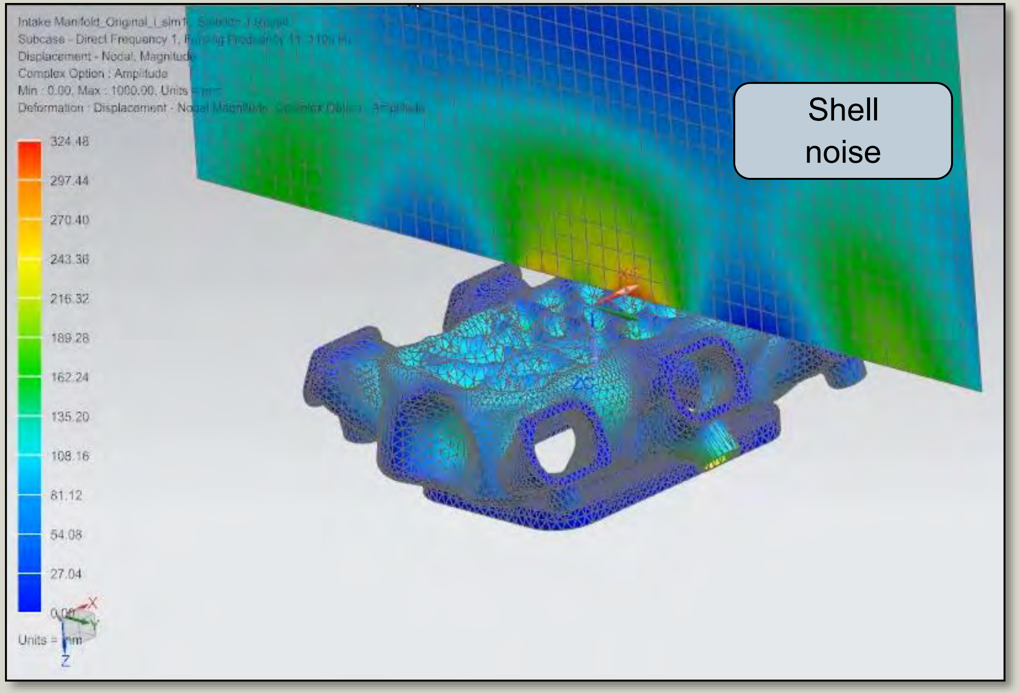
# Orifice Noise and Shell Noise

SIEMENS
Ingenuity for life

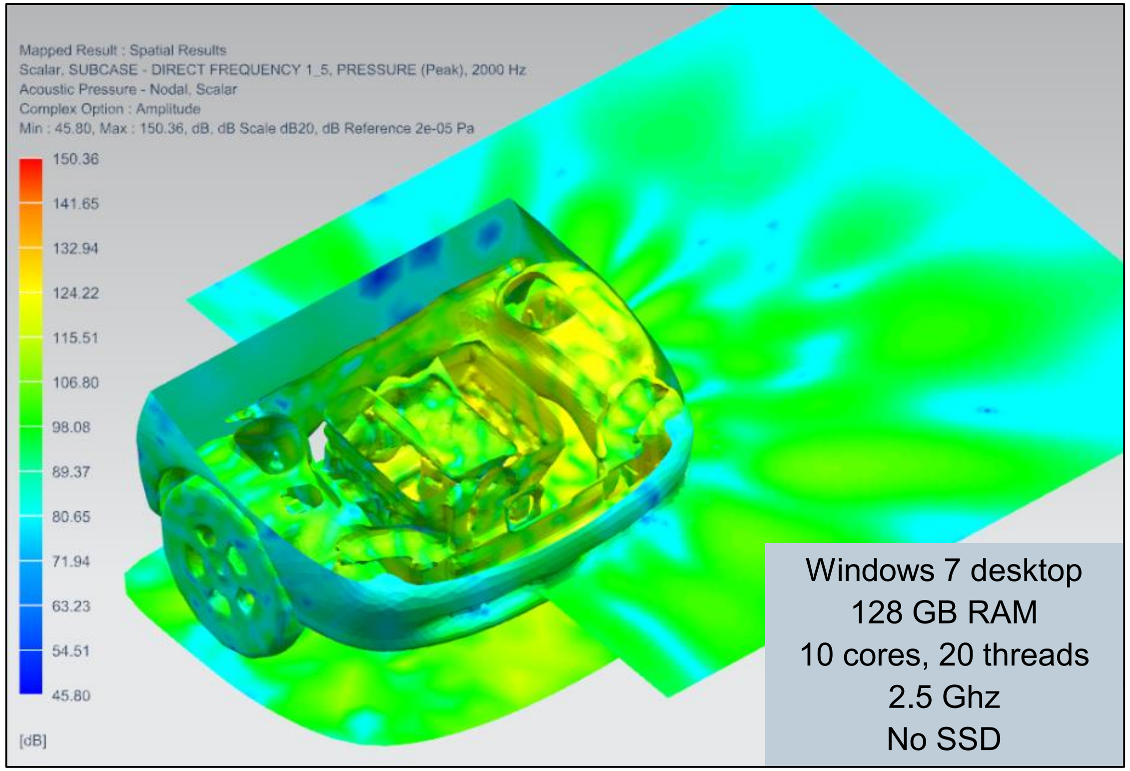
Combined Acoustic and Vibro-Acoustic problems
Intake ducting system
with fluid mesh reach in- and outside



