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Simcenter 3D Acoustics
Loudspeaker and Car Audio Design

Realize innovation.

Car Audio Design– Why Acoustic Simulation?

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Trends in the market

Abundant audio and multi-media

Dolby Surround Systems
Bluetooth Phone Communication
Audio-assisted navigation system
Voice-operated control system

Sound Quality

Part of the branding

Important for overall costumer satisfaction

Addressing Specific Market Requirements

Audio Equipment

Loudspeakers

Directivity and frequency characteristics of loudspeakers.

Design of horns and loudspeaker arrays.

Headphones

Objective: to have good frequency characteristics even with very thin (flex) membranes.

Distortion should be kept to a minimum.

Microphones

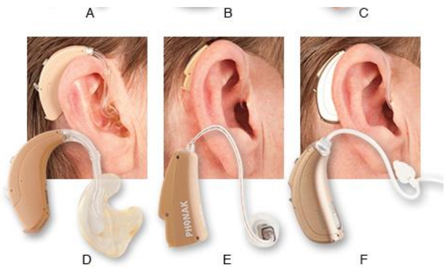
Need to have good frequency curves and directivity.

Wind noise could be a problem when used outside (professional walky-talkies).
Very thin membrane.

Hearing Aids

Ensure good directivity of (external shielded) microphone picking up the sound

Filter out unwanted noises from background/wind..



Car Audio Design Challenges

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Improve the overall audio experience in the vehicle

Challenge

How to design Passive and Active Components to optimize In-Vehicle Acoustic Comfort?

- Loudspeaker positioning and orientation
- Strengths and delays per loudspeaker
- Door Structure and Cavity design
- Choice of Trim Fabrics

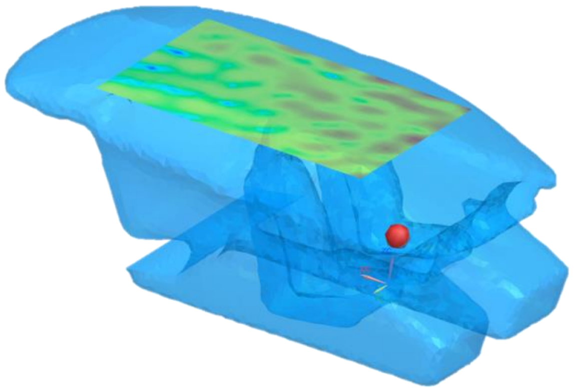
Objective:

- Cost Effective Solution
- Design-Right-First-Time: Use simulation to reduce expensive prototyping

Simcenter 3D Acoustics
Best-in-Class Solution

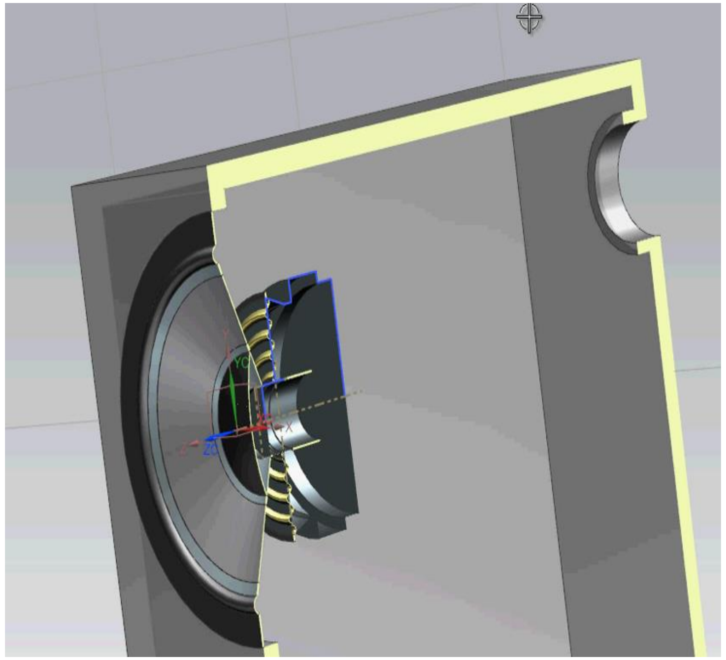
Capabilities

Realistic simulations for a variety of different applications



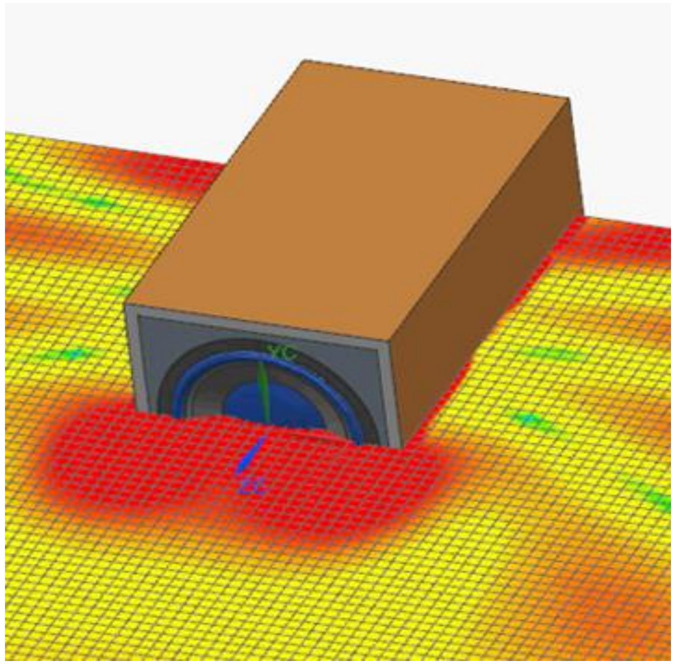
Highly Efficient Process

Easy to operate: from CAD to Acoustics

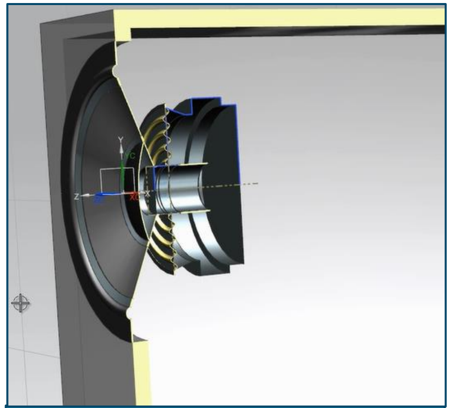


Most Performant

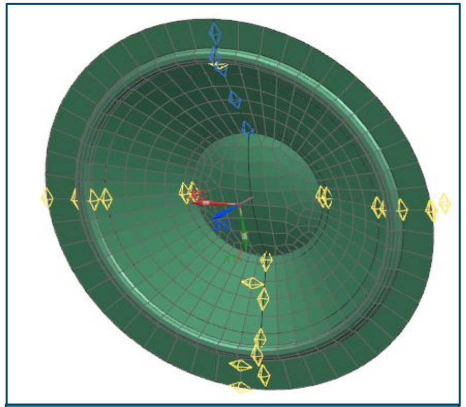
Get results fast: superior and unique solving technologies



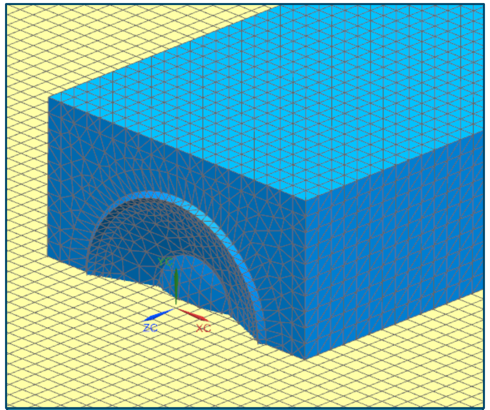
An End-to-End Process
Example: Loudspeaker



Design (CAD)

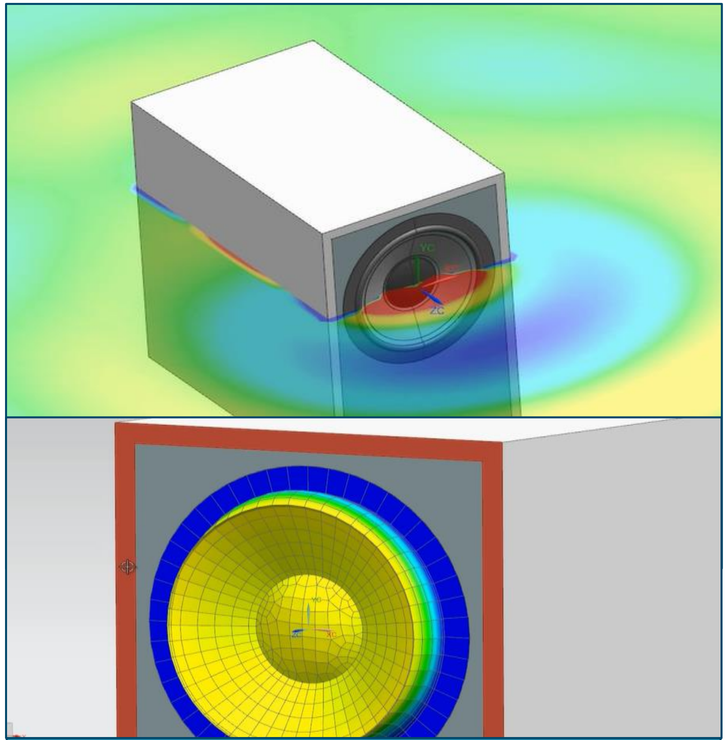


Meshing of structural components



Acoustic meshing (BEM), LBCs, microphone points

1D



Post-processing
Directivity, impulse response, distortion

Design Optimization

Loudspeaker design

Simcenter 3D 2020.1 Acoustics

Vibro-acoustics aspects of car audio

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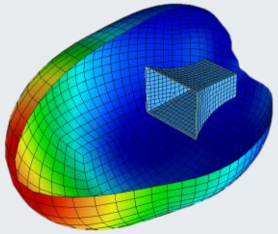
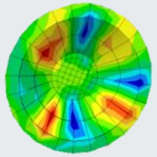
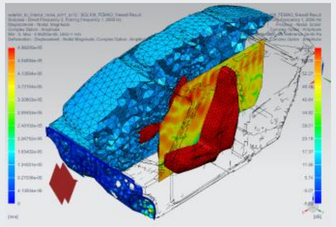
Source

