Vibroacoustic analysis of a gearbox

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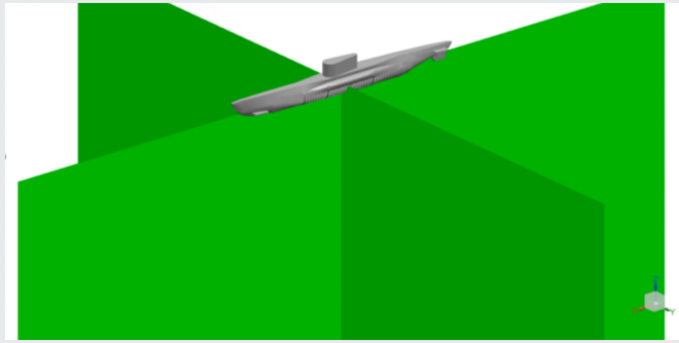
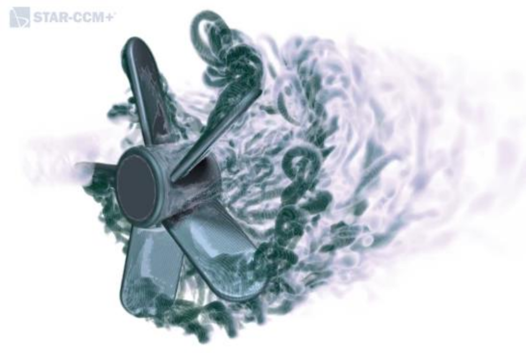
Introduction
What is Acoustics?

Acoustics = Study of compressional waves in a fluid medium

Source

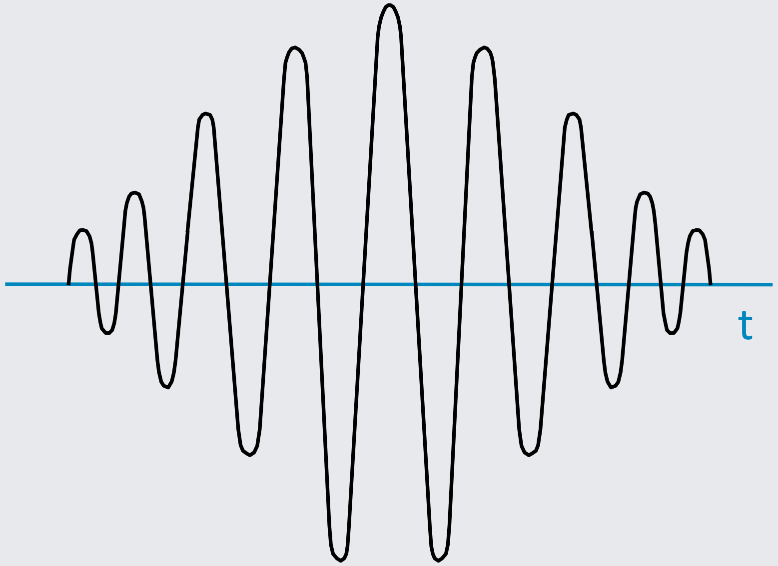
- Vibrating body
- Air turbulences





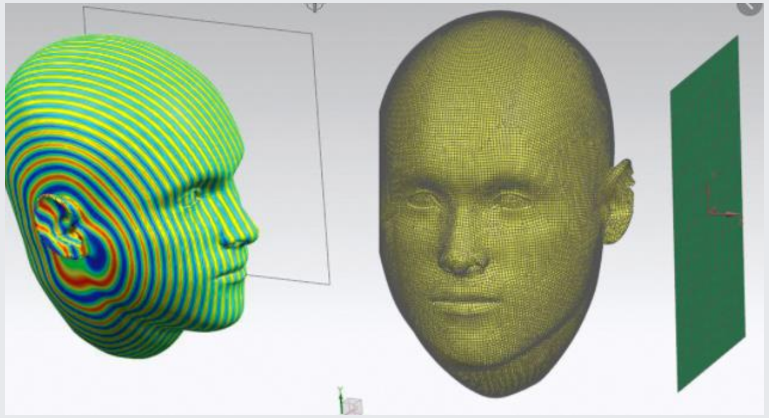
Propagation

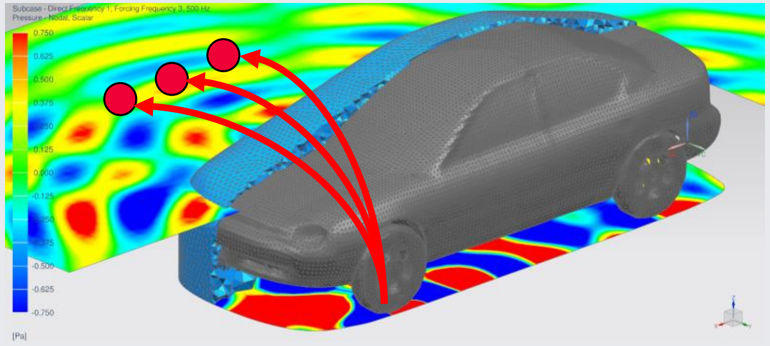
- Sound path and absorption
  - Airborne
  - Structure-borne
  - Mixed



Receiver

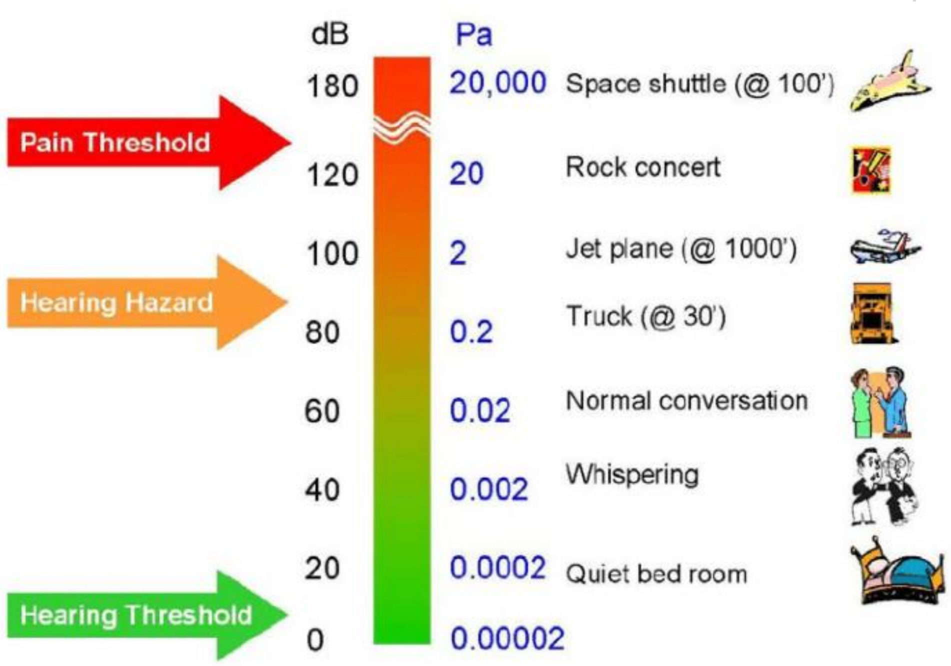
- Microphone, ear

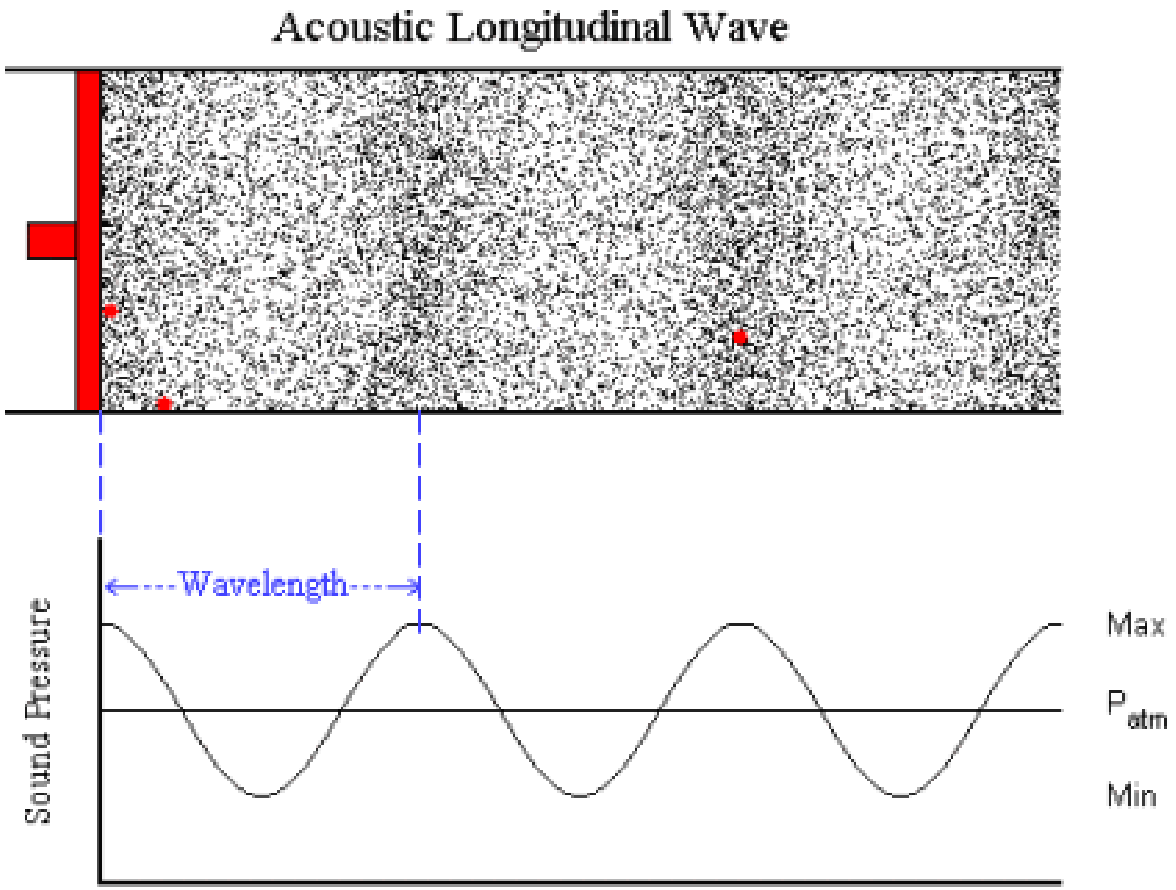




DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service
KIT Karlsruhe Institute of Technology
UNIVERSITY OF PATRAS

Introduction
What is Acoustics?