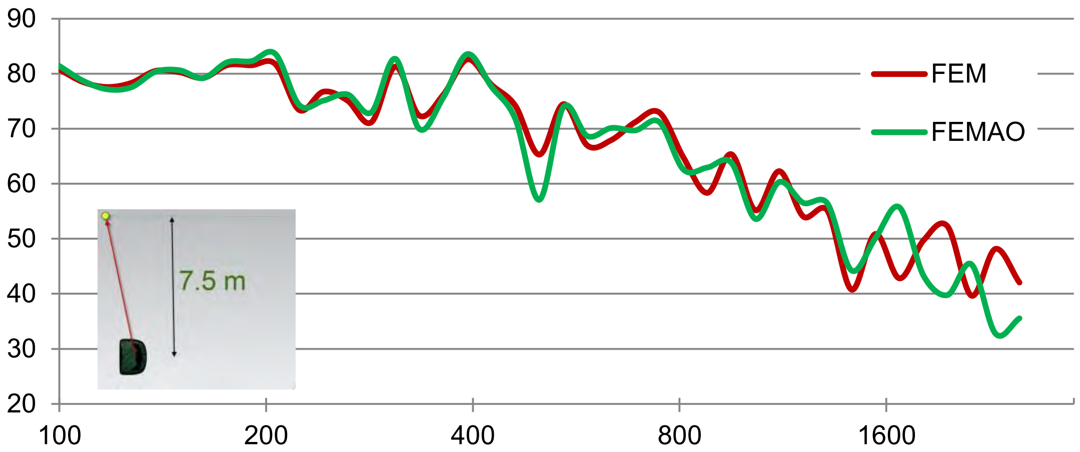

Pure Vibro-Acoustic Shell Radiation
Intake manifold
with separated meshes in- and outside



# FEMAO example
## Prediction of acoustic transfer functions of an engine bay for pass-by noise




| 1 node, smp=8 | SOL108 FEM AML | SOL108 FEMAO AML |
|---|---|---|
| Frequencies | 100 – 2500 Hz | 100 – 2500 Hz |
| Time forced response | **97 min** | **22 min** |