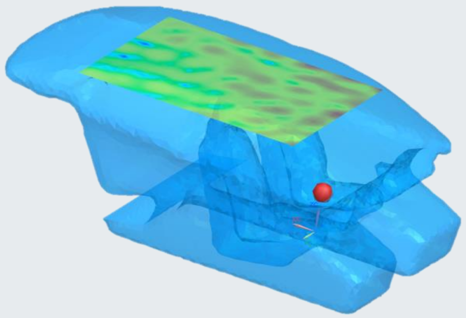
Loudspeakers
Time Delays
Gains
Directivity
Door 'Cabinet' Design
EM forces



Transfer

Car Cavity
Air
Panels' Absorptive Properties
Reflections and Diffraction

High-end FEM solutions
(FEM AML, FEM AO)
Simcenter NASTRAN

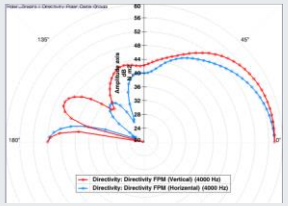
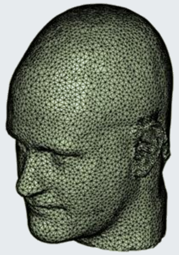
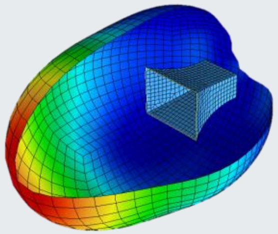
High Frequency Acoustics
Simcenter 3D Ray Acoustics

High-end BEM solutions
(FMM, H-Matrix, Time Domain)
Simcenter Acoustics BEM

High Frequency Vibro-Acoustics
InterAC SEA+

Receiver

Passenger's Ears
Frequency Results
Transient Results
Sound Quality
Binaural Response*

Speaker Components

Diaphragm :

Dome or cone shape

Paper, plastic, metal, composite

Ideally : stiff + light + damped

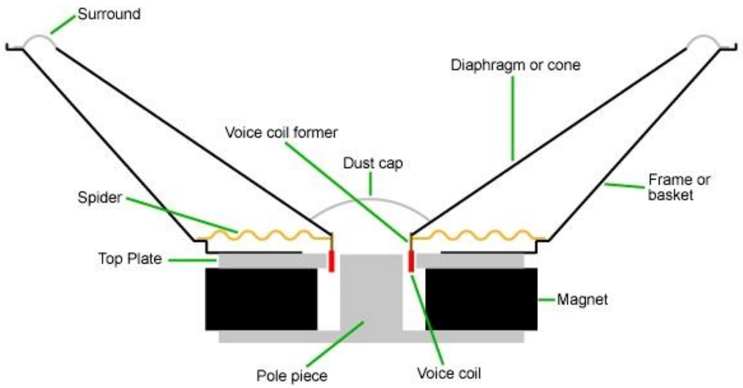
Voice coil :

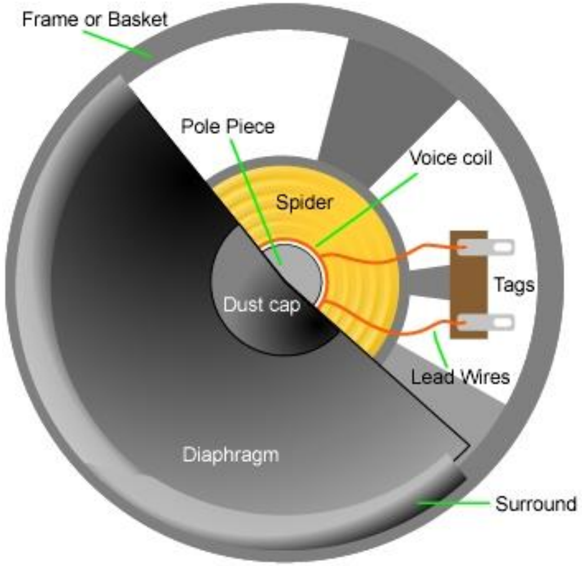
Copper + lacquer coating

Magnet

Enclosure / cabinet

Prevent destructive interference of waves from the back





Speaker Modeling

Lumped parameter models :

- Thiele-Small parameters
- Characterize speaker performance (resonant frequency, damping, maximum excursion,…)

Too simple model

- Not applicable for complex systems
- Vibration system modeled by single mass system
- Only piston mode
- Limited to low frequency

FEM / BEM Models :

- Fine discretization of structural and acoustic domain
- Fluid loading on the diaphragm

More accurate approach

- Applicable for complex systems
- Near-field and Far-field effects of 3D sound radiation
- High frequency analysis
- Design Optimization possible

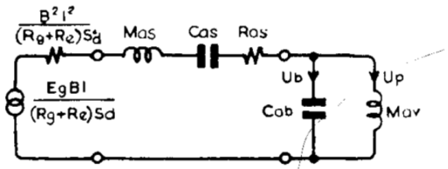
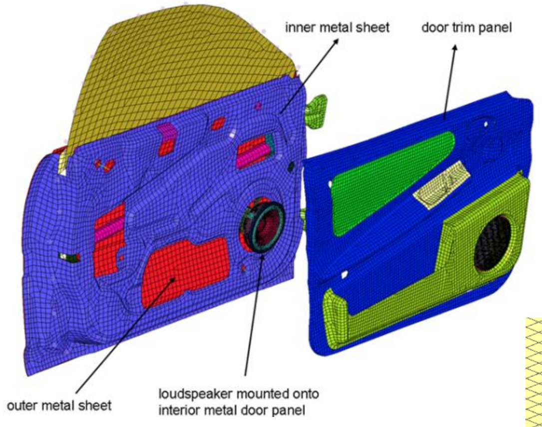
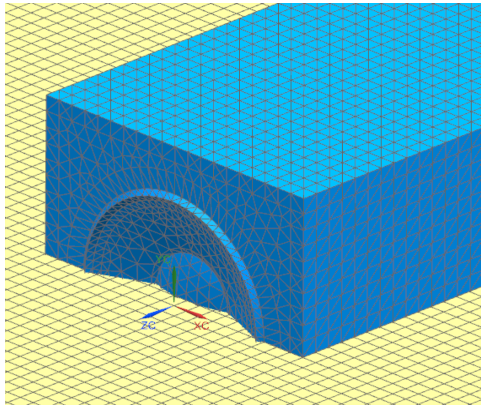


Fig. 2. Simplified acoustical circuit of loudspeaker in vented box.

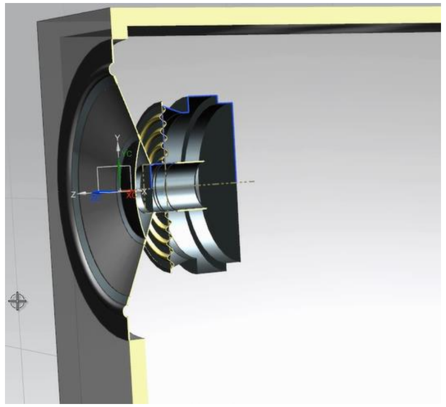


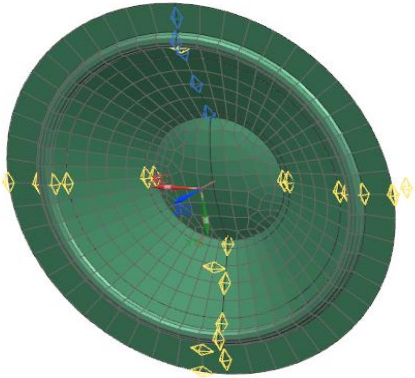


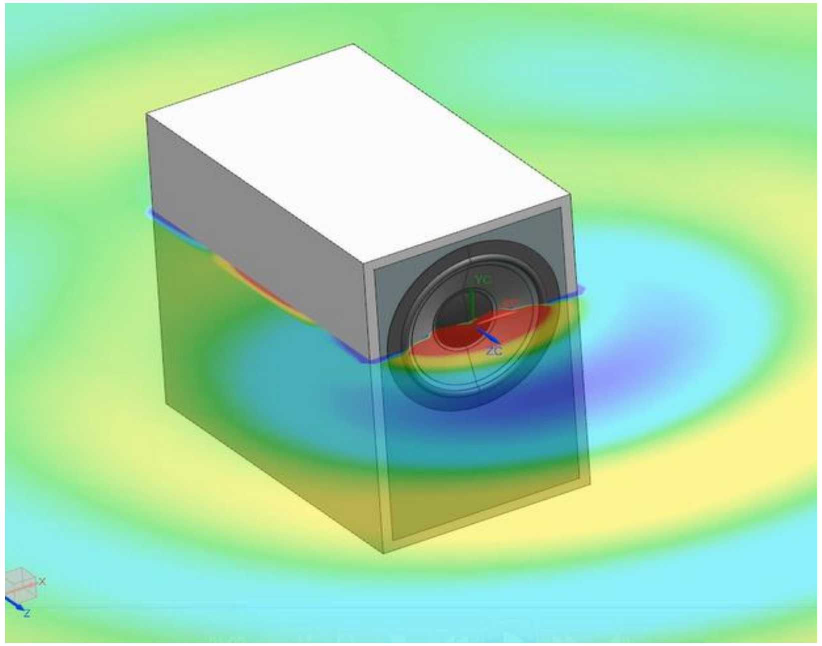
Speaker Modeling

Strong coupling (2 way-coupling):