Source:
http://blog.soton.ac.uk/soundwaves/wave-basics/the-nature-of-waves/

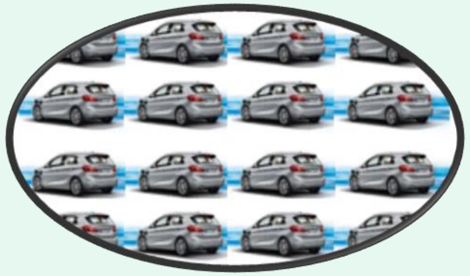
isvr

- Sound = **Small variations** of an acoustic medium around a state of equilibrium (**linear acoustics**):

$$p(t) = p_0 + p'(t)$$

$$p_0 = 101300 \text{ Pa}, |p'(t)| \sim \text{typically } 0.01 \text{ Pa} - 20 \text{ Pa}$$

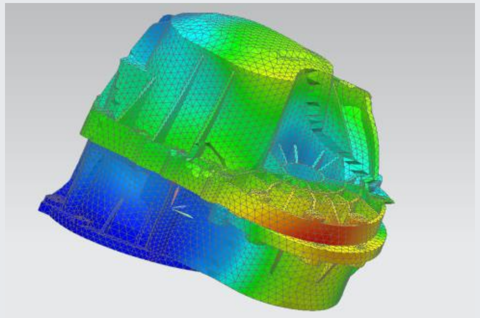
Introduction
Why Acoustics Simulation?

Key Trends		Key Implications		
Electrification	**Globalization**	**Regulation**	**Comfort**	**Productivity**
		• Pass-by, fly-over, wayside, ICAO, AVAS; environment 	• Sound quality, low noise, brand image, energy labels 	• Mass customization, variant explosion; simulation vs test 
Brand Identity	**Connectivity**	**Cost Reduction**	**Fuel Economy**	**Failure Reduction**
		• Less material (easier vibro-acoustic coupling) 	• Lightweight (transparency to more noise sources) 	• Structure resilience to high noise environment 

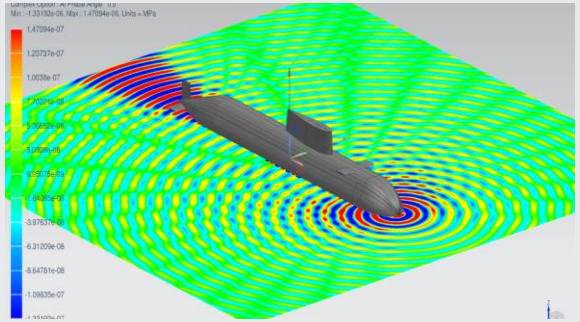
Introduction
Why Simcenter 3D Acoustics?

Ability to Capture All Relevant Physics

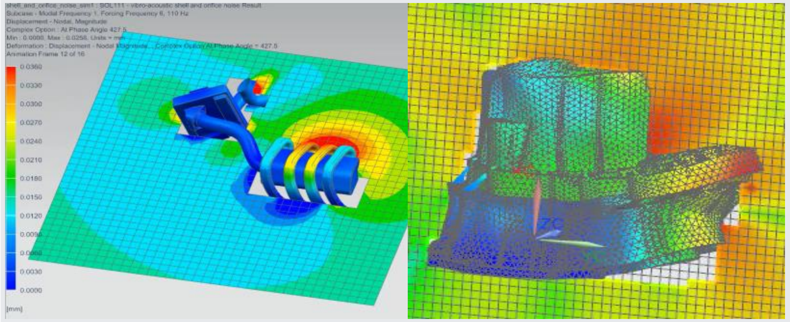
Structural
Only vibration is studied + Optionally ERP



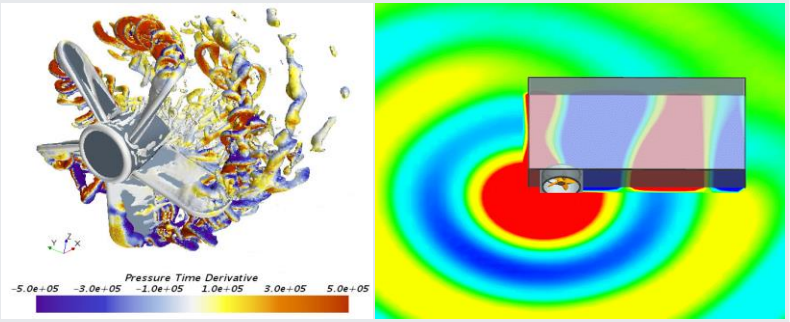
Acoustic
Only fluid is involved in noise propagation



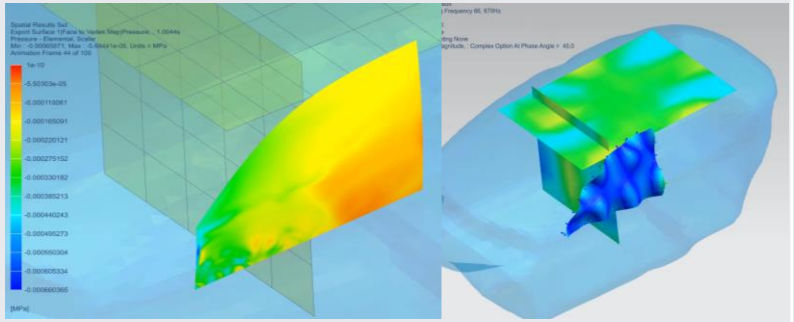
Vibro-Acoustic
Noise propagation through structure-fluid interaction



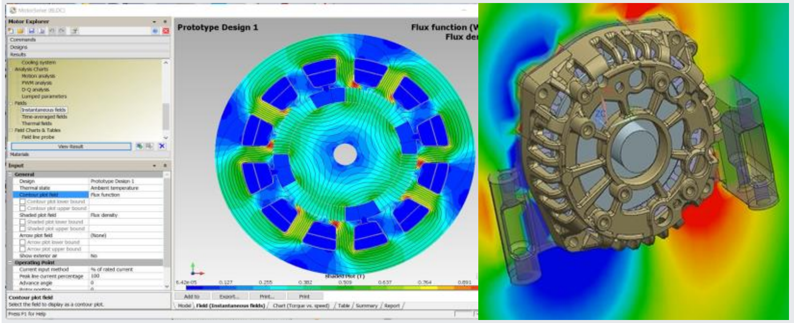
Aero-Acoustic
Turbulent flow makes noise on its own



Aero-Vibro-Acoustic
Turbulent flow make structure vibrate, radiate noise



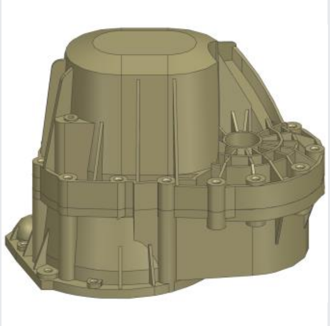
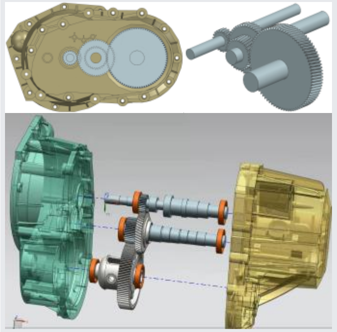
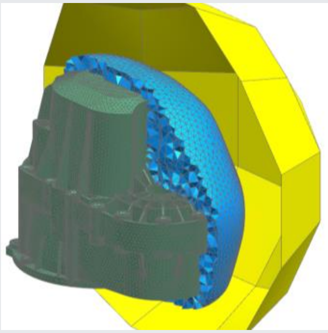
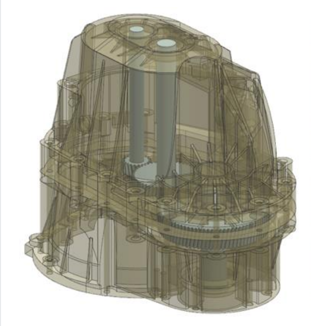
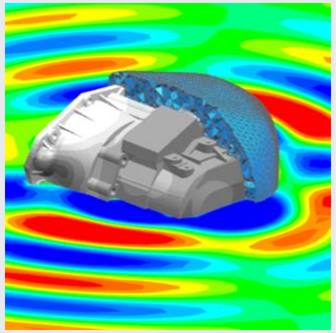
Electro-Magneto-Vibro-Acoustic
EM forces make structure vibrate, radiate noise



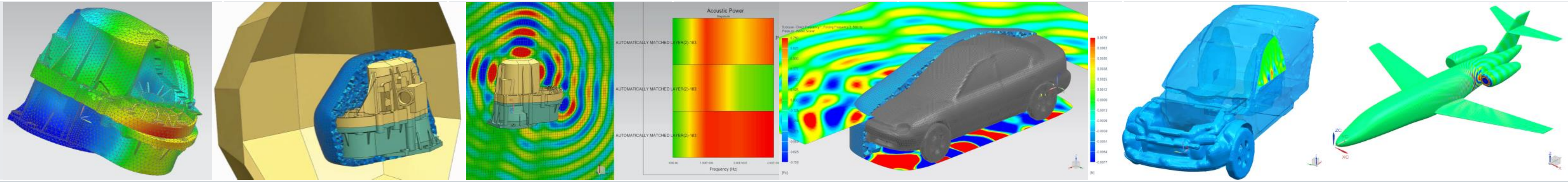
Introduction

Why Simcenter 3D Acoustics? *WORKFLOW*

Unique Combination of Process Efficiency and Expertise

CAD	Assembly	Meshing	Pre-Processing	Solver	Post-Processing	Optimization
				**Simcenter Nastran** **Simcenter 3D Acoustics BEM** **Simcenter Ray** **Ansys** **Abaqus**		HEEDS

Range: Structural & Acoustics Meshing, CAD or Orphan FE based, Synchronous Modeling, Simcenter Nastran/Acoustics BEM, Contribution Analysis, Optimization…



Depth: Acoustic Technologies – FEM AML, FEMAO, RDMODES, Aero-Acoustics, Conservative mapping, FSI, ATV, VATV, duct modes, high-end BEM methods…

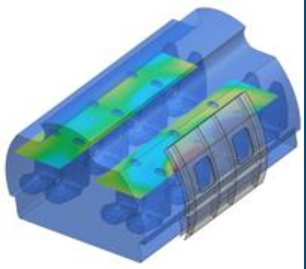
Simulation Data Management

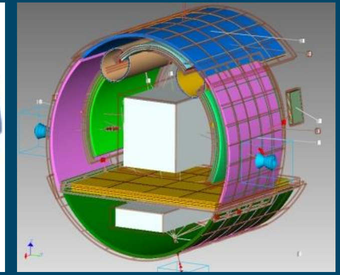
Introduction

Why Simcenter 3D Acoustics? *EXAMPLES*

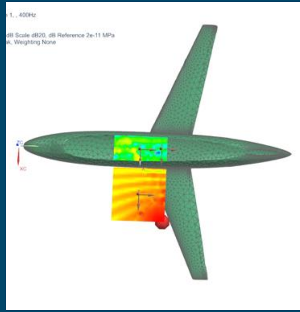
AERONAUTICS

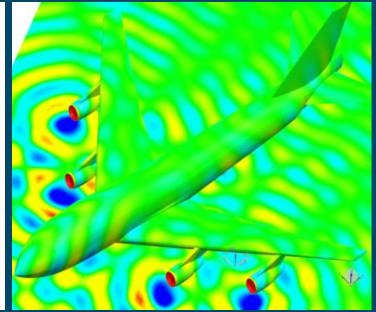
Cabin Noise from Turbulent Boundary Layer and Shock Cells, Panel Transmission Loss

