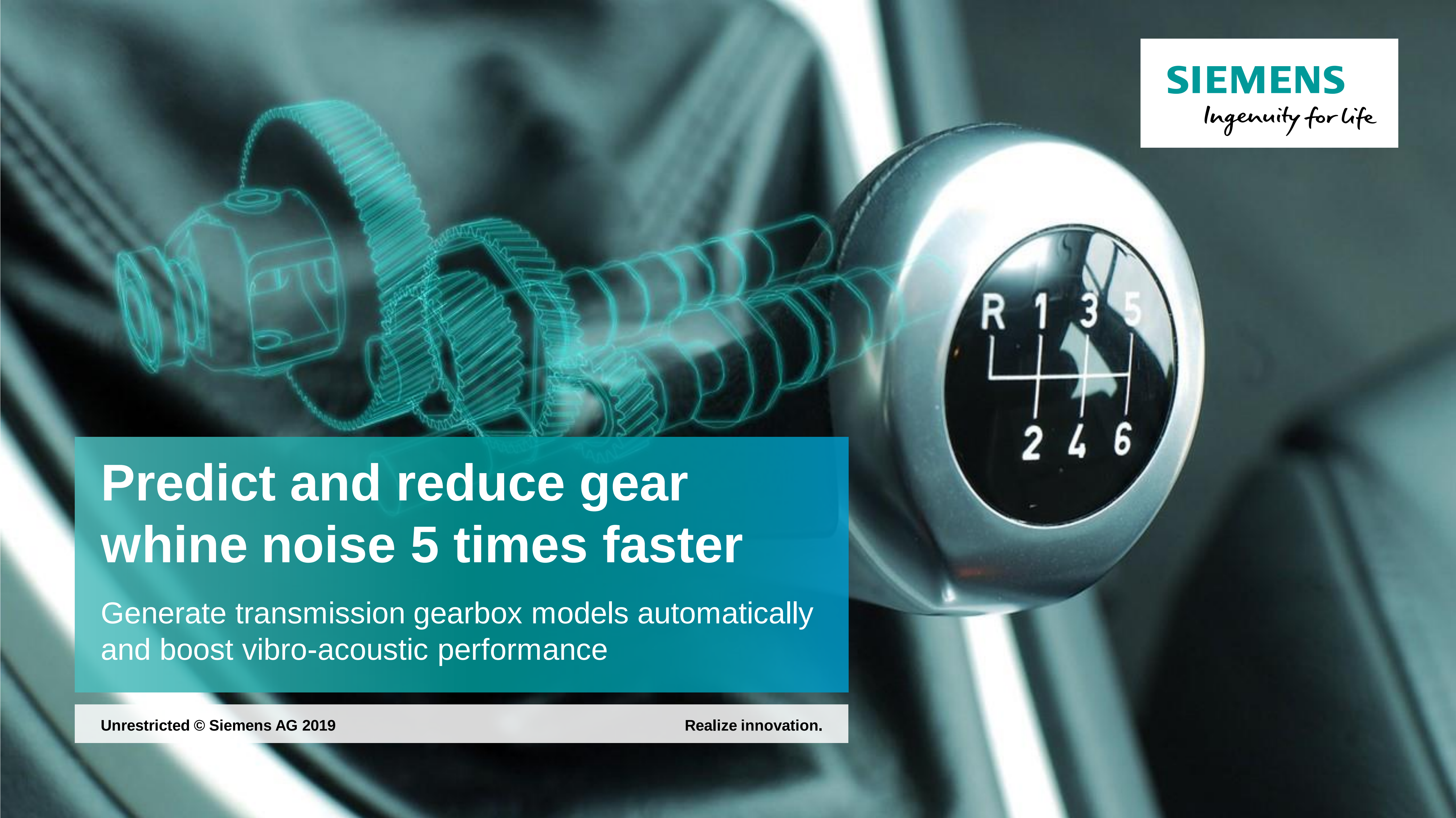


SIEMENS
Ingenuity for life

Predict and reduce gear whine noise 5 times faster

Generate transmission gearbox models automatically and boost vibro-acoustic performance

Realize innovation.