- Membrane vibration generates sound
- Acoustic waves influence vibrations of the membrane







Membrane is very light → fully couples with air

Response Objectives

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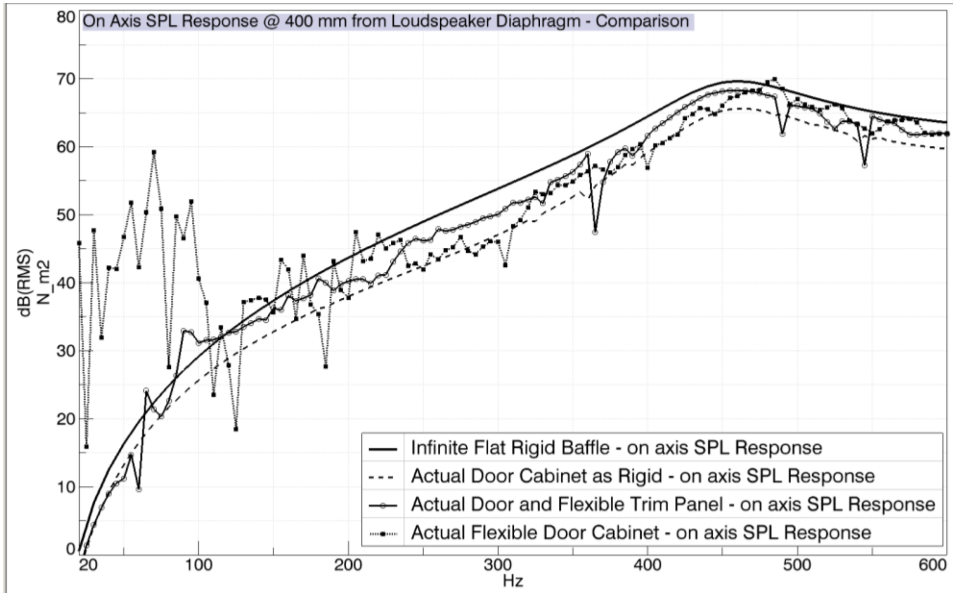
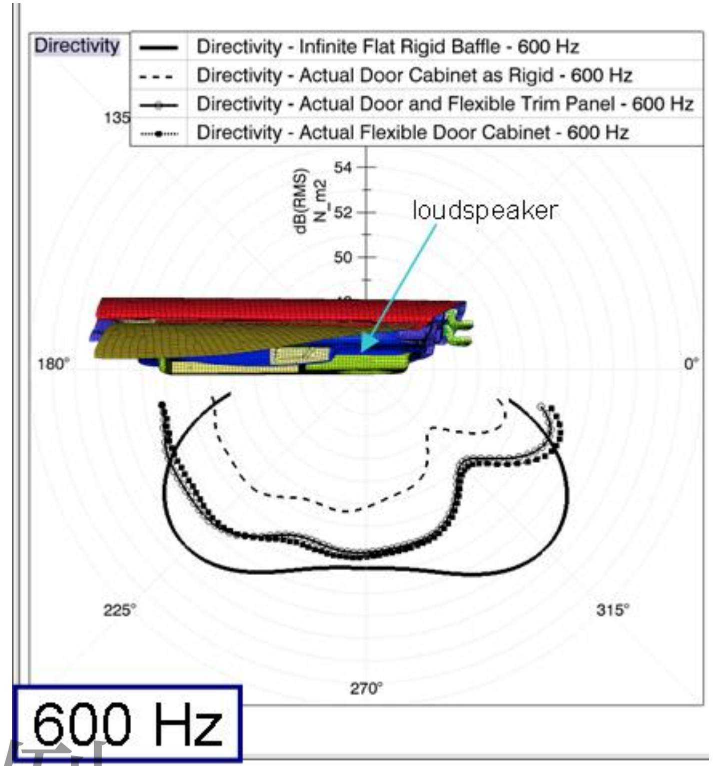
2 Main Goals:

- Get **flat response** over frequency range ➔ the loudspeaker doesn't 'color' too much the sound

- Get desired **directivity** pattern





Speaker Modeling – Structural model

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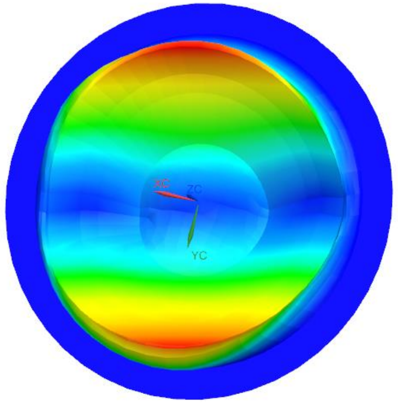
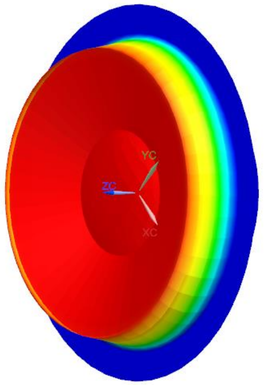
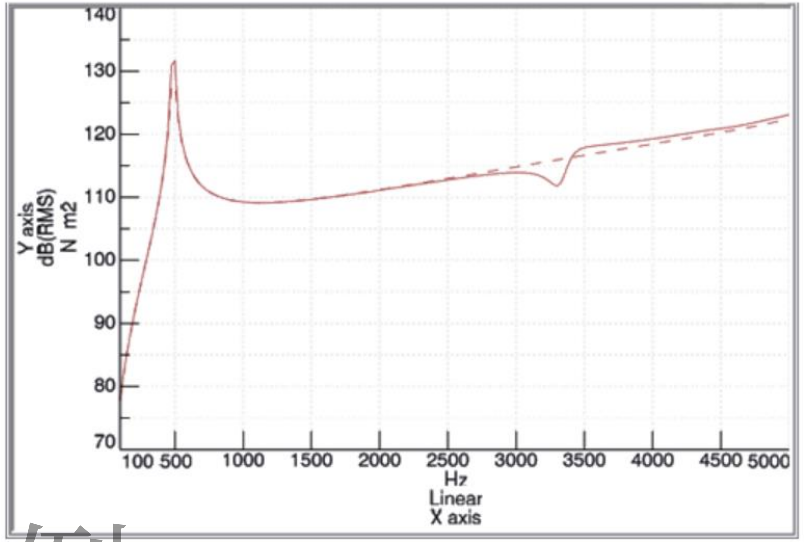
Structural Model definition:

- Material properties and thicknesses
- Sometimes tricky to estimate
  - E.g. Voice coil made of copper wires and lacquer coating
- Handling of non-linearities is difficult

→ **Computation of structural modes**







Non-pistonic modes have an influence on the acoustic response, typically not predicted by lumped parameters

Speaker Modeling – Distortion Effects

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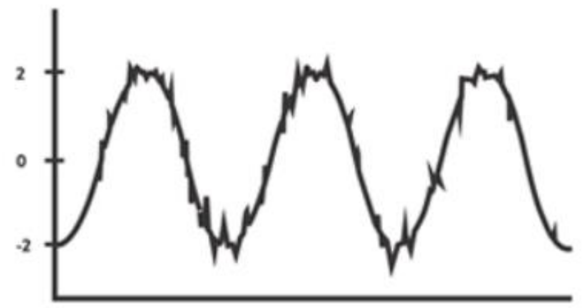
High membrane excursion → Non linear behavior → Distortion of input signal

Evaluation of Harmonic distortion :

THD = Total harmonic distortion

$$= \frac{\text{Sum Harmonics Power}}{\text{Fundamental Frequency Power}}$$



→ Acoustic coupling has an effect on distortion

→ **Difficult to model because Vibro-acoustic tools are based on linear theory**

Electromagnetic coupling

Multiphysics simulation

Use of electromagnetic forces – linear domain

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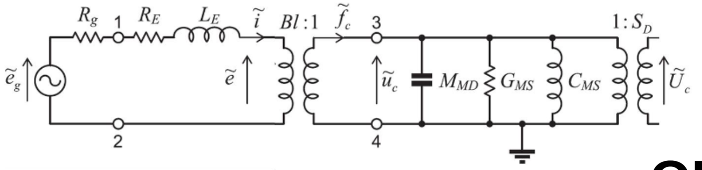
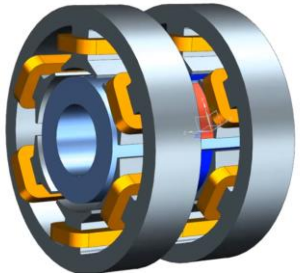
1D models for the coil: Thiele-Small model