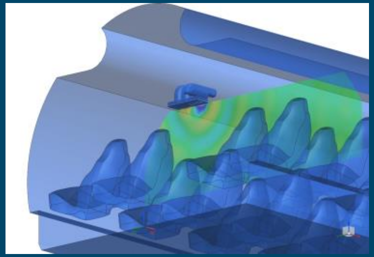




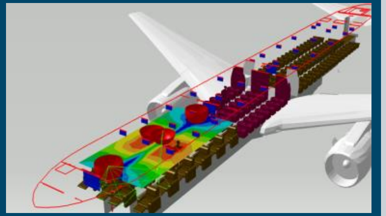
Cabin Noise from Aeroengine or Propeller, or from ECS System



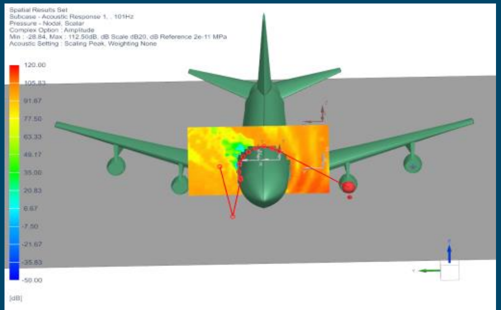




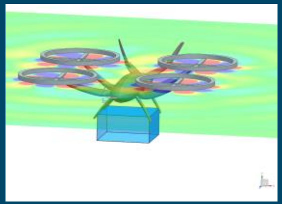
Cabin Audio Quality and Speech Intelligibility

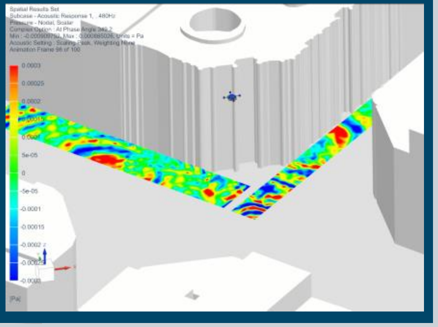


Ramp Noise on Ground



Flyover Noise: Airframe, Aeroengine, Propeller



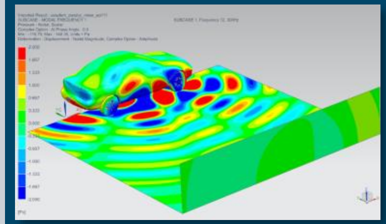


Introduction

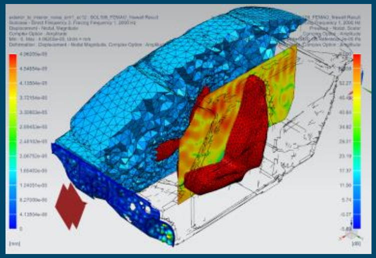
Why Simcenter 3D Acoustics? *EXAMPLES*

AUTOMOTIVE

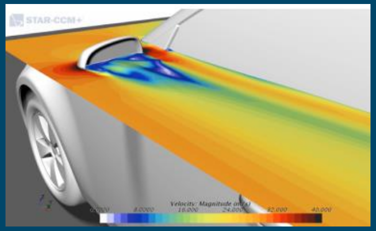
Pass-by Noise from PWT and Tires and AVAS



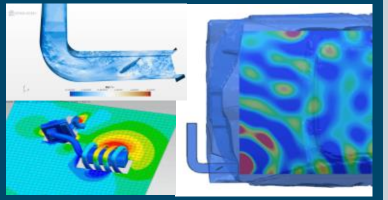
Cabin Noise from PWT and Road Loads



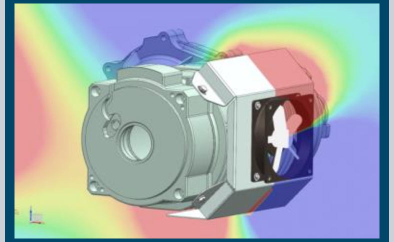
Wind Noise



Intake/Exhaust Noise HVAC Noise

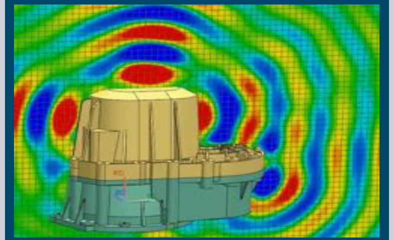


Electric Motor Noise



Low Speed Nearfield Sensing (ADAS/Parking Sensor)

Gearbox Noise

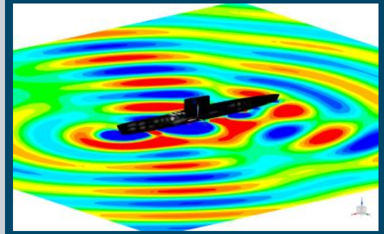


Introduction

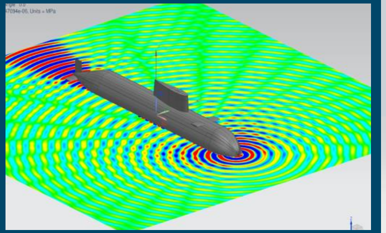
Why Simcenter 3D Acoustics? *EXAMPLES*

MARINE

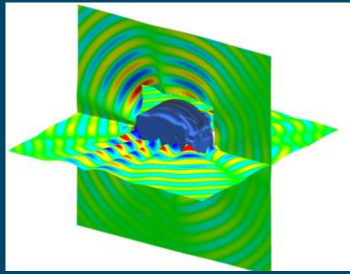
Hull Radiation



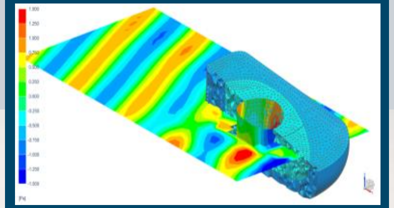
Hull Scattering (SONAR Target Echo Strength)



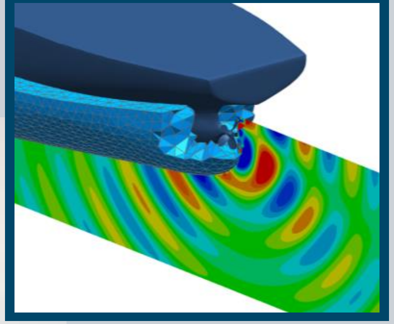
Diesel & Electric Motor and Gearbox PWT Noise



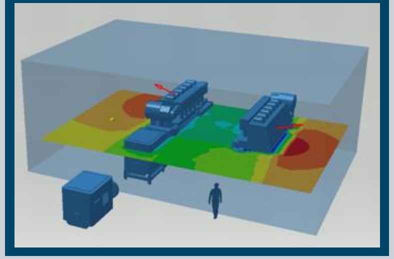
SONAR



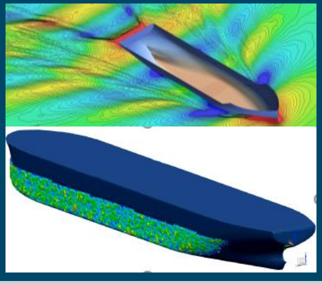
Propeller Noise



On-Deck and Engine Room Noise



Turbulent Boundary Layer Noise

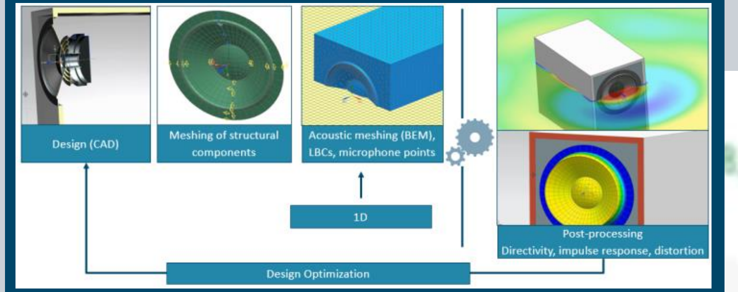


Introduction

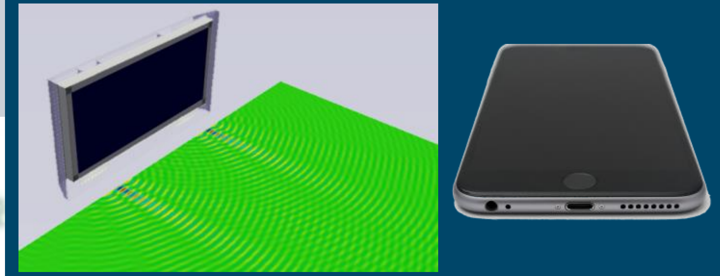
Why Simcenter 3D Acoustics? *EXAMPLES*

ELECTRONICS

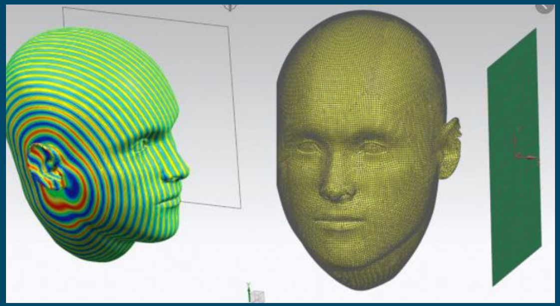
Loudspeaker Design



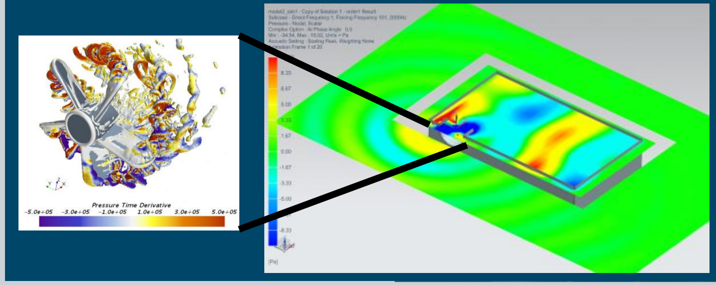
Integrated Loudspeaker and Microphone: TV, Smartphone, Tablet, Gaming Console…



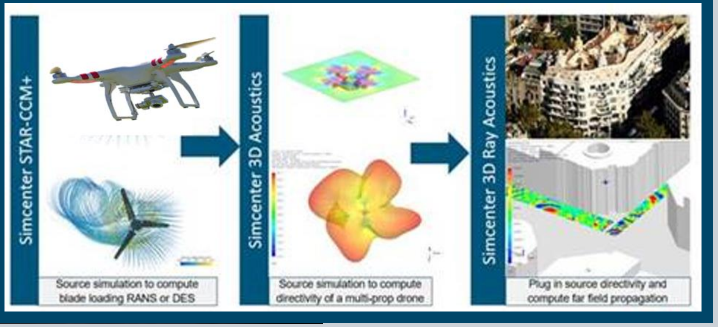
Cabin Audio Quality and Speech Intelligibility