Transmission Engineering Challenges

SIEMENS
Ingenuity for life

Guarantee Performance and Durability

Prototyping can cost up to 200k$ -- per single gear

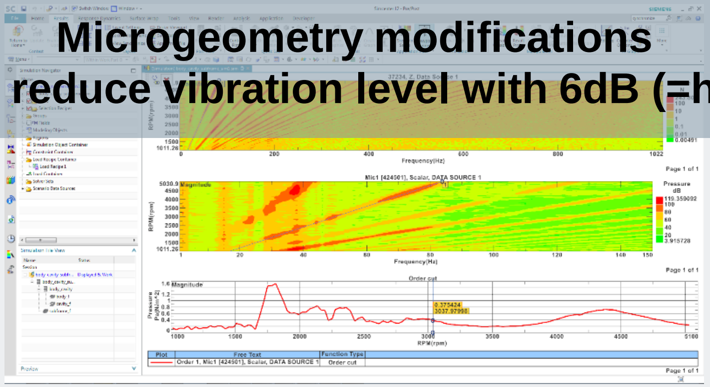
Reduce Time for Simulation

80% of time for manual model creation

Results

Minimize Vibration and Noise Levels

Microgeometry modifications
can reduce vibration level with 6dB (=half!)



Reduce Weight with Lightweight Designs

Transmission Error can increase 10x or more!

Transmission Engineering Process

SIEMENS
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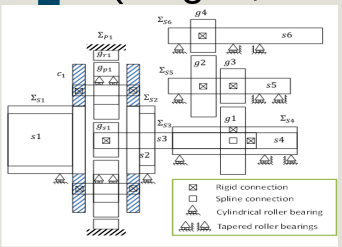
Typical process for NVH analysis

Transmission layout (stages, dimensions)

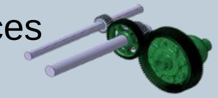
Transmission Error or Stiffness, parameters

Pre-processing of loads or surface vibrations

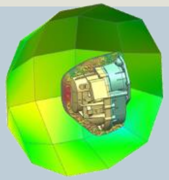


Gear-centric tool
- Analysis of gear pairs

Multi-body simulation
- Simulation of forces and dynamics

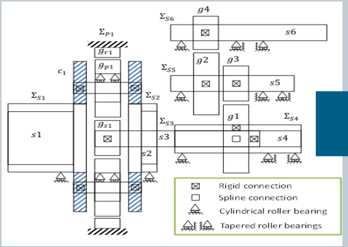


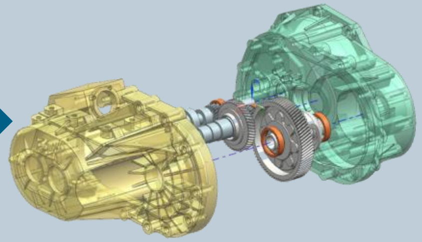
Acoustics, NVH
- Gear whine
- Gear rattle



Positioning, dimensions…

More efficient process in Simcenter 3D

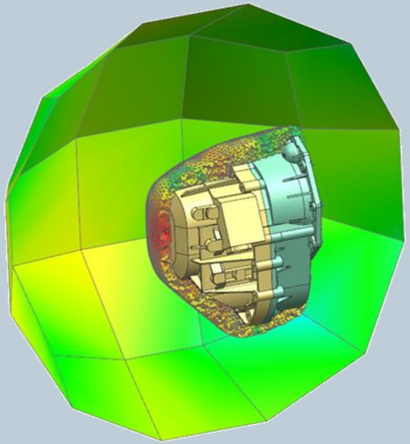




End-to-end integrated process for transmission simulation from CAD to Loads to Noise

Transmission Builder → Motion → Motion-to-Acoustics → Acoustic Analysis

- **Automatic** creation of multi-body simulation models
- Accurate 3D simulation of gear forces
- Semi-automatic link of gear forces to vibro-acoustics
- Efficient and accurate acoustic simulations



Multi-Body Simulation of Transmissions

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Transmission Engineering Process

SIEMENS
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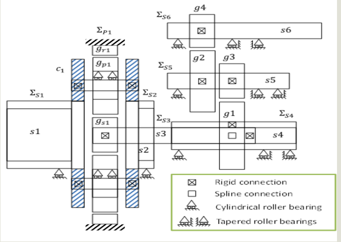

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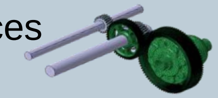

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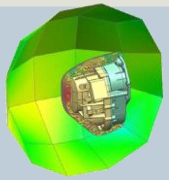

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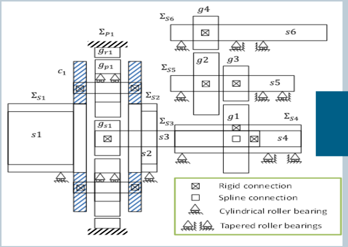

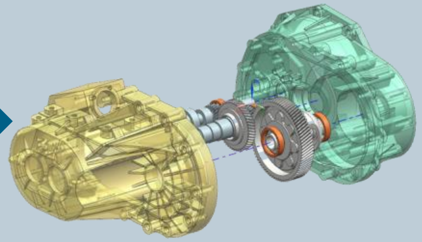

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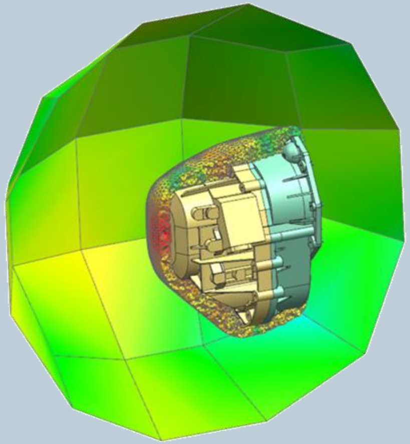
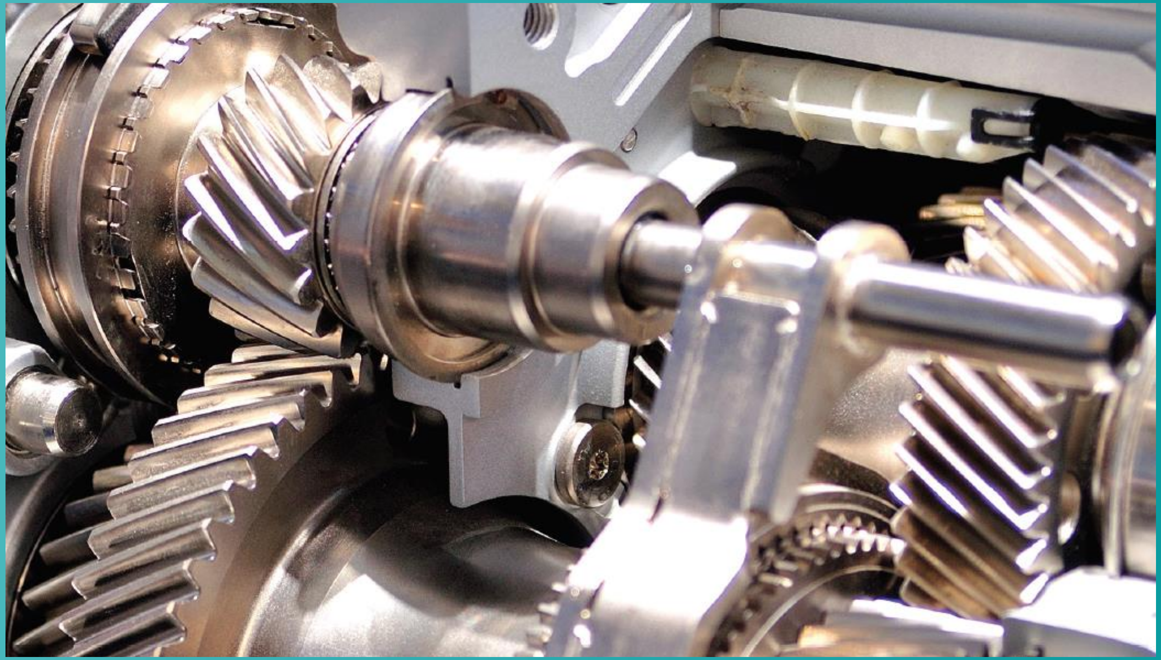


Multi-Body Simulation of Transmissions



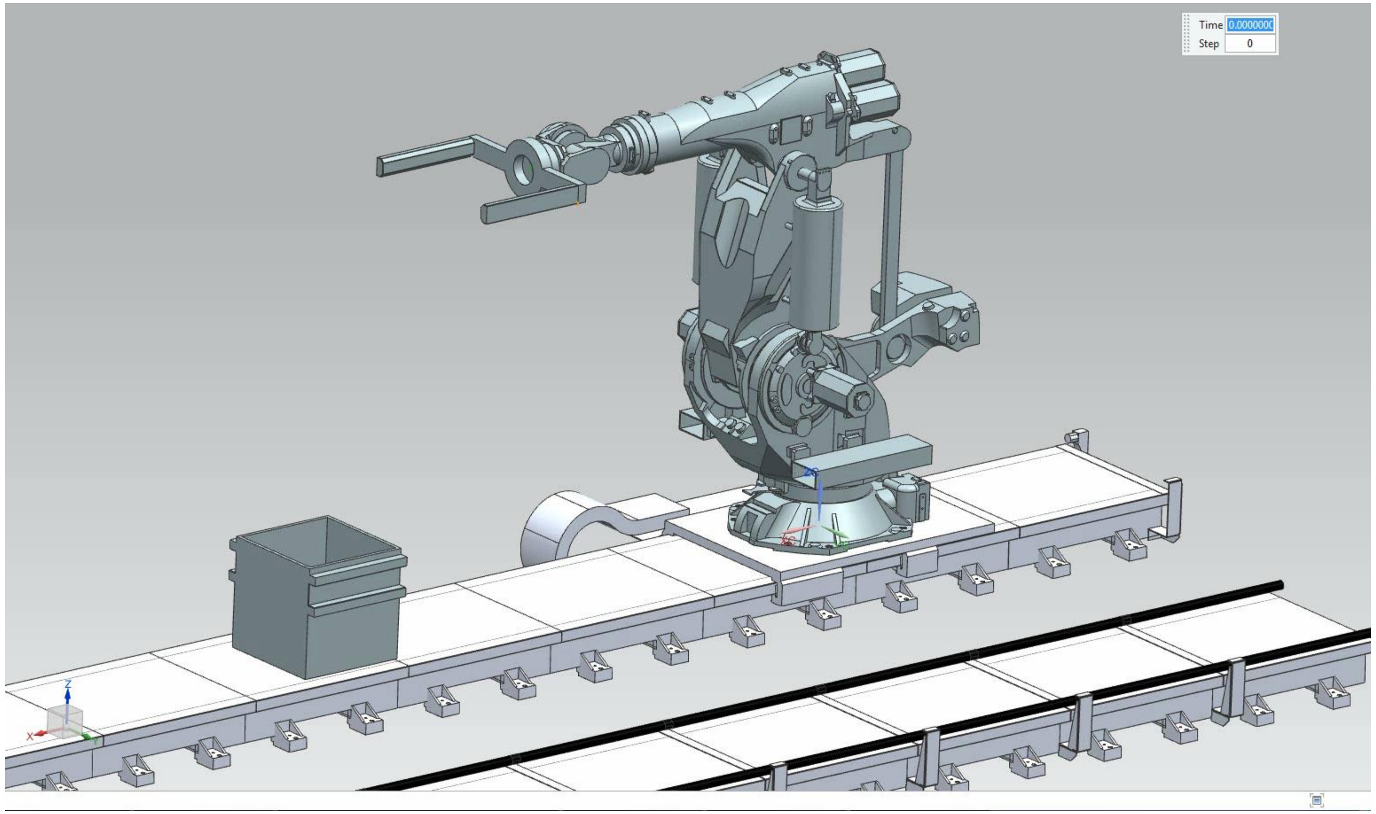
Transmission Builder

New Simulation Solution for Gears

Summary

Multi-Body Simulation
Scope

Predicting, **Analyzing**, **Improving** the positions, velocities, accelerations and loads of a mechatronic system using an accurate and robust 3D multi-body simulation approach



Simcenter 3D Motion for Transmission Simulation

Critical features

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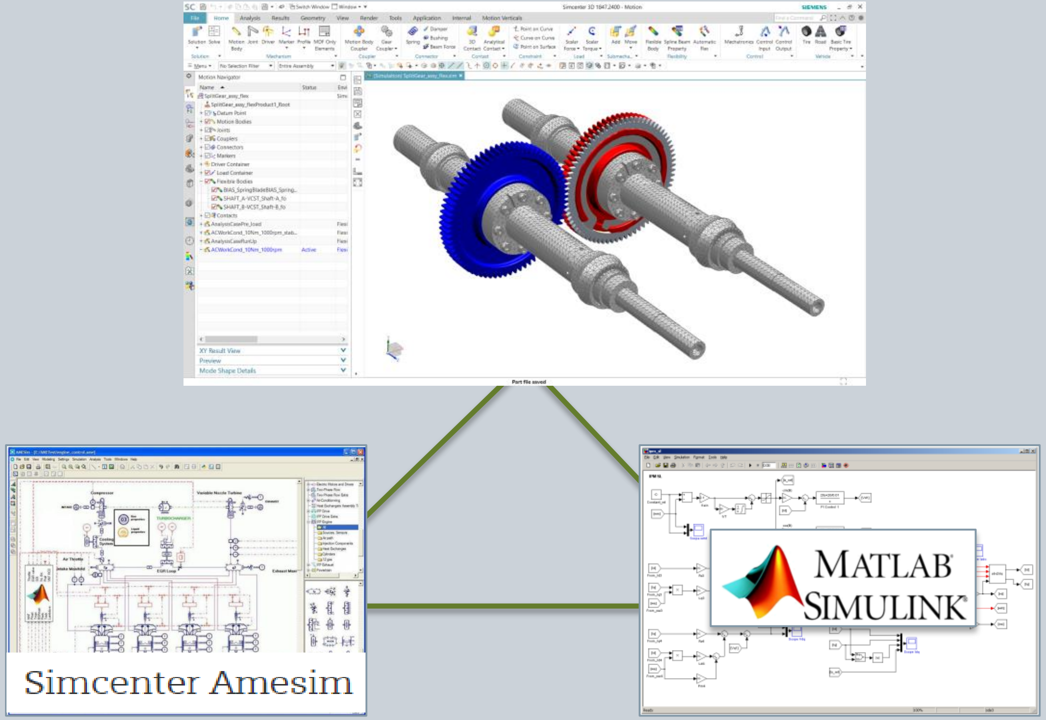
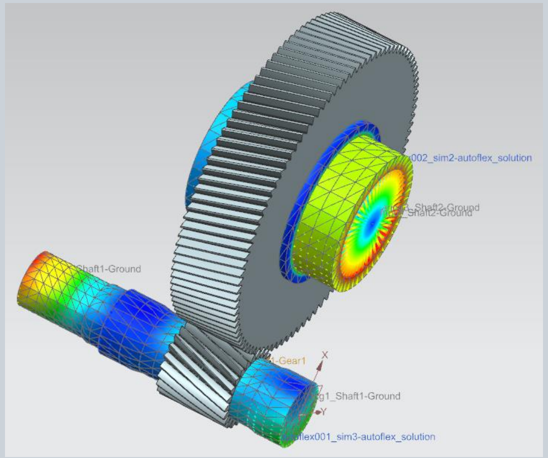
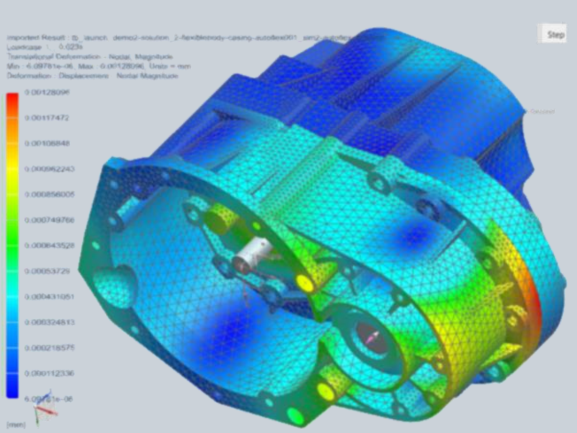