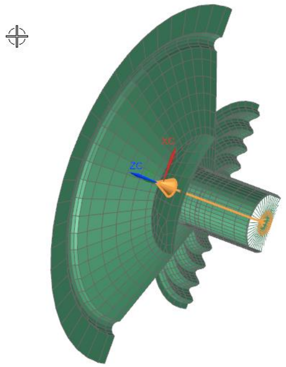


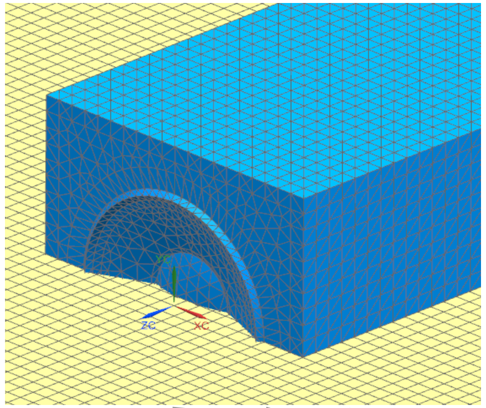
Full FEM EM Simulation (2D or 3D)

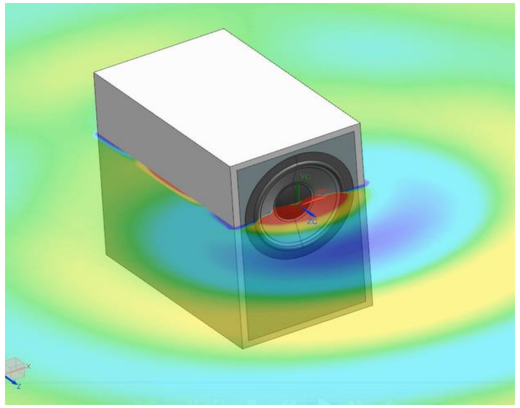
OR

Forces on the Coil → **Vibro-acoustic simulation (strongly coupled)** → **Post-processing**

Improve the 1D model with a more accurate acoustic Impedance





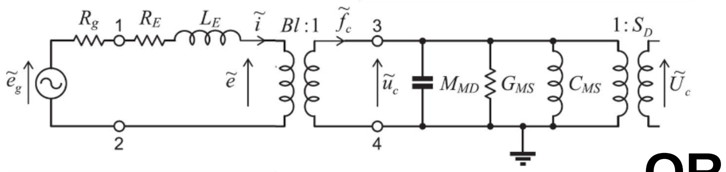


Multiphysics simulation

Non-linear effects – difficult to capture in full 3D models

Limited to pure propagation (weak coupling)

1D models for the coil: Non-linear Thiele-small model



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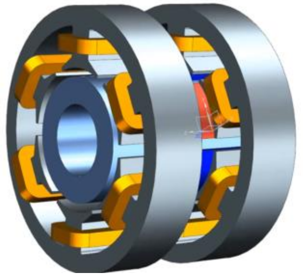
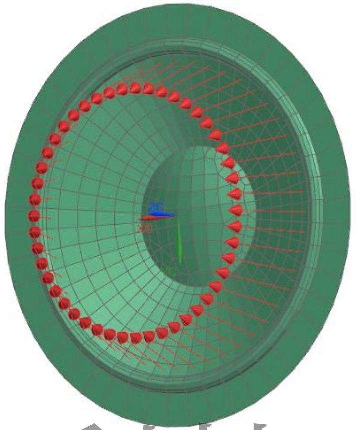
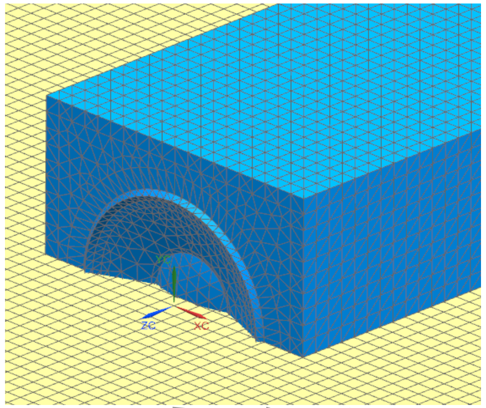


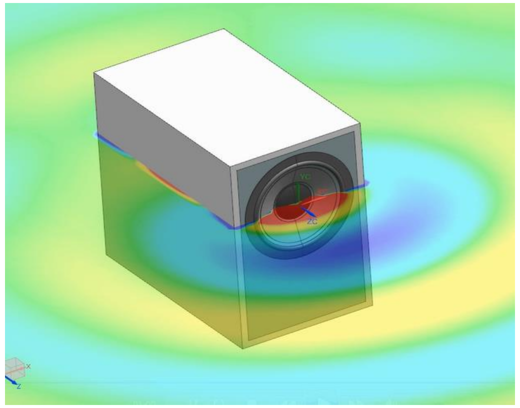
Full FEM EM Simulation (2D or 3D)

(rigid body motion)

→ **Acoustic panel (piston) velocity** → **Acoustic simulation** → **Post-processing**







Installation effects

Car Audio Design– Why Acoustic Simulation?

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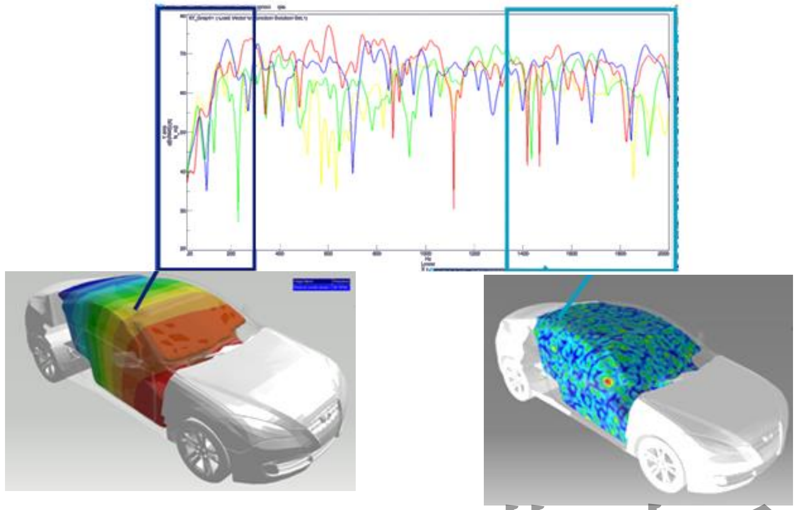
Cabin Acoustics

At low frequencies (< 100 Hz) sound field is deterministically defined by few modes ➔ typical positions for woofers in the corners

At higher frequencies the sound field is more diffuse + peaks and dips are result from many overlapping resonances

Frequency marking the transition = Schroeder Frequency (~ 200-300 Hz for a typical car compartment)

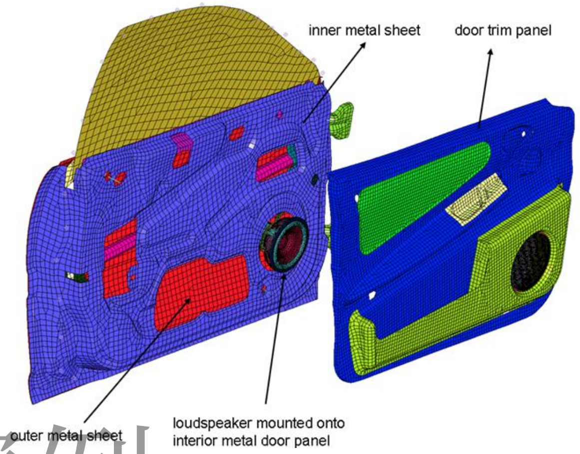


Automotive Door Acoustics

Also ‘**cavity’ acoustics**: shape, size and flexibility of door ‘cabinet’ will influence loudspeaker performance

Trend towards **thinner inner metal panels** with smaller area ➔ more flexible door structure

Challenge is to prevent unwanted vibrations on the trim panel as these will pollute targeted directivity and amplification spectrum of the loudspeaker



Full Frequency Vibro-Acoustic Simulation

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Vibro-Acoustic Analysis	Structural FEM Acoustic BEM and FEM (Simcenter Nastran)	SEA
Acoustic Analysis	BEM FEM	Ray Acoustics

Low Frequency → **High Frequency**

Using Best-in-Class Acoustic Technology

Simulation Techniques for In-Car Audio Design

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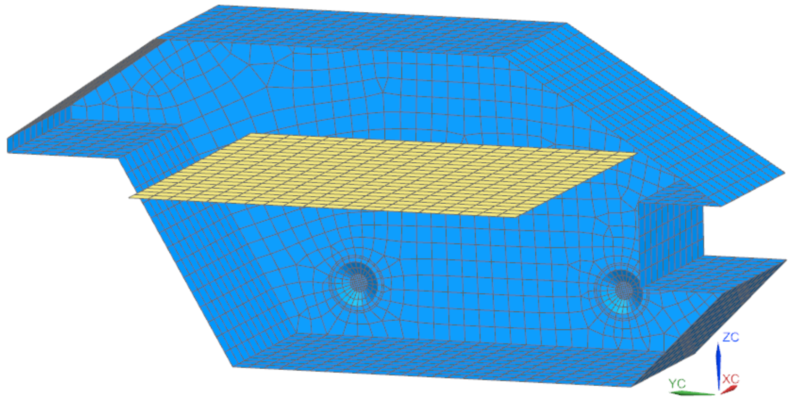