Fan Noise from Brown Goods: Laptops, Server Rooms, Projectors…



Drone Noise

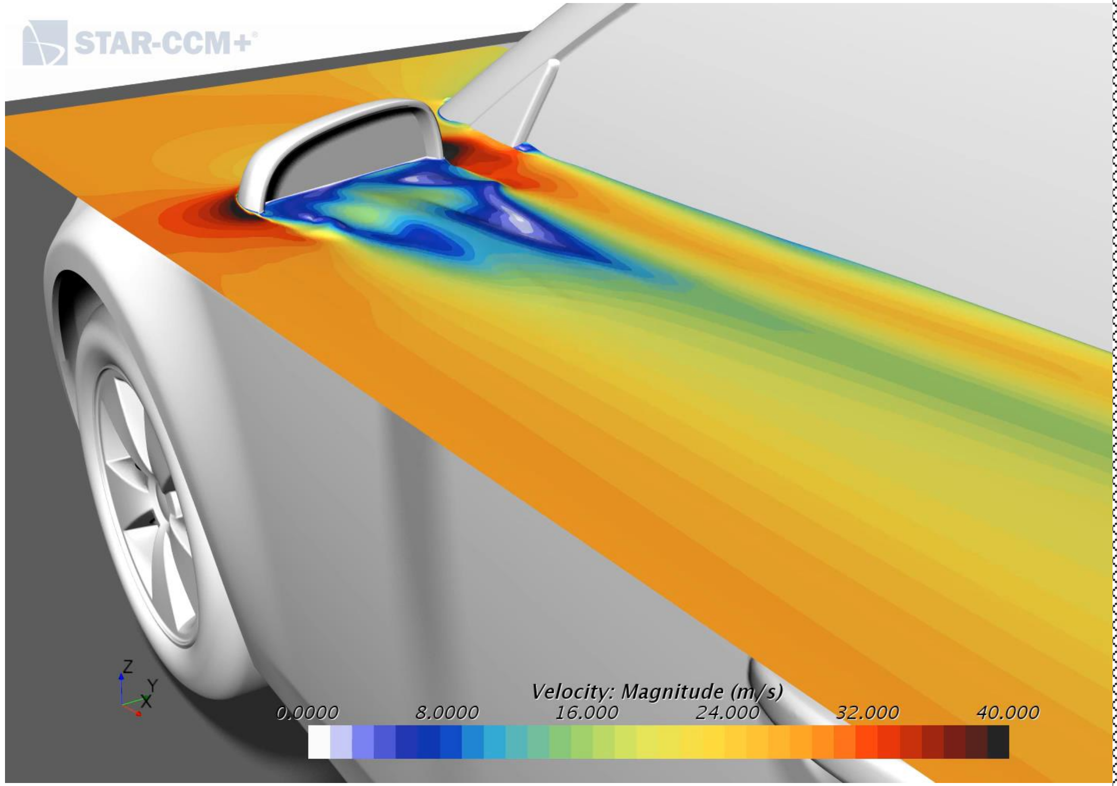


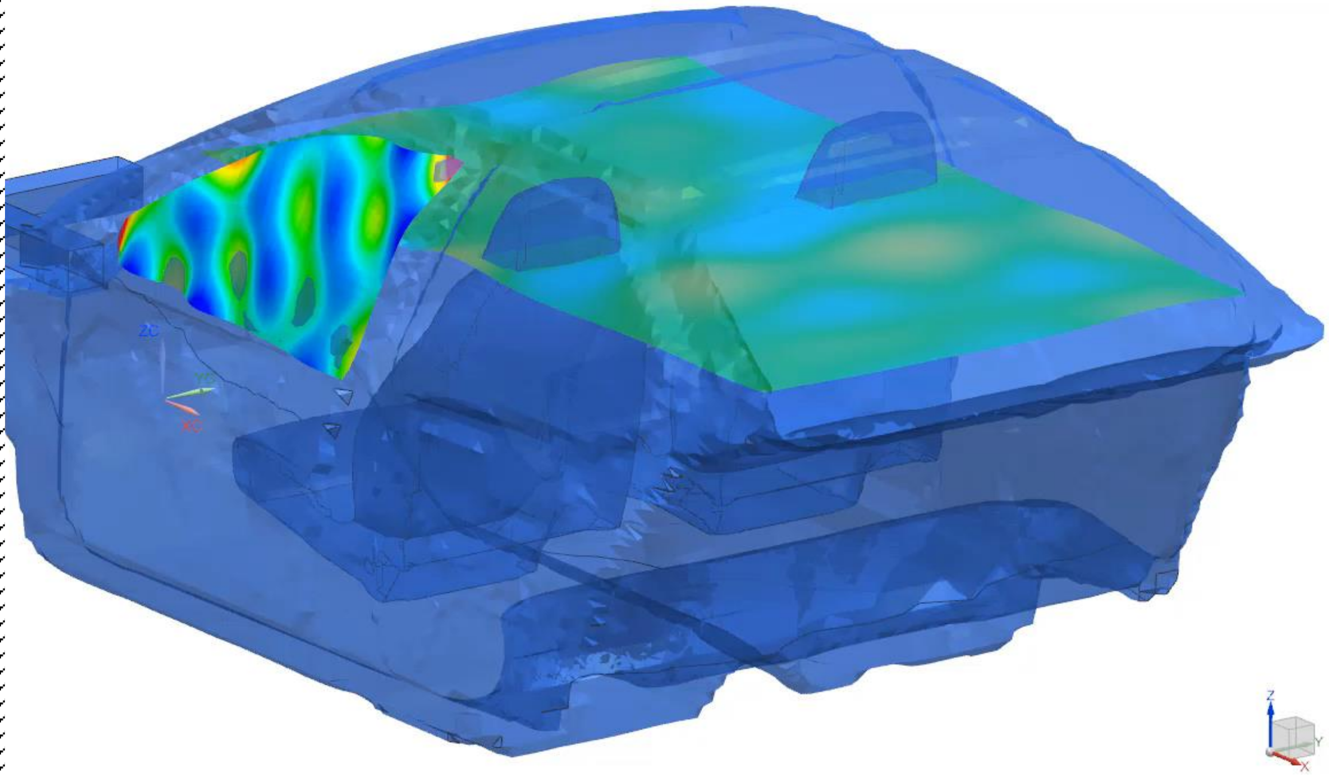
EXAMPLE 1

1. Fan Noise

Typical workflow to solve aero-acoustics

Aerodynamic Pressures Field → Map Pressures on Structural Model → Vibro-Acoustics Solution





Leverage synergies between Simcenter 3D and Simcenter STAR-CCM+

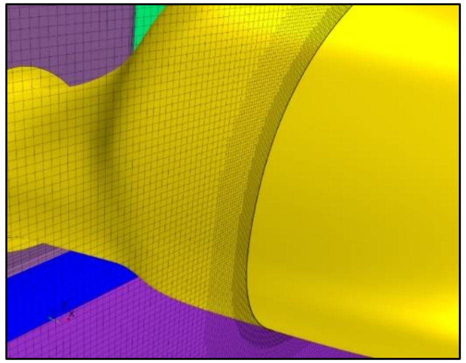
Simcenter STAR-CCM+ | **Simcenter 3D Acoustics**

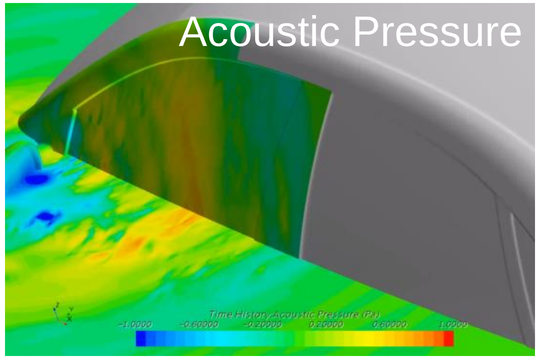
Geometry Preparation
Meshing Exterior

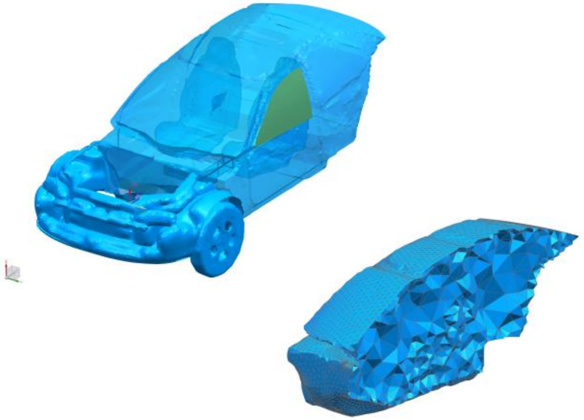
→ External Flow
External Noise

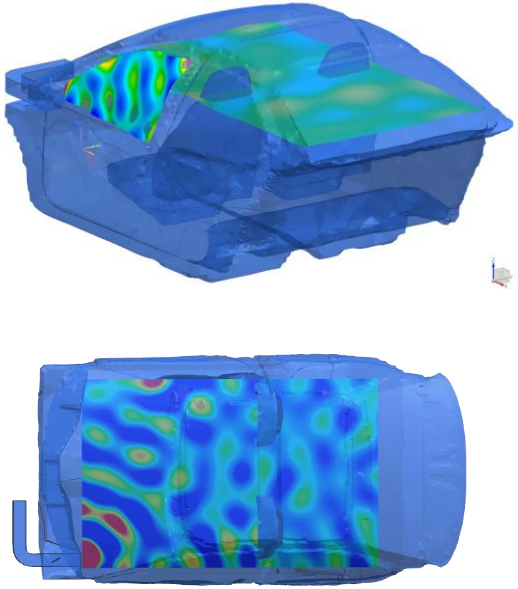
→ Geometry Preparation
Meshing Interior

→ Interior Noise









Finite Element Method Adaptive Order (FEMAO)

- The Finite Element Method Adaptive Order (FEMAO) method is a higher-order polynomial technique that provides more accurate and faster solutions for acoustic and vibro-acoustic analyses than previous methods.

- You can use the FEMAO method for one-way coupling vibro-acoustic analysis, two-way coupling vibro-acoustic analysis, and uncoupled acoustic analysis.

- You can use the FEMAO method for prediction of acoustic transfer functions for pass-by noise, prediction of engine intake noise for aero-engine, perfection of transmission loss for an industrial muffler, and so on.