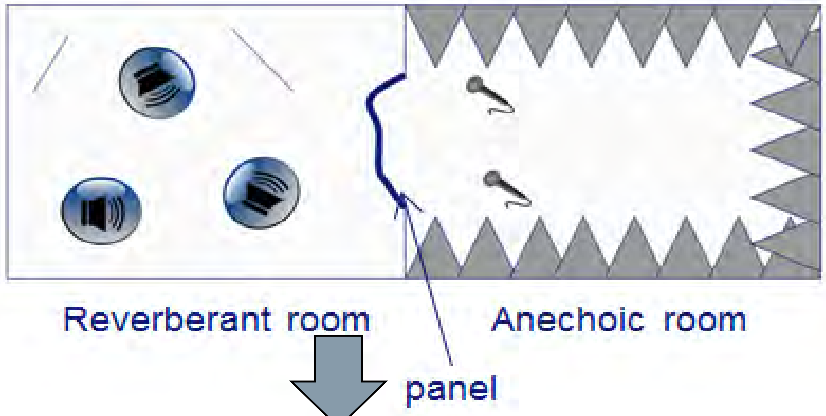


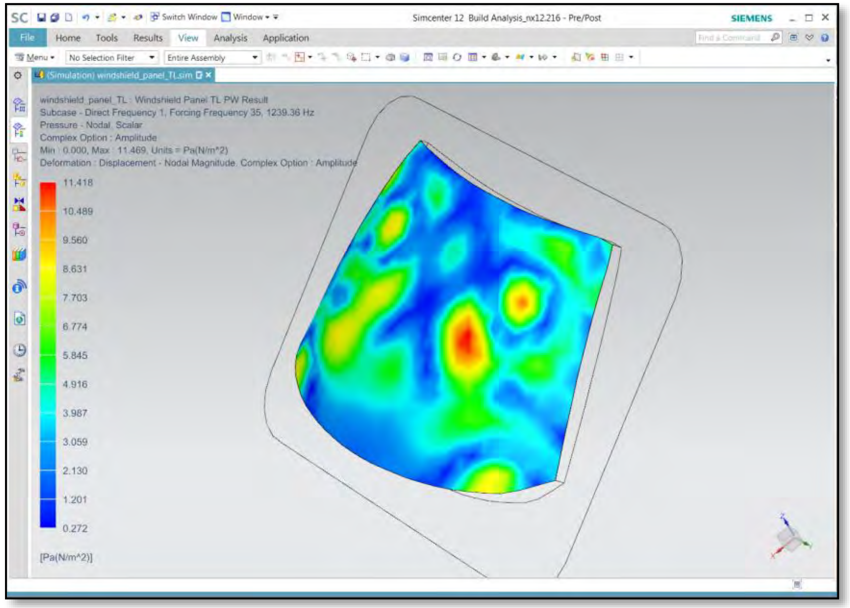
# Panel Transmission Loss
# Modeling Process using FEM AML