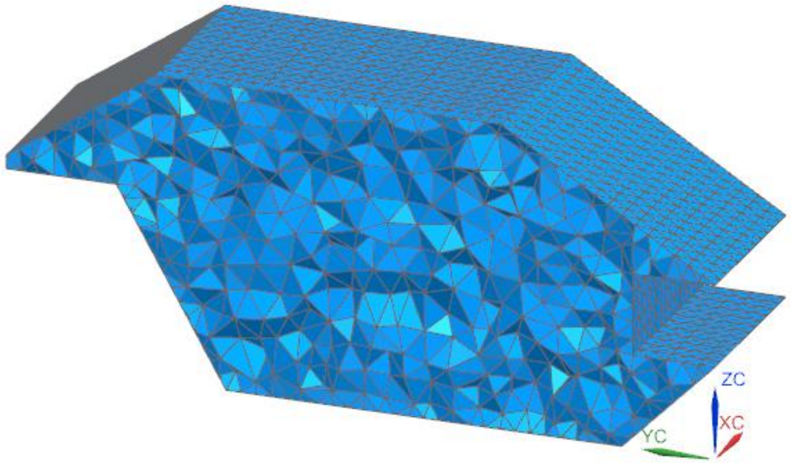

BEM

- Discretize the envelope of the domain → fewer nodes needed
- Fully populated matrices
- Conventional Direct or Indirect BEM → up to several 100's Hz
- Fast Multipole BEM → up to several 1000's Hz overnight with multi-core machine

FEM

- Discretize the volume of the domain → more nodes needed
- Sparse matrices and efficient algorithms for fast solving
- FEM Adaptive Order →high order functions automatically adapted on the solver = 2 to 10 times faster

Simulation Techniques for In-Car Audio Design
FEM Coupled Vibro-Acoustic Simulation for Loudspeakers in Doors

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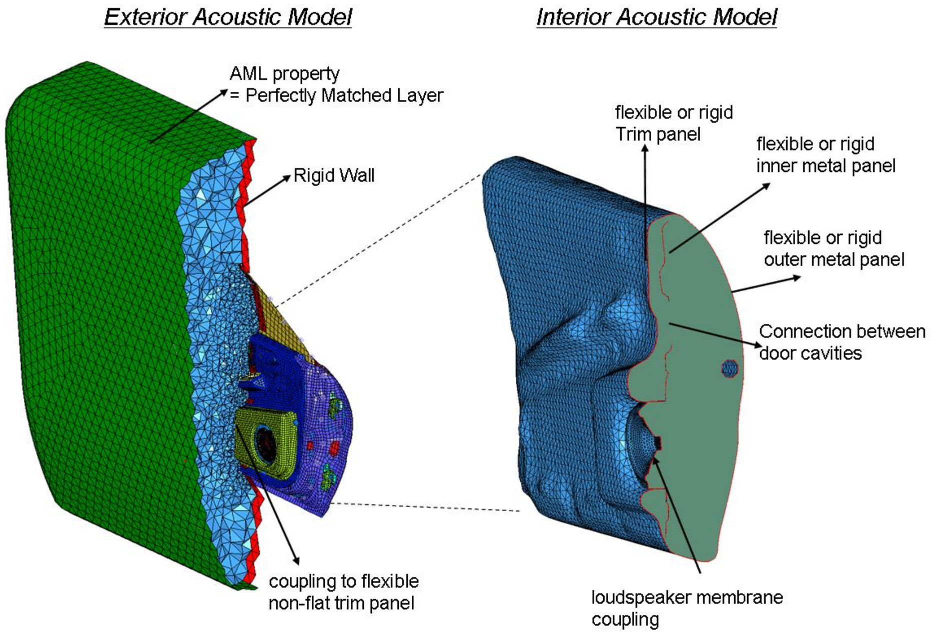

Model Setup
- FEM inside door = cavity mesh
- FEM outside door = FEM elements + AML
  → model size remains reasonable
- Take advantage of coarser meshes with **FEMAO**

Several Models possible:
- Loudspeaker mounted in infinite and stiff baffle
- Actual door cavity and trim panel shapes but rigid door panels
- Actual door cavity + flexible trim panel
- Actual door cavity + fully flexible door

Simcenter 3D Ray Acoustics

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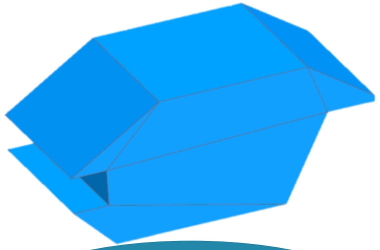
High frequency acoustics in minutes

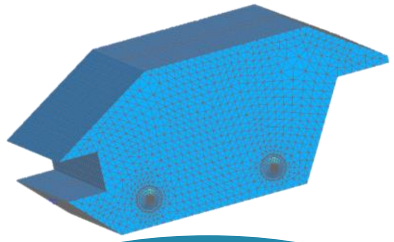
Challenge:
- Boundary Element Method and Finite Element Method compute time become tedious at high frequencies

Solution:
- Simcenter 3D Ray Acoustics:
  - Based on ray tracing → 10 to 100x faster than FEM/BEM
  - Good at high frequencies and/or large geometries
  - Pure acoustics (for now)
  - Output on both frequency and time domain

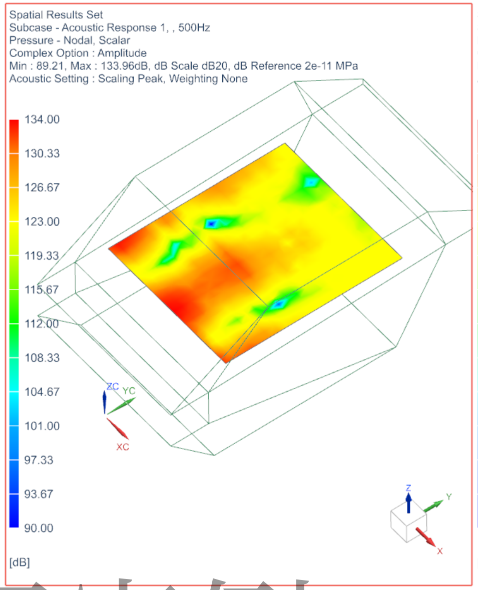
  - Support of diffraction (planned for 2020.2)

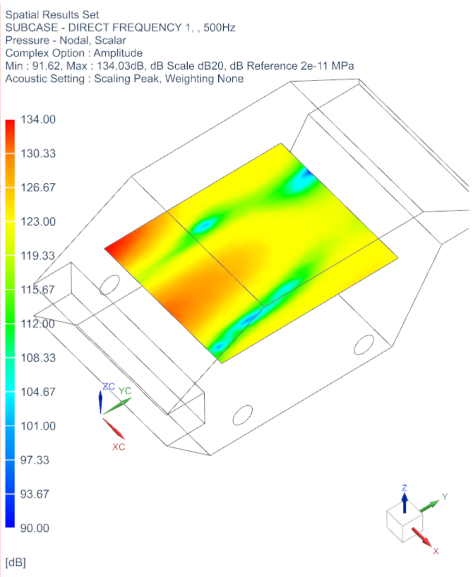


20 kHz Ray Acoustics
21 elements



5 kHz FEMAO
45000 elements





Simcenter 3D Ray Acoustics

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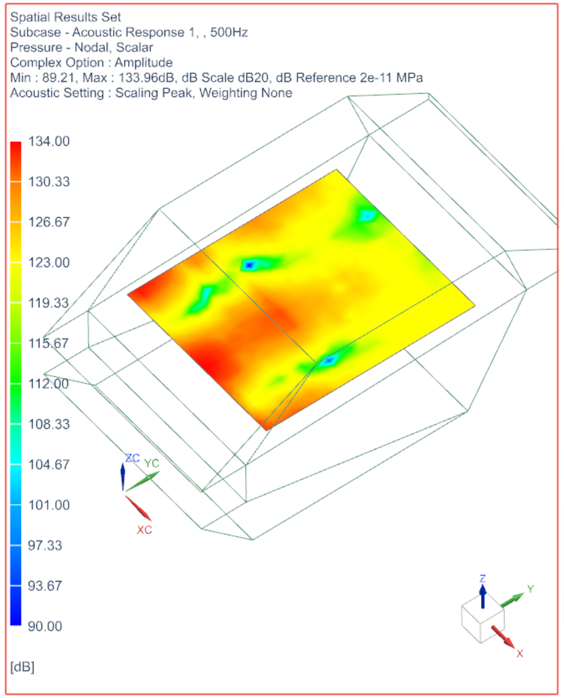
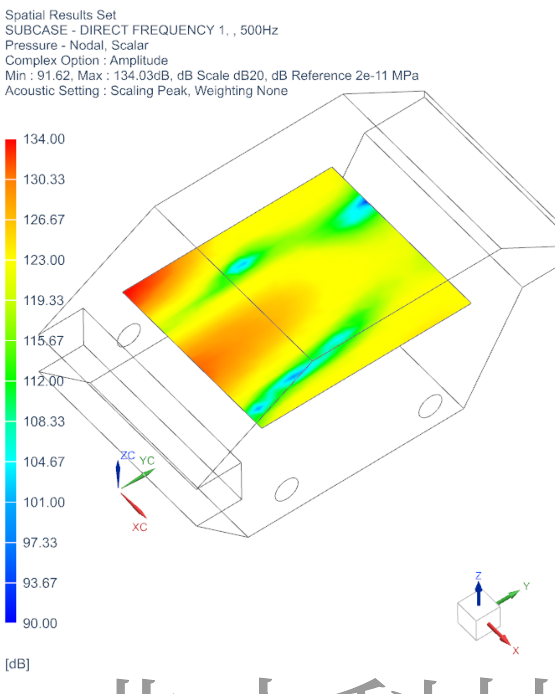
High frequencies 100 times faster!