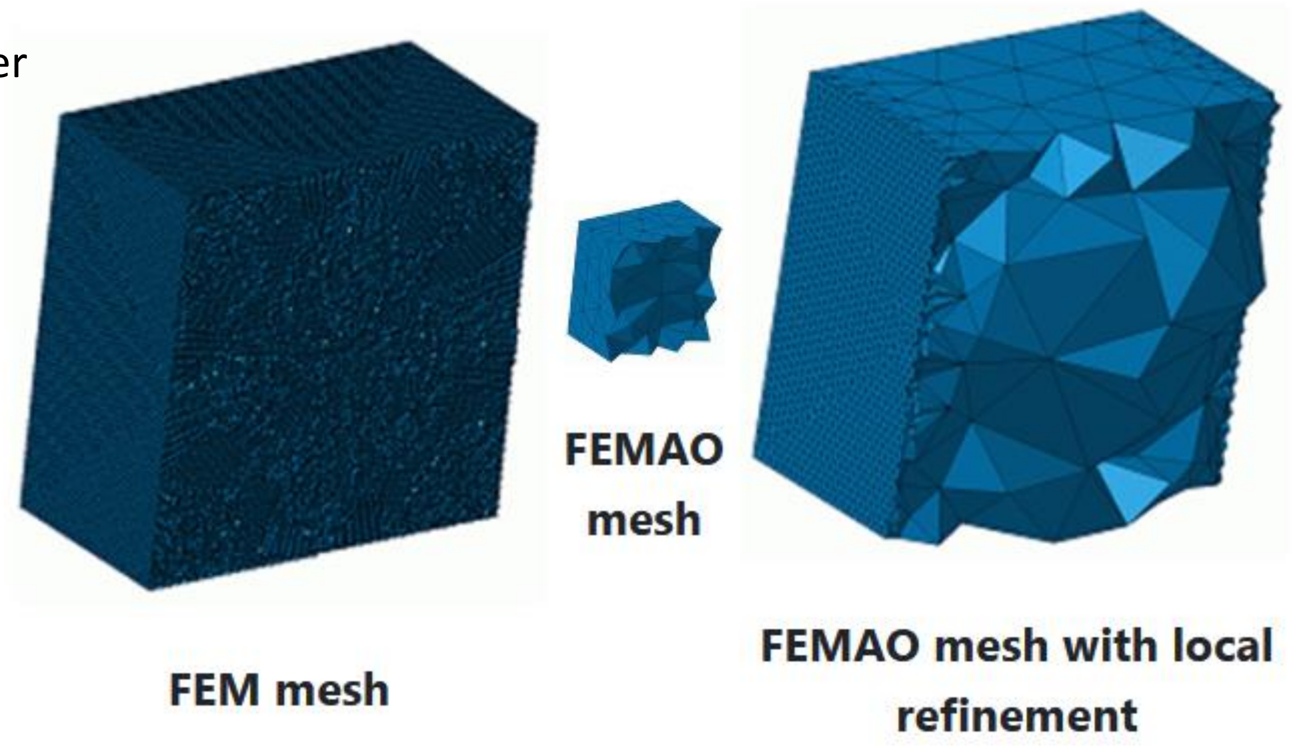
Benefits of FEMAO over standard FEM

- Improved accuracy. FEMAO adjusts the element order (shape functions) automatically, which provides greater accuracy. FEMAO automatically adapts the order, and the model is represented each time with the correct number of degrees of freedom to reach the desired accuracy.

- Improved performance through adaptability.

- Improved performance through shape function efficiency.

- Improved performance in pre-processing.



Example Workflow:

Import CFD data to vibro-acoustic model → **Map the data to correct model locations** → **Add Fan noise segmentation** → **Create Vibro-acoustic solution**

Map the data to correct model locations:

- Map the CFD fan mesh to transient fan blade elements.
- convert to fan blade force excitation

Add Fan noise segmentation: applied as a source using an equivalent acoustic rotating force

Create Vibro-acoustic solution: apply the excitation as a fan blade load to the acoustic solution to excite the acoustic fluid.

↓

Add BC → **Solver Settings** → **Solve** → **Post-Processing**

Part 2

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REVIEW PAPER
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A Review of Recent Advances in Design Optimization of Gearbox

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ORCID: 0000-0001-9803-0272

KEYWORDS: Gearbox, Design optimization, Macro geometry, Micro geometry, NVH, Strength

Gearboxes find extensive use in a wide variety of fields. Over the years, a great deal of research has been devoted to prevention of gear failures and gear noise. Devising an optimal design is often considered as the most important stage in the development of a new gearbox. Similar to the varying requirements of different applications, the directions and method of gearbox design optimization are also varied. Usually, gear geometry optimization has a great influence on the strength and transmission error which is the excitation factor that affects the noise level. The main objective of this article is to summarize common optimization methods that have been recently studied by scholars. Moreover, a review of recent patents status quo, both domestic and overseas, is carried out.

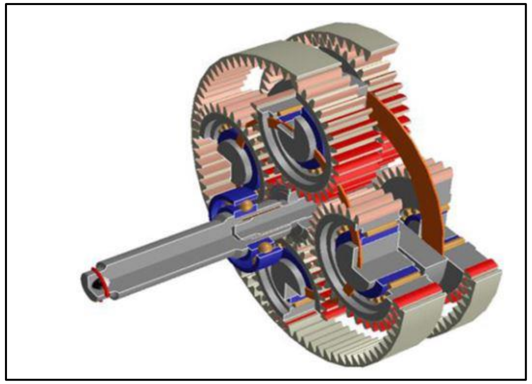
Manuscript received: July 14, 2018 / Revised: August 29, 2018 / Accepted: September 10, 2018 (Invited Paper)

1) Automobiles, aircrafts, wind turbines, industrial machinery

2) Prototyping costs

3) High quality gearboxes with low noise emission

4) Legal issues



Components: Gears, bearings, shaft, housing. Oil is used to reduce gear abrasion and heat generation

Measurement 100 (2017) 139–149

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

A CAD-FEM-QSA integration technique for determining the time-varying meshing stiffness of gear pairs

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Quasi-static algorithm
Time-varying
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Gear

ABSTRACT

Estimation of time-varying meshing stiffness (TVMS) is a vital process as it is one of the primary sources of vibration and noise. There are two ways to evaluate the TVMS, the analytical method (AM) and the finite element method (FEM). Owing to the complex geometries and the use of empirical values, analytical model is not precise to perform the exact calculation. The current FEM is inconvenient due to the use of complex programming codes. Therefore, the first aim of this study is to develop a new technique to determine the TVMS based on NX, ANSYS Workbench, and Quasi-static Algorithm (QSA). The second aim is to compare results of the analytical method (AM) and the proposed method. The effects of tip radius and misalignment of gear pair are also analysed using this new method.

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Gearbox Noise & Vibration Prediction and Control

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Abstract - This paper will review practical techniques and procedures employed to quiet gearboxes and transmission units. The author prefers solving the gear noise problem at the very source to introduce an enclosure as a means to reduce radiated noise, which seems to be easy but its effect on the sound pressure level is small. The gearbox noise problem solution is focused on the improvement of gear design; on the verification of its effect on the radiated noise and the determination of the gears' contribution to the truck's or car's overall noise levels and on the analytical and/or numerical computer-based tools needed to perform the signal processing and diagnostics of geared axis systems. All of the analytical methods are based on the time and frequency domain approach. Special care is addressed to the smoothness of the drive resulting from the transmission error variation during a mesh cycle. This paper will review the progress in technique of the gear angular vibration analysis and its effect on gear noise due to the self excited vibration. This presentation will include some examples of the use of such approaches in practical engineering problems

Key Words: Gear Noise, Gearbox Vibration, Taguchi Method, Tools for Gearbox vibration analysis, etc .

categories: driving noise, paper noise, and mechanical noise. Driving noise is produced by the operation of rotating parts such as motors, gears, the laser scanning unit (LSU), and fans. Paper noise is caused by friction and the impact of paper through the paper path of the laser beam printer. Finally, mechanical noise is produced in the pick-up, actuator, clutch, cam, etc., which all control the rotating parts. A dominant source of driving noise is the vibrations due to transmission error (TE) of the gears. TE of the gears has been studied extensively in attempts to reduce printer noise and vibration. Usually, the gear noise that results from the meshing of gear teeth is transmitted via forces and motions to the shafting, bearing, and transmission housing where it is then radiated to the surroundings, as depicted in Fig. 1 [2, 3]. Non-measurable factors for gear design such as temperature and material humidity are not major contributors to TE. However, both TE and noise are influenced by the load on the gears [4]. In this sense, Houser designed optimal gears that gave minimum noise and stress by using a unique method such as Run-Many- Cases [5]. Also, an attempt was made to reduce the gear noise by either reducing the excitations at the mesh via minimizing the dynamic forces due to TE or by reducing the force transmissibility from the mesh to the noise-radiation surface [6].