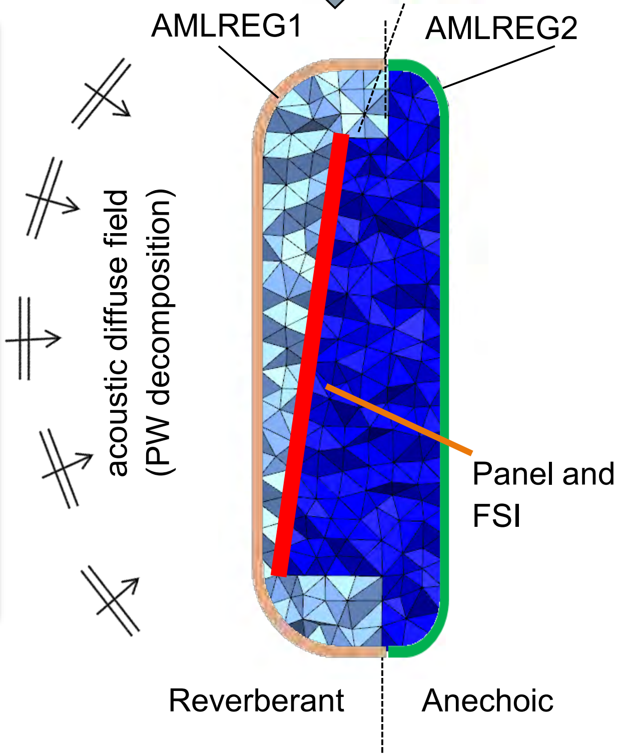
SIEMENS
Ingenuity for life

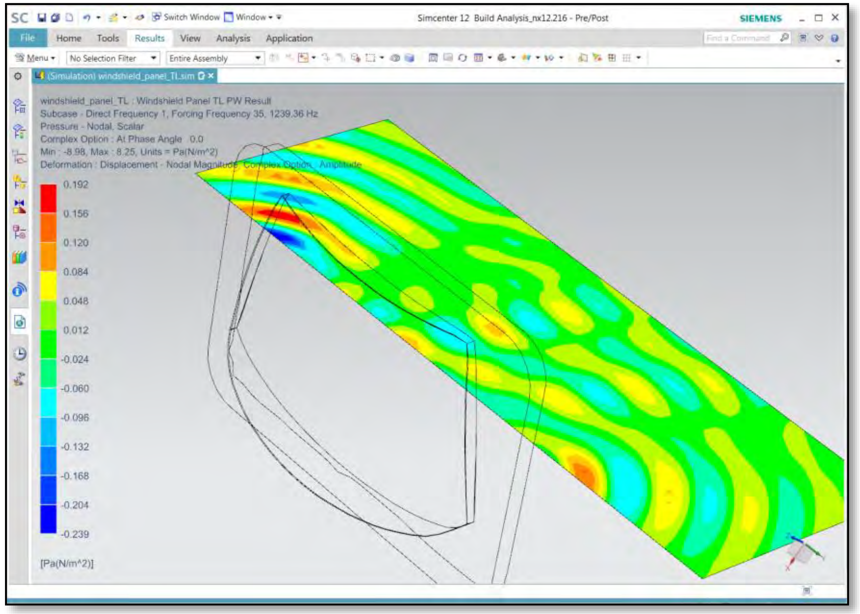
The AML is applied as absorbent BC for both reverberant and anechoic domains.

Only few elements required between panel and AML surface
➔ LEAN and FAST Models





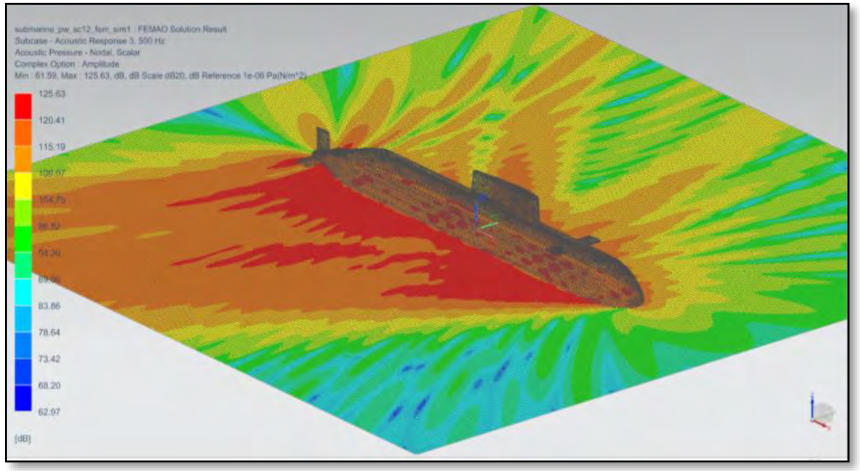
# FEMAO Example
## Submarine (BeTTSi) Target Echo Strength

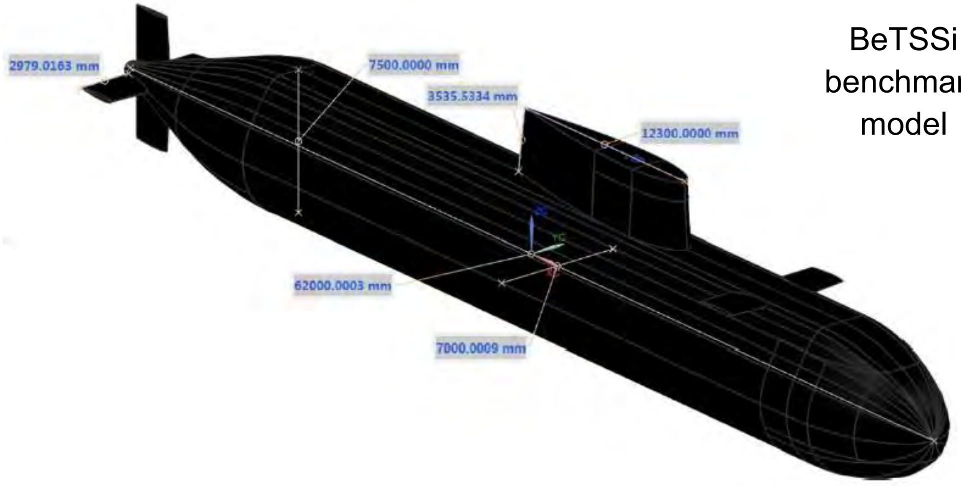
SIEMENS
Ingenuity for life

<u>SUBMARINE STEALTH</u>

TES: Target Echo Strength
How much energy from an impinging SONAR signal is reflected?