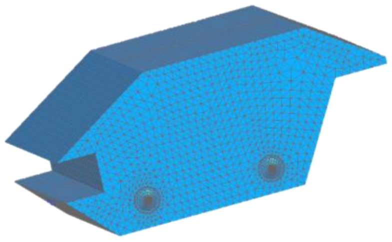
Ray Acoustics

FEMAO

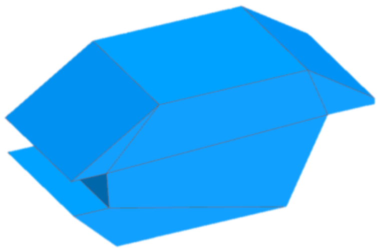




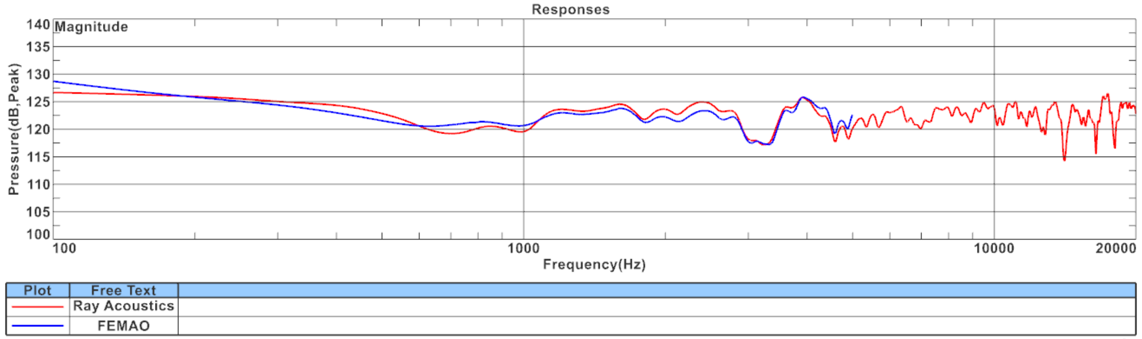
FEMAO



Ray Acoustics

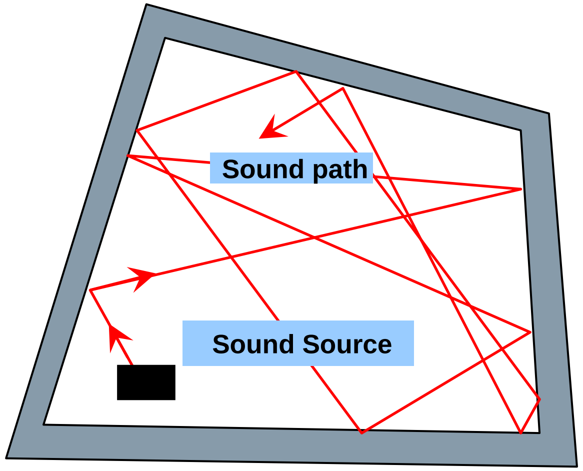


	FEMAO	Ray Acoustics
Frequency	100-5000 Hz	**0-20000** Hz
# Freqs	490	**2000**
Elements	45k	**21**
Solution time	X min	**X/150** mins

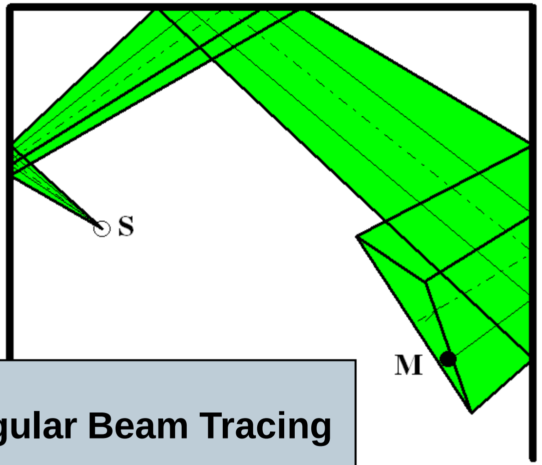


Ray Acoustics – supported technology

- At high Helmholtz number sound travels like rays.
- Surface modeling is sufficient, and discretization only needs to capture geometry detail, but is not depending on frequency!
- Absorption in air, and through reflections on surfaces, and diffractions on edges and surfaces are captured



- We can simulate sound by tracing rays shooting from a point source location: triangular beam tracing
- We keep track of which beams cross the receiver microphone and what their strength is when passing to get the overall response, per frequency line, including phase info



Triangular Beam Tracing

Simcenter 3D Ray Acoustics
Point Ray Source

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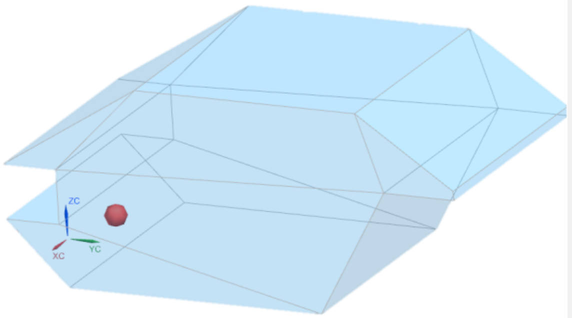
Flexible modeling of speakers as equivalent point sources

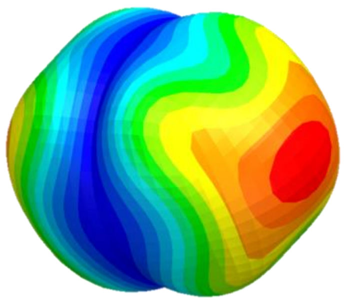
Complex amplitude (expressed pressure or power)
- Include delay as a phase shift
- Include a “real” signal and compute the output in time domain
- Attach a DSP filter to the source

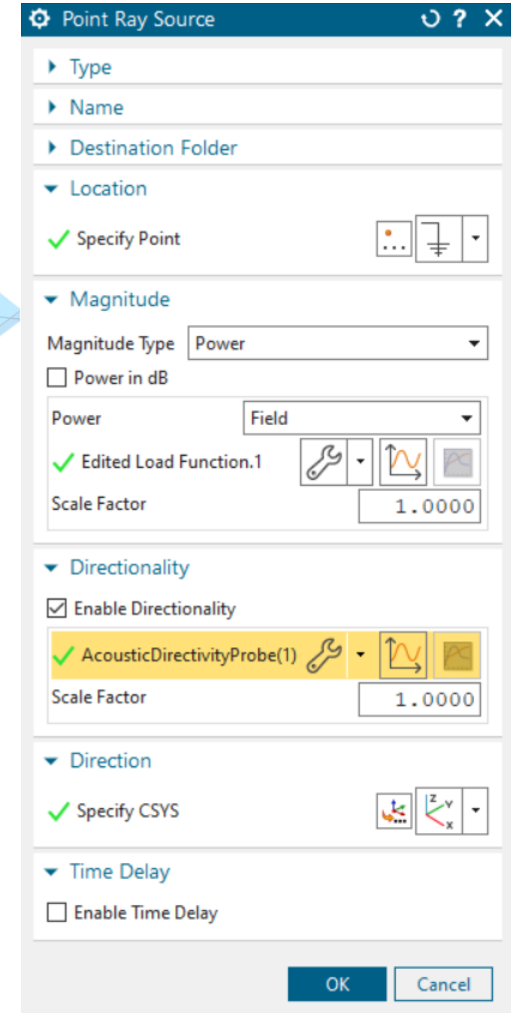
Spherical or hemispherical sources

Full 3D directivity
- Directivity can be expressed in a full sphere
- Can be imported from a **FEM/BEM solution**
- Easily **change the orientation** of the source with local CSYS

Time delay can be defined in the source







Simcenter 3D Ray Acoustics
Unique capabilities

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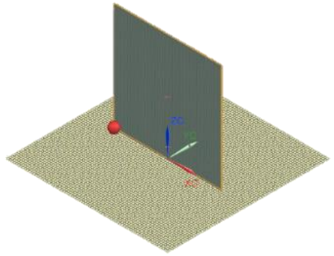
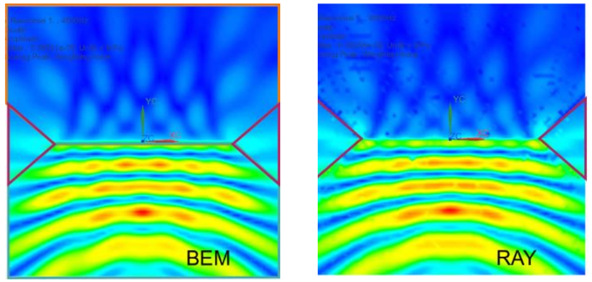
Ingenuity for life