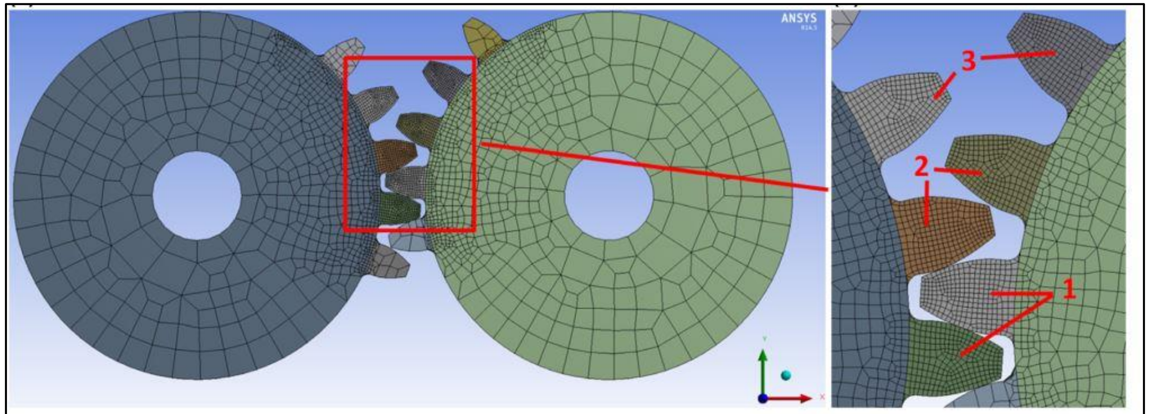


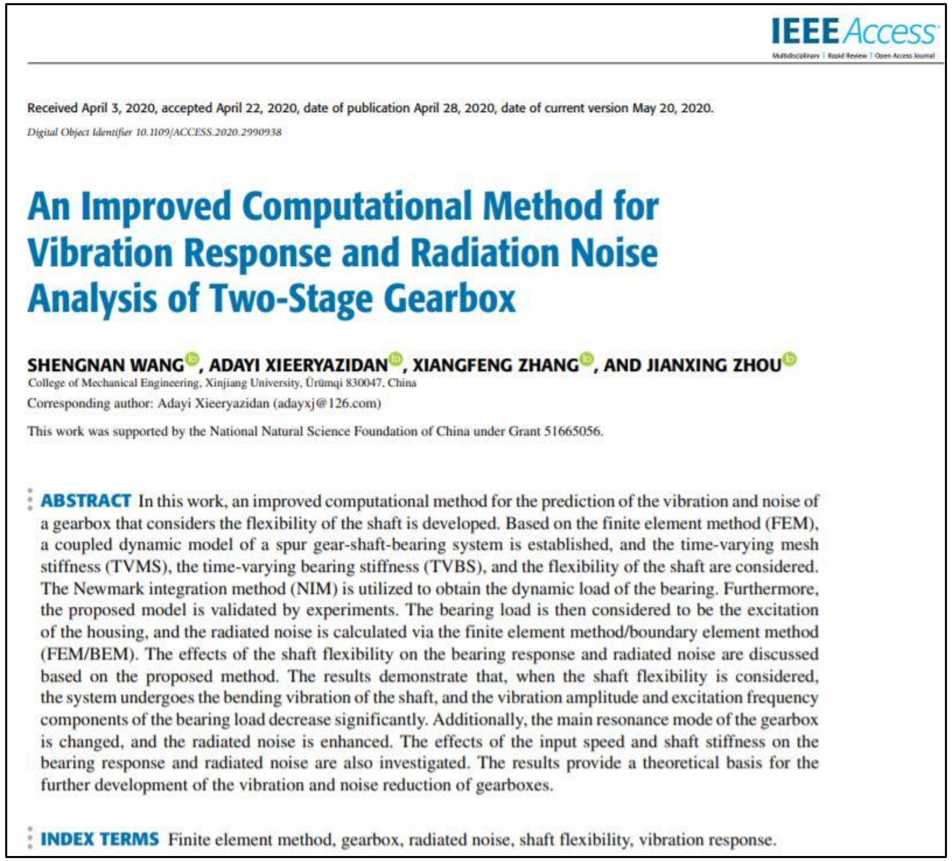
Fig. 9. Finite element model of meshing pair: (a) general mesh a gear pair; (b) enlarged fine mesh of three teeth pairs.

Gearbox noise is **tonal**: The noise frequency spectrum consists of sinusoidal components at discrete frequencies with low-level random background noise

- Main source of noise: **Transmission error**
- **Transmission error (TE):** Difference between the actual position of the gear and its theoretical position
- Sources of TE: Bending of the gear teeth, defects, dynamic behavior of the gearbox
- Other noise sources: shaft unbalance, misalignment, bending (Low frequency vibration)

Numerical methods and modelling

Accurately capturing the impact of non linearities (contact) requires detailed models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An Improved Computational Method for Vibration Response and Radiation Noise Analysis of Two-Stage Gearbox

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This work was supported by the National Natural Science Foundation of China under Grant 51665056.

ABSTRACT In this work, an improved computational method for the prediction of the vibration and noise of a gearbox that considers the flexibility of the shaft is developed. Based on the finite element method (FEM), a coupled dynamic model of a spur gear-shaft-bearing system is established, and the time-varying mesh stiffness (TVMS), the time-varying bearing stiffness (TVBS), and the flexibility of the shaft are considered. The Newmark integration method (NIM) is utilized to obtain the dynamic load of the bearing. Furthermore, the proposed model is validated by experiments. The bearing load is then considered to be the excitation of the housing, and the radiated noise is calculated via the finite element method/boundary element method (FEM/BEM). The effects of the shaft flexibility on the bearing response and radiated noise are discussed based on the proposed method. The results demonstrate that, when the shaft flexibility is considered, the system undergoes the bending vibration of the shaft, and the vibration amplitude and excitation frequency components of the bearing load decrease significantly. Additionally, the main resonance mode of the gearbox is changed, and the radiated noise is enhanced. The effects of the input speed and shaft stiffness on the bearing response and radiated noise are also investigated. The results provide a theoretical basis for the further development of the vibration and noise reduction of gearboxes.

INDEX TERMS Finite element method, gearbox, radiated noise, shaft flexibility, vibration response.

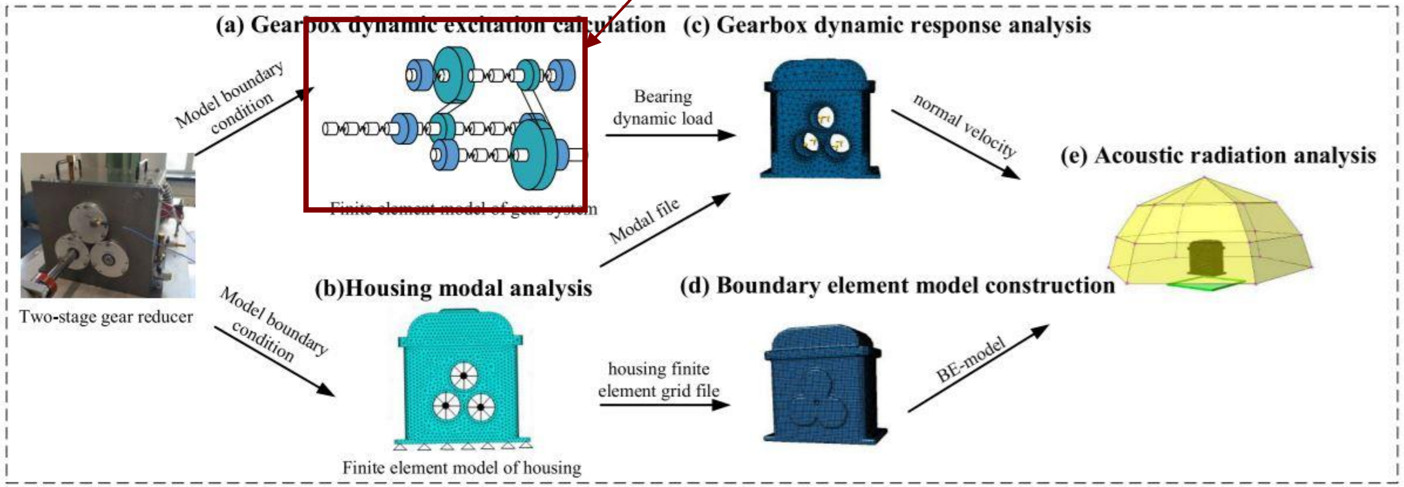

FIGURE 2. The computational process of noise radiation from gearbox.

- Weakly coupled vibroacoustic model

FEM (modal analysis of housing, gear contact analysis)

BEM (acoustic radiation)

Multibody simulation

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Multibody approach for the dynamic analysis of gears transmission for an electric vehicle

G Belingardi, V Cuffaro and F Curà

Abstract
The dynamic analysis of a gear transmission system for electric vehicle is analyzed by means of a multibody approach. The architecture of the transmission is constituted of one gear ratio, with the differential integrated in the same gear box. The multibody model of the complete transmission has been created and optimized in order to get the dynamic response of the system. In particular, the frequency response function of the system in terms of rotational speed and loading forces has been determined. Furthermore, the dynamic transmission error has also been determined.

Keywords
Gear transmission, electric vehicle, multibody approach, dynamic transmission error

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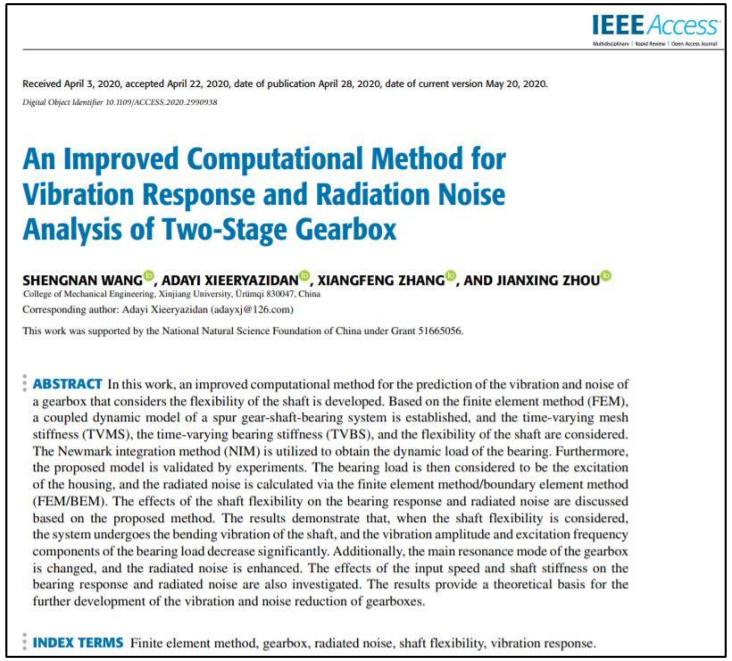
FEM	**MULTIBODY**
Deformable bodies	Rigid bodies
Stress, Strain	Acceleration, Velocity, Loads on moving bodies

FEM + Multibody **----** Very powerful machinery!

↓

Multi – flexible body dynamics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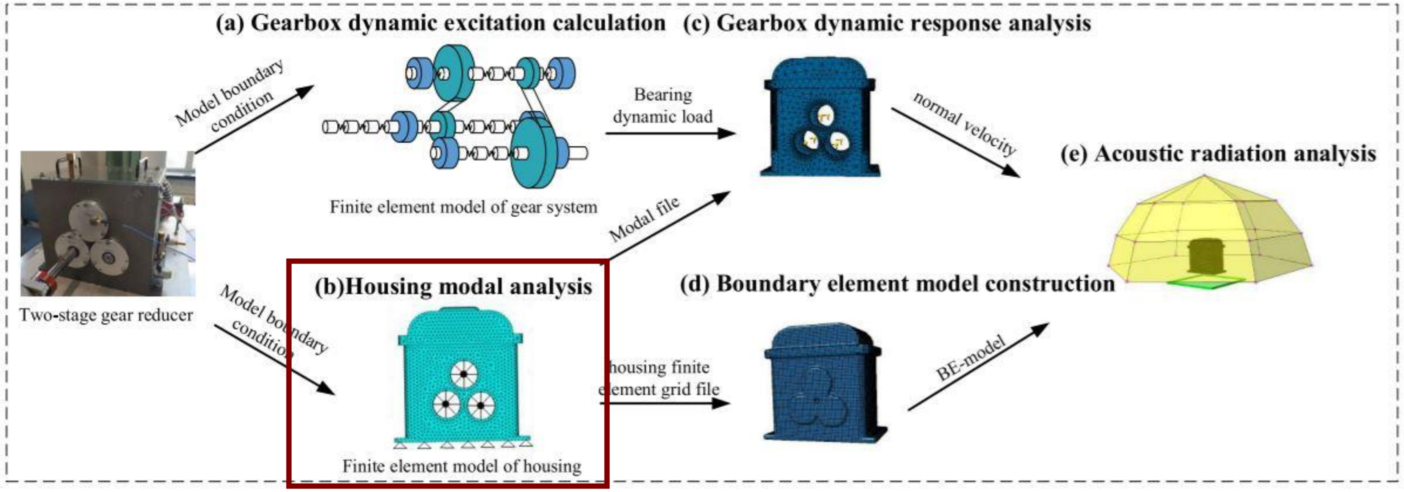

FIGURE 2. The computational process of noise radiation from gearbox.