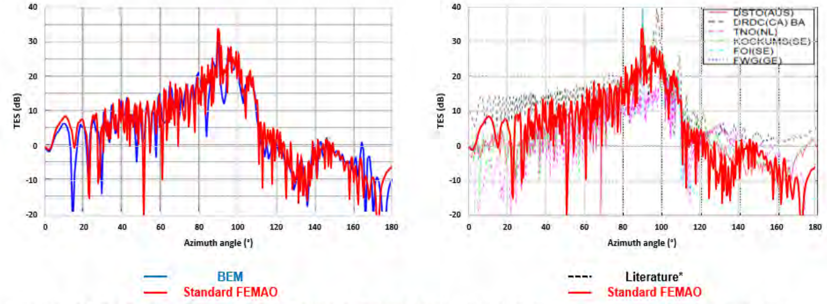
Addressed with FEMAO up to few kHz






BeTSSi benchmark model

- Monostatic TES: $\mathrm{TES} = 20\log_{10}\left(\frac{r}{r_0}\frac{|p_s|}{|p_i|}\right)$

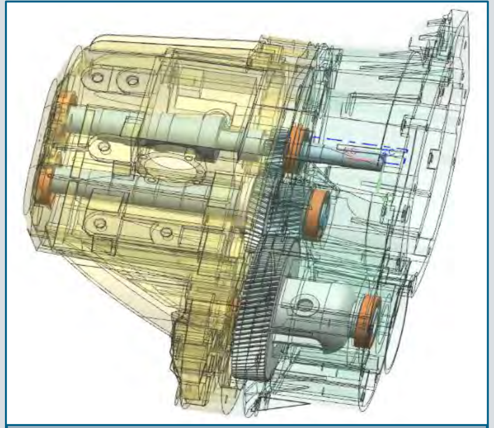



* Schneider, H.G., Berg, R., Gilroy, L. E., Karasalo, I., MacGillivray, I., TerMorshuizen, M., Volker, A. (2003). *Acoustic scattering by a submarine: results from a benchmark target strength simulation workshop*: ICSV10, Stockholm, Sweden. 2475-2482.

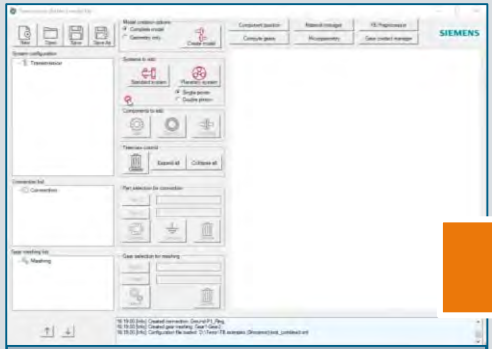
# Simcenter 3D Acoustics
## Powertrain Applications

SIEMENS
Ingenuity for life

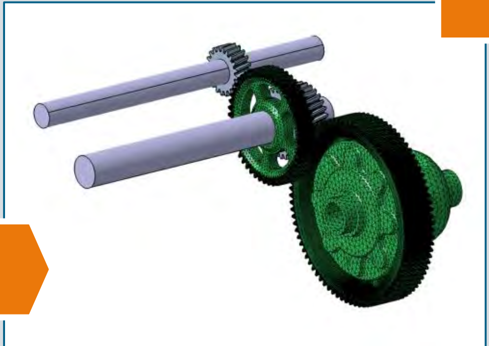
### Gearbox Noise Radiation – From Design to Acoustic Response