Diffraction

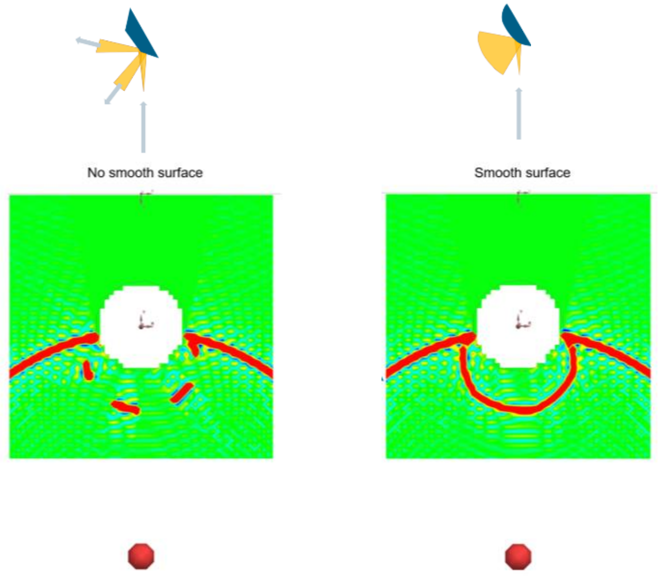
Account for both **edge and surface diffraction** (creeping waves)





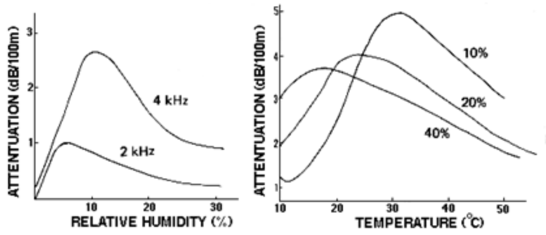
Smooth surfaces

Accurately captures **curvature** of discretized surfaces



Absorption

Use frequency dependent **surface impedance** or **absorption coefficients**
Account for **air absorption**



Auralization and sound quality

兆水科技應用案例

Simcenter 3D Ray Acoustics

Auralization and sound quality

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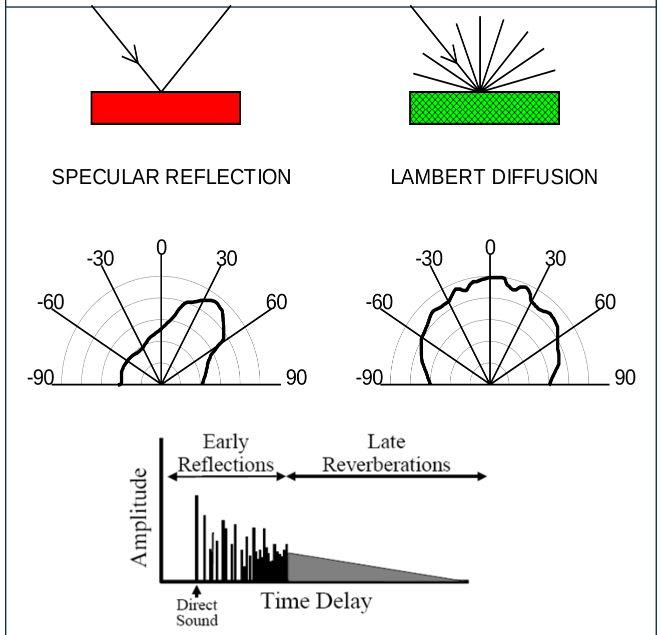
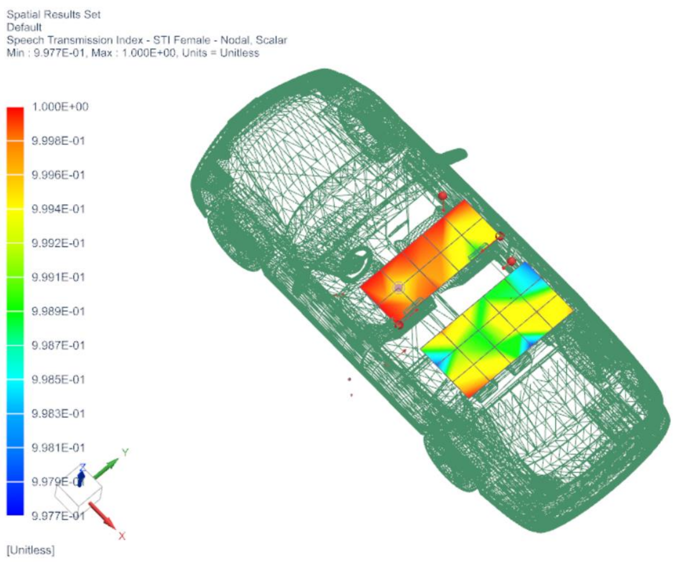
Wall diffusion and late reflections

Using particle tracing computation



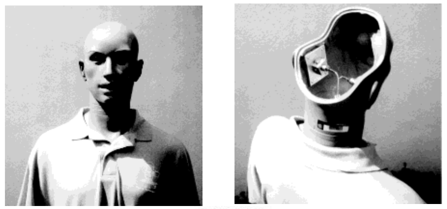
Sound Quality Parameters

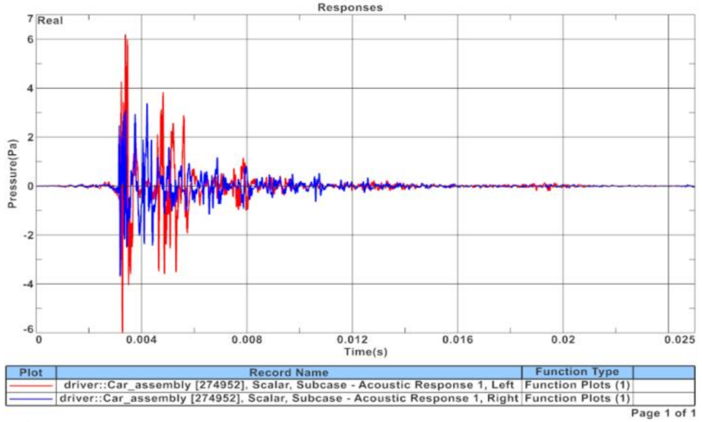
RT10, RT30, Clarity(C80)
STI,RASTI, IAAC,…



Auralization

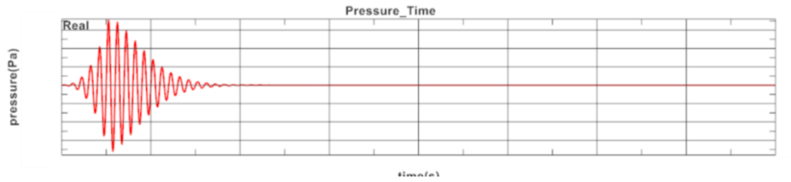
Export of time signals to wave file
Binaural responses

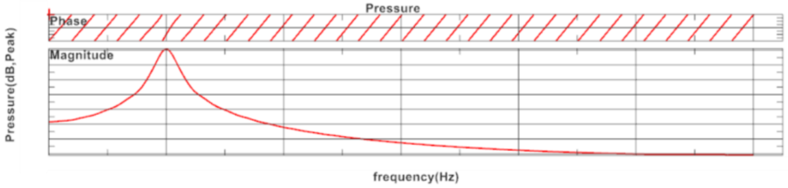




Auralization
Time-domain signal and export to audio file

1. FFT of Input signal can be used as modulation for your source

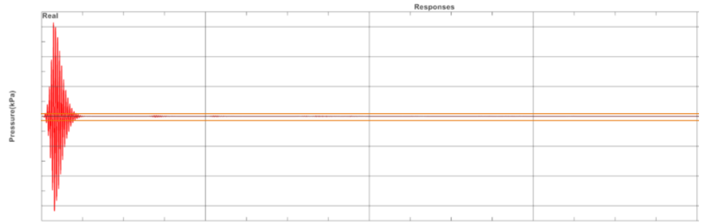




2. Ray Acoustics solution in narrow band for the full audio range
   - Take into account installation effects (car cabin geometry, trim package changes…)

3. Output **time domain response** (based on inverse FFT)

4. Play the sound in Simcenter 3D or export it into an **audio file**



Binaural Response
Head Related Transfer functions

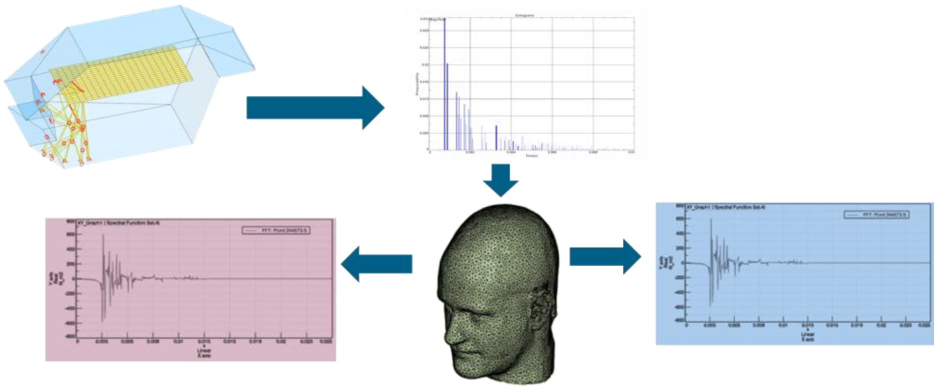
Transformation of ray acoustics results into Binaural Impulse Response (BIR)