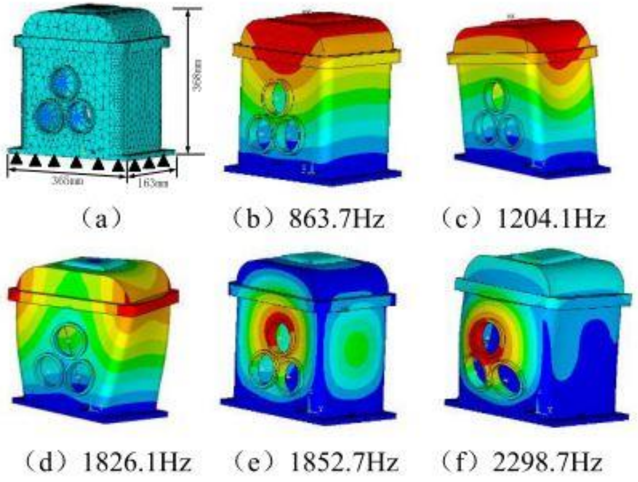

FIGURE 15. (a) Finite element model. (b) 1st mode. (c) 2nd mode. (d) 3rd mode. (e) 4th mode. (f) 5th mode.

Modal analysis is typically performed with FEM

$$[\mathbf{K}]\cdot\mathbf{A} = \omega^2[\mathbf{M}]\cdot\mathbf{A}$$

- Eigenfrequencies and mode shapes

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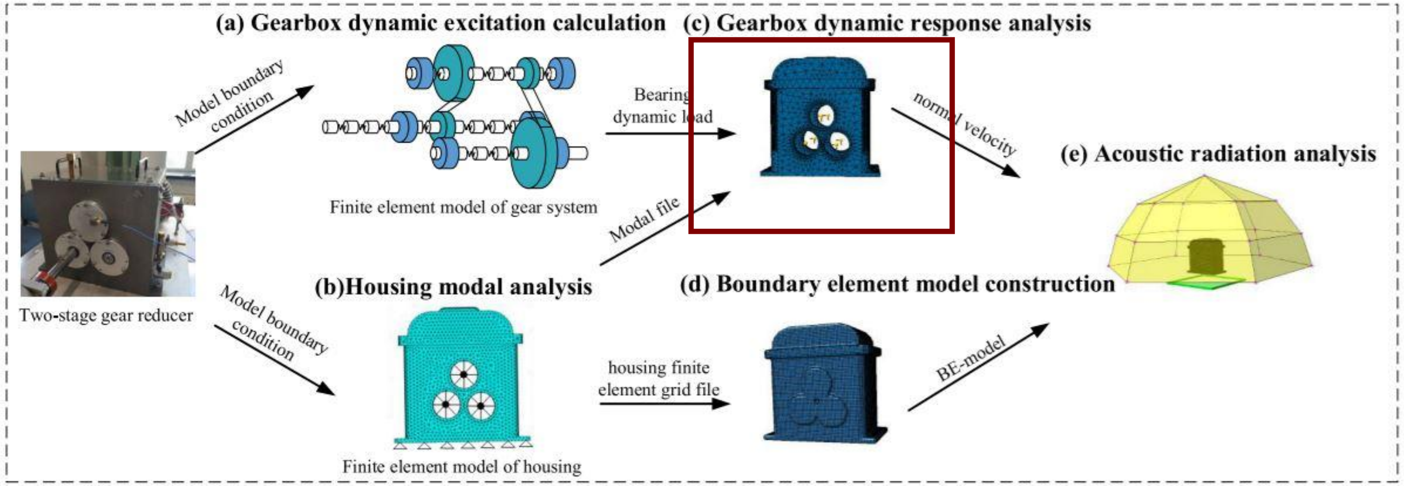


FIGURE 2. The computational process of noise radiation from gearbox.

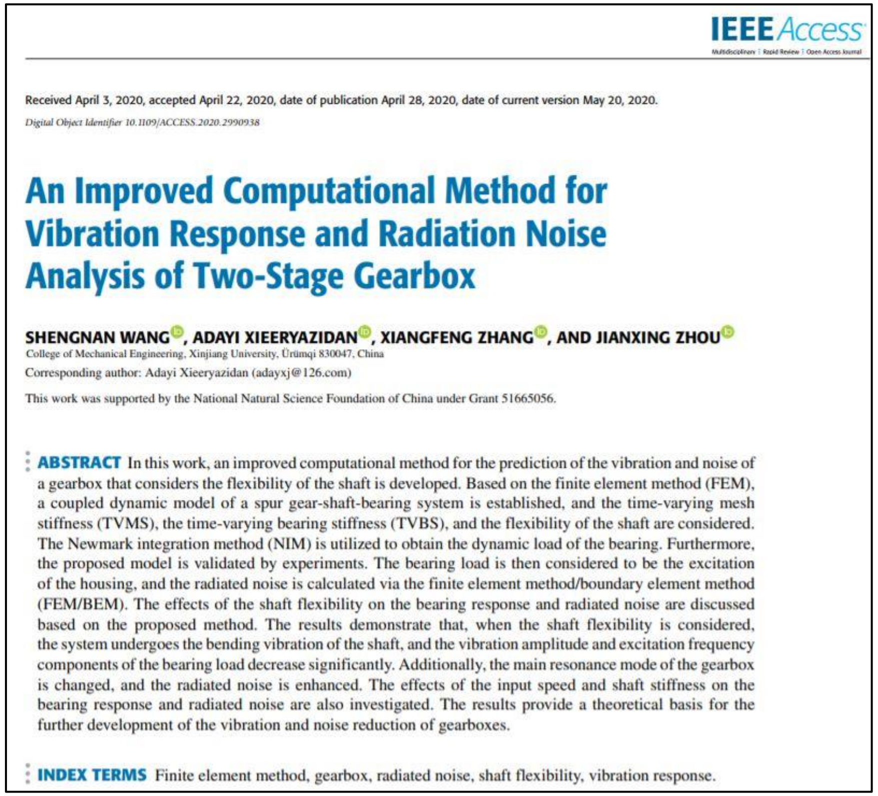
$$[\mathbf{M}]\{\ddot{\mathbf{x}}(t)\}+[\mathbf{K}]\{\mathbf{x}(t)\}=\{\mathbf{F}(t)\}$$

$$\{\mathbf{x}(t)\}=[\mathbf{\Phi}]\{\mathbf{q}(t)\}$$

Projection in modal space

$$[\mathbf{m}]\{\ddot{\mathbf{q}}(t)\}+[\mathbf{k}]\{\mathbf{q}(t)\}=\{\mathbf{P}(t)\}$$

$[\mathbf{\Phi}]$: **Matrix of eigenvectors**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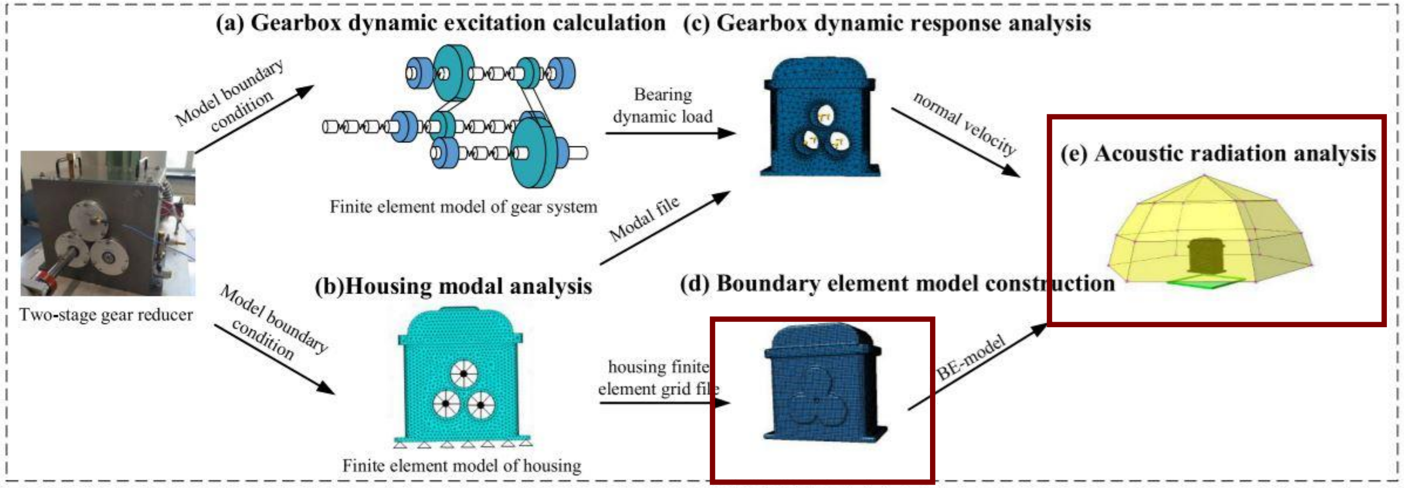

FIGURE 2. The computational process of noise radiation from gearbox.

1) Create an acoustic mesh around the housing
2) Map normal velocities calculated in previous step
3) With boundary condition the acoustic velocities solve the acoustic problems

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Modal acoustic transfer vector approach in a FEM–BEM vibro-acoustic analysis

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Abstract

The aim of the present work is to set up an integrated approach for an automobile vibro-acoustic analysis, useful to assess, visualise and compare vibro-acoustic performance to pre-determined design targets, while identifying and quantifying the forces and sound sources responsible for the current behaviour. Such design approach, based on experimental and numerical procedures, enables the prediction of noise emissions and the correlation with the structural vibration source.

Vibro-acoustic prediction in the low- to mid-frequency range is generally performed through finite element method (FEM) or boundary element method (BEM) but in this work a combined usage of the two methodologies is adopted: FEM is used for the structural dynamics and BEM for the acoustic problem resolution. The BE methodology adopted is based on an indirect formulation and on a variational solution scheme.

The adopted FEM–BEM approach takes advantage of the Modal Acoustic Transfer Vector algorithm that is particularly useful when big problems are to be analysed. The comparison between numerical and experimental results enables an assessment of the accuracy level.

Keywords: Integrated FEM–BEM; Vibro-acoustic; BEM indirect formulation; BEM variational solution scheme; MATV

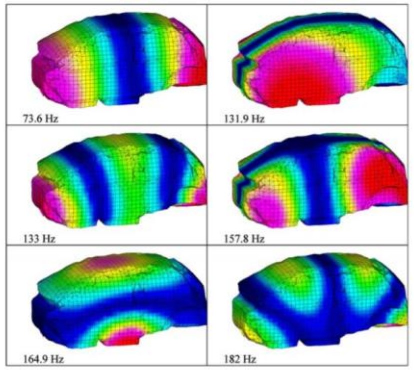


Fig. 10. Acoustic modes by FEM cavity analysis.

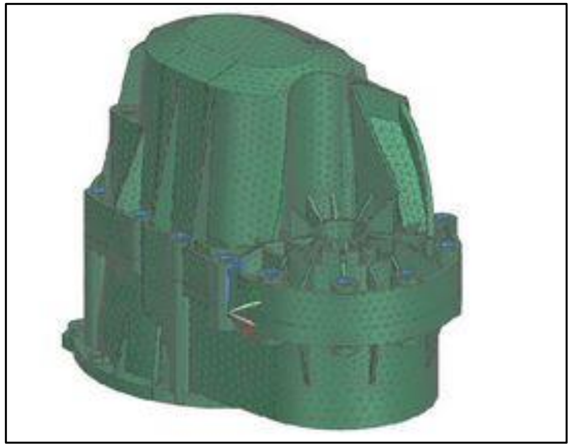
Acoustic Transfer Vectors (ATV)

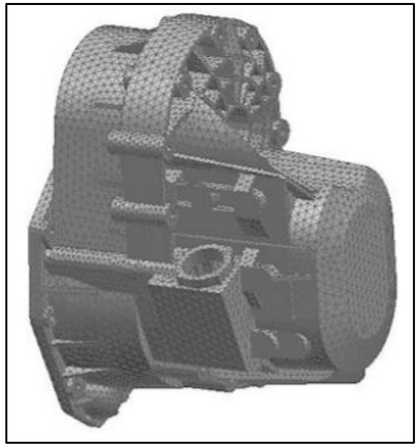
$$\{p(\omega)\} = [\mathbf{T}(\omega)]\{v_n(\omega)\}$$

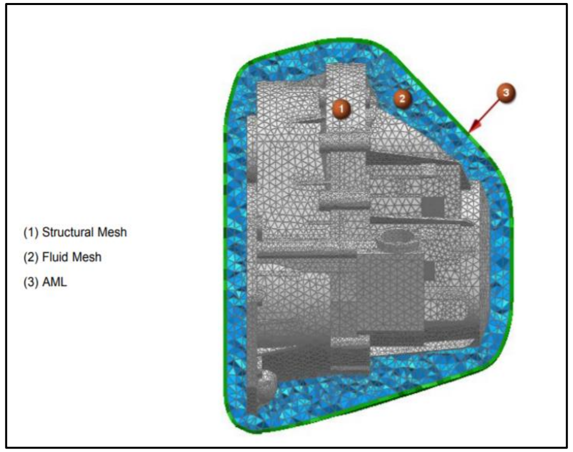
$[\mathbf{T}(\omega)]$: acoustic transfer vector matrix. Connects the normal velocities of the surface with pressures of points inside the fluid domain. **Needs to be calculated only once.**

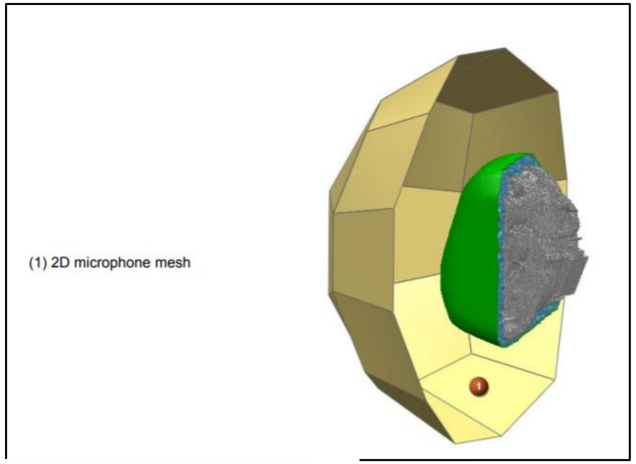
$\mathbf{T}_{ij}(\omega)$: contribution at the angular frequency ω of the j element vibration to to the pressure of the i point inside the fluid domain

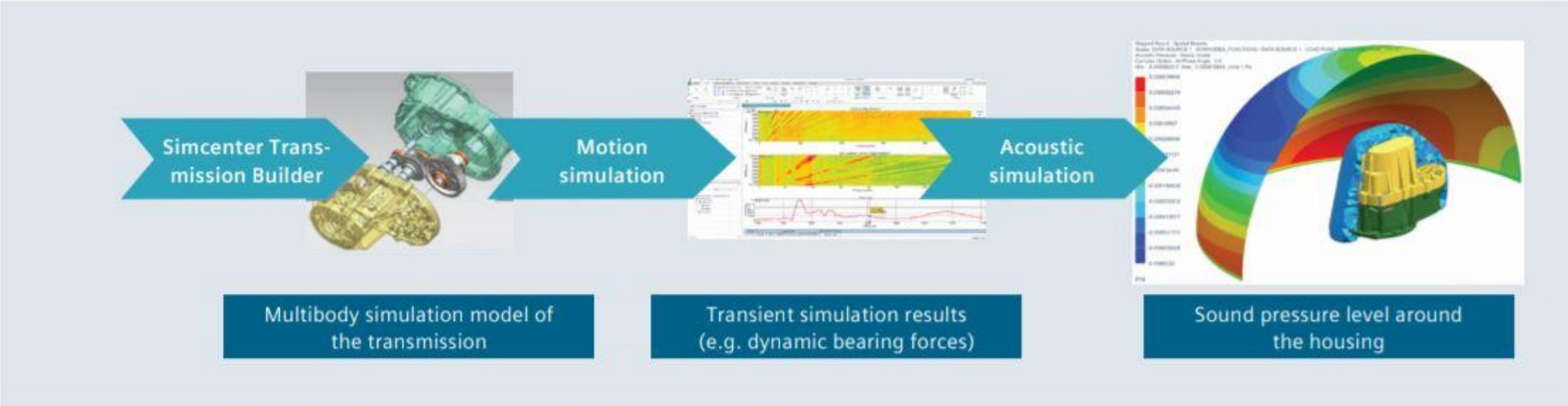
EXAMPLE CASE STUDY: ESTIMATION OF THE VIBROACOUSTIC BEHAVIOR OF A GEARBOX USING **SIMCENTER3D**

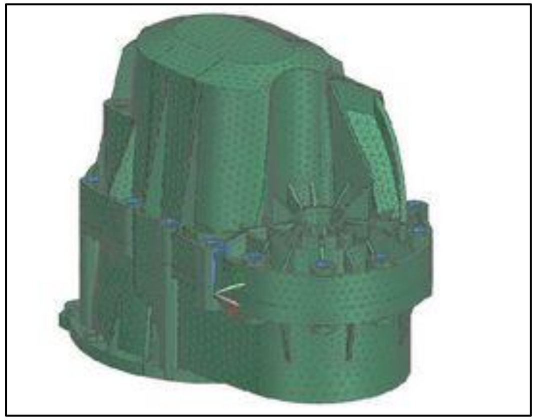






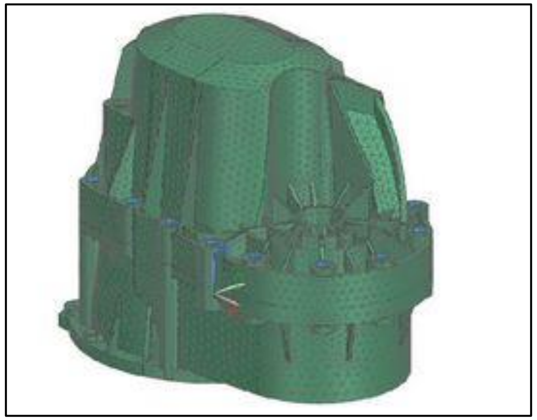




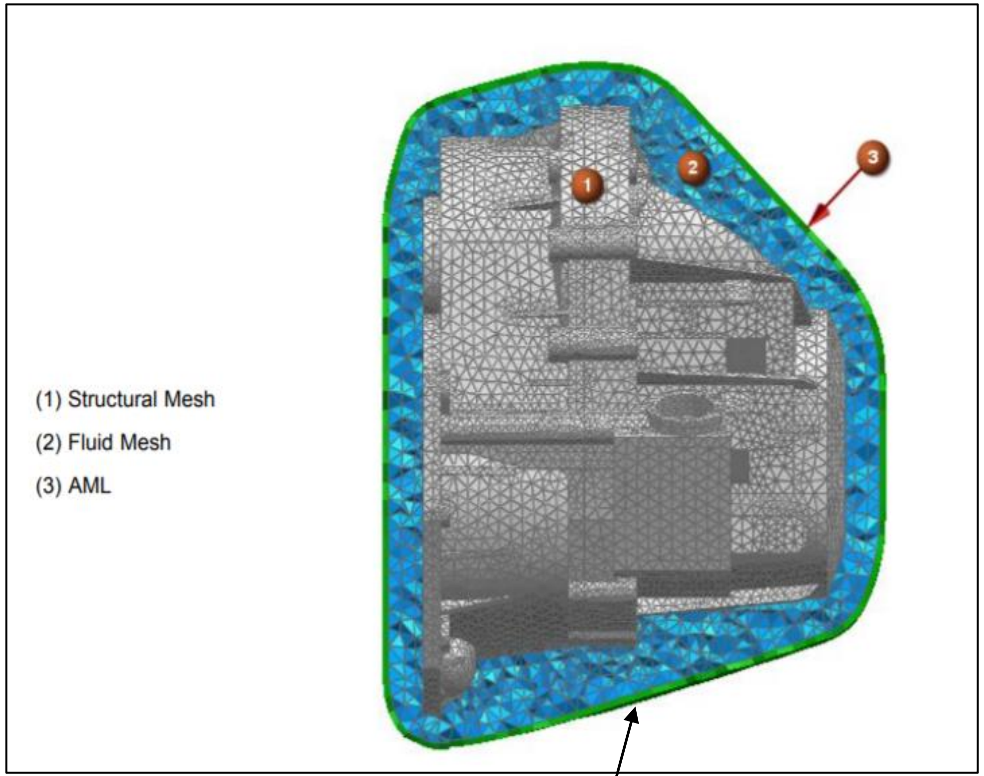


Modal analysis of housing

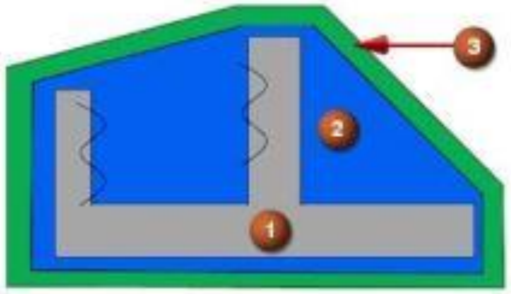
Transmission modelling



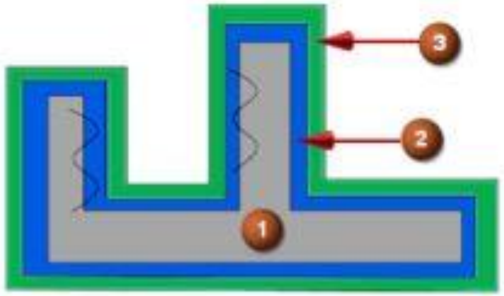
Multibody motion simulation



Absorbing boundary



The waves radiating from the structure are not absorbed, as no non-convex regions exist between the two vibrating surfaces.



The waves radiating from the structure are absorbed in the non-convex region between the two vibrating surfaces.