Gearbox Housing

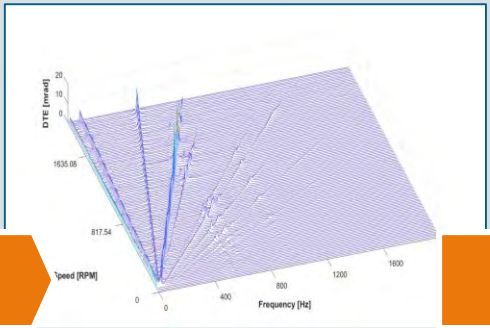


Transmission Builder

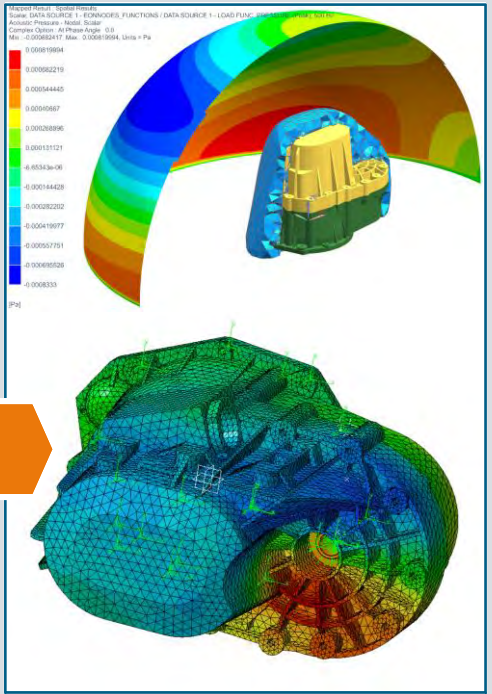


Gear System From Transmission Builder

Multi Body Simulation Model



Import of Motion Results
Time → Frequency
Load Recipe
Selection Recipe

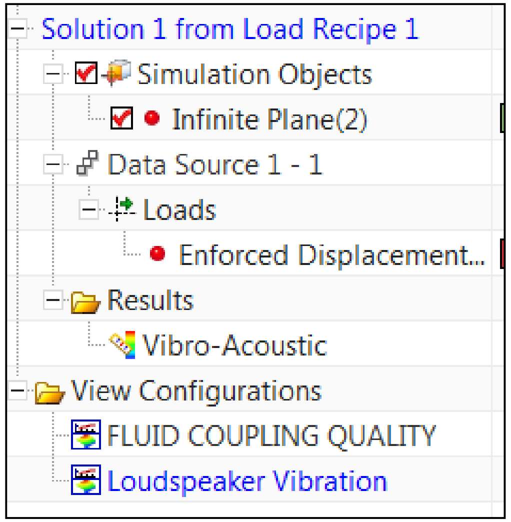


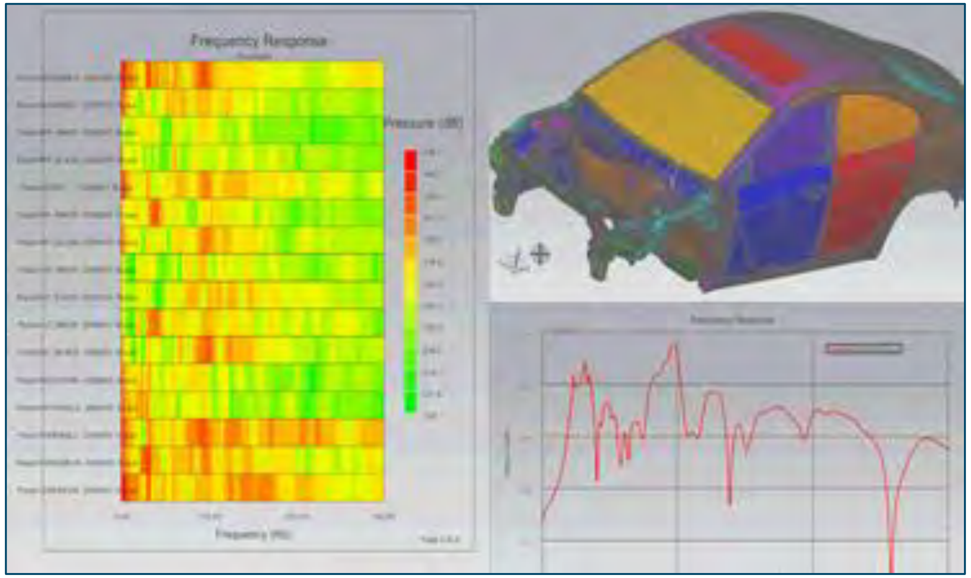
Simcenter Nastran Vibro-Acoustic Response

# Simcenter 3D Acoustics Key Capabilities
## Application, industry specific modeling

SIEMENS
Ingenuity for life

**Application Specific Noise and Vibration analysis**
**Efficiency in handling ‘industrial, application specific data’**

From Measured data → Load recipe → Cabin Comfort

# 3D CAE for the digital twin

SIEMENS
Ingenuity for life

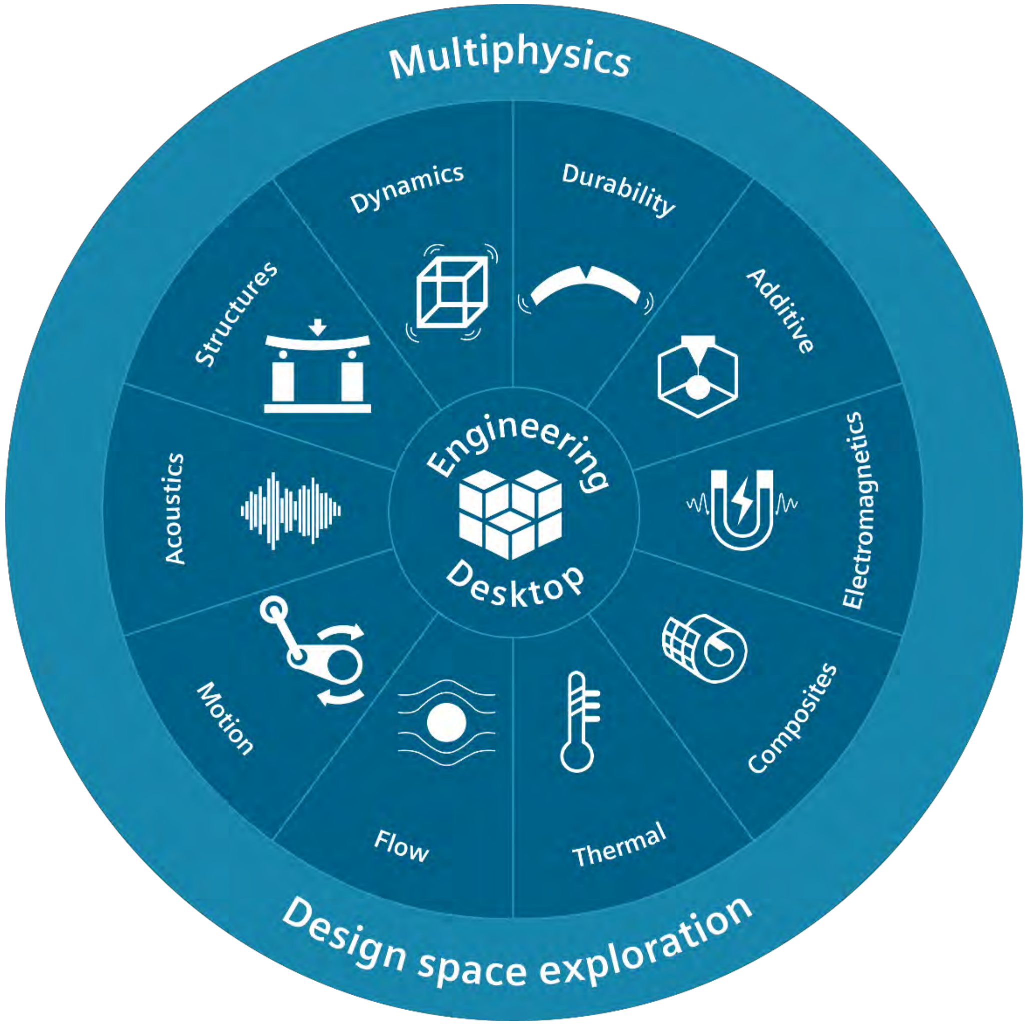
**Best-in-class simulation modeling**

**Multi-discipline integration**

**Openness and scalability**

**Leading in system simulation**

**Leverage industry expertise**



Ingenuity for life

# www.siemens.com/simcenter