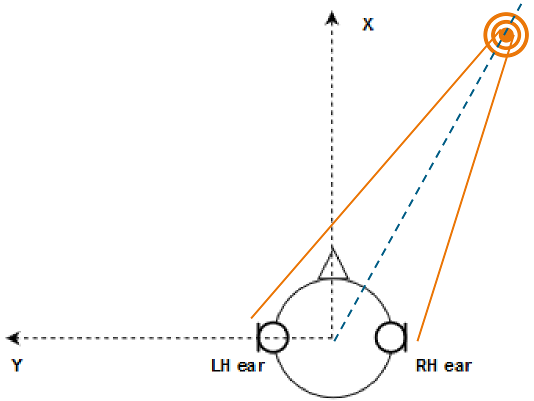
Stored as a stereo audio file format

Performed for each field point selected during the analysis case definition

Depends on the view angle = viewing direction of the binaural head in each field point:

- To request BIRs we need to define the axis system of the head
- The arrival angle is computed for each ray





Interior Acoustic Simulation for In-Car Audio Design
Hyundai Motor Company

SIEMENS
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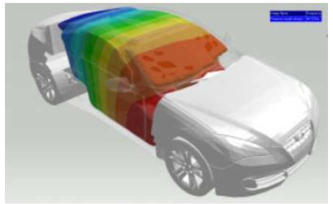
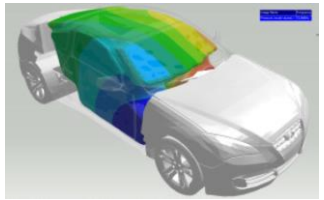
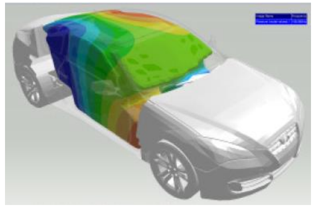
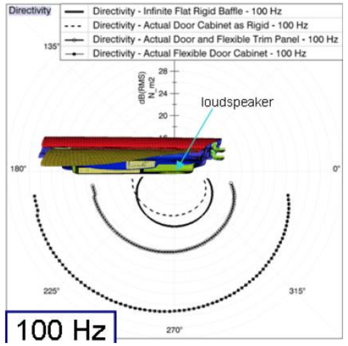
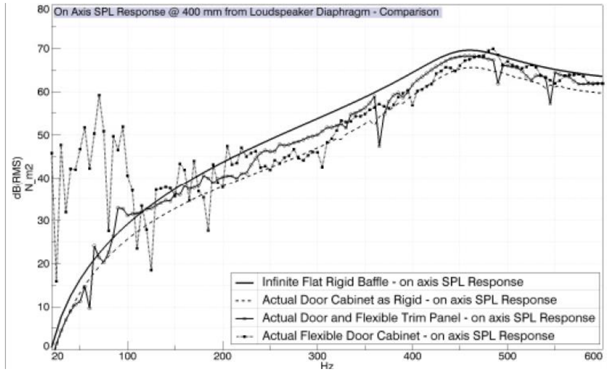
Investigate a set of vibro-acoustic simulation tools for full frequency In-car Audio Design

- FEM Acoustics: for **cavity modes** and **door acoustics**
- Fully coupled vibro-acoustics FEM/BEM: for **automotive door design**
- Ray Acoustics for response **above 5kHz**, **sound quality criteria** and **binaural** response





Validation of results with experimental data

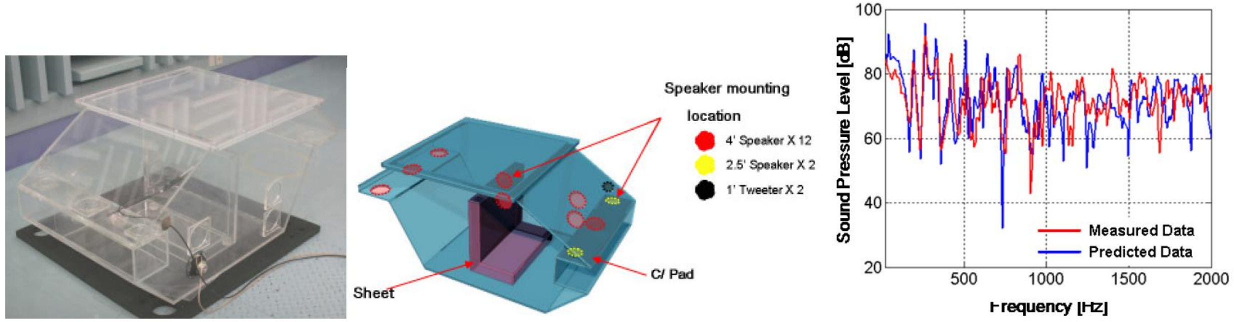


Figure 11 – Validation of BEM simulation in a ½-scale Acryl Car Interior

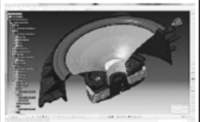
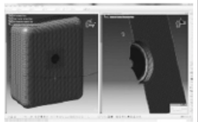
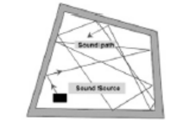
From Internoise 2011 (Osaka, Japan)

Car Audio Design
Denso-Ten / Fujitsu-Ten

SIEMENS
Ingenuity for life

From Fujitsu-Ten Technical Journal *NO.38(2013).*

Table 1 Acoustic analysis methods

	FEM	BEM	Sound ray tracing method
			
Characteristic	An object is divided into elements inside of it. Method focusing on internal behavior	Only the surface of an object is divided into elements. Method focusing on surface behavior Infinite radiation problem is figured out.	Method focusing on reflection and diffusion, treating sound as beam Analysis precision is reduced in low band.
Analysis upper limit frequency	A side length of an element: 1/6 of the wavelength e.g.) Analysis upper limit frequency: 20kHz A side = (340 [m/s] / 20 [kHz]) / 6 = 0.28 [mm] An object is divided into elements whose side length is 0.28 mm.		No limit
Calculation time	Proportional to the square of the number of elements		Proportional to the frequency of reflection and the number of sound rays

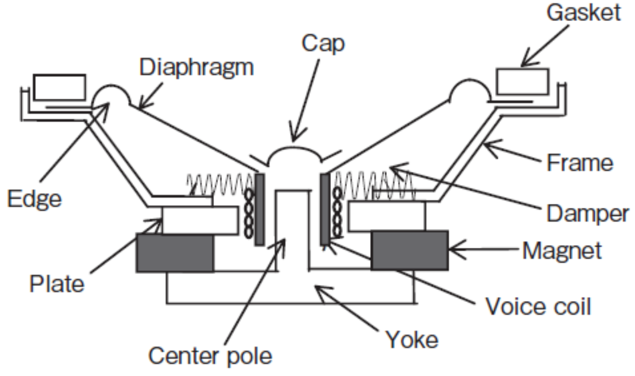


Fig.1 Cross-sectional view of loudspeaker

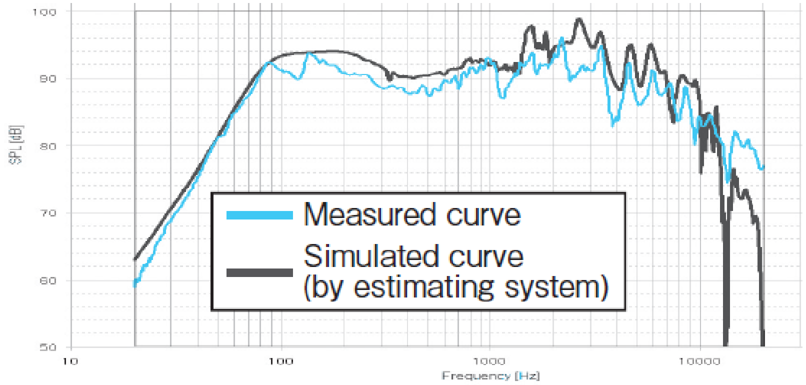


Fig.3 Comparison of frequency response between measured curve and simulated curve

Table 4 Analysis method suitable for the characteristics of each band

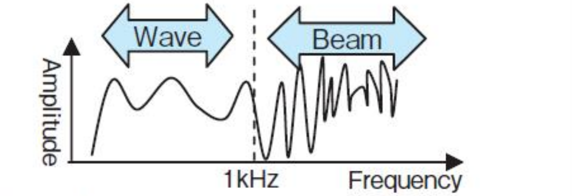
		
Charac-teristic	Sound is steady. It is calculated by wave equation.	Linear sound beam It is calculated by geometry and statistics.
Method	BEM	Sound ray tracing method

Fig. 4 (a) shows an example of distribution of sound pressure in the vicinity of the listening position by BEM, and (b) shows an example of the direction of arrival of sound by the sound ray tracing method.

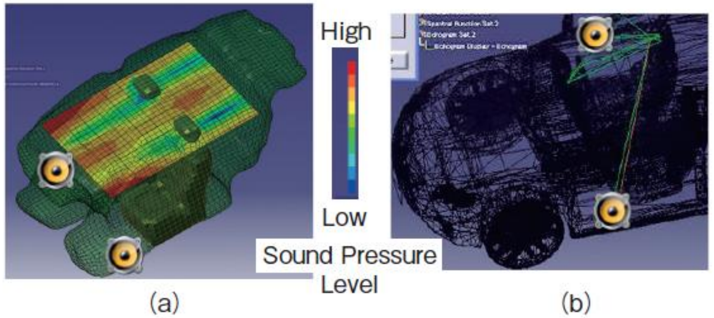


Fig.4 (a) Distribution of sound pressure in the vicinity of listening position by BEM
(b) Direction of arrival of the sound by Sound ray tracing method

Thank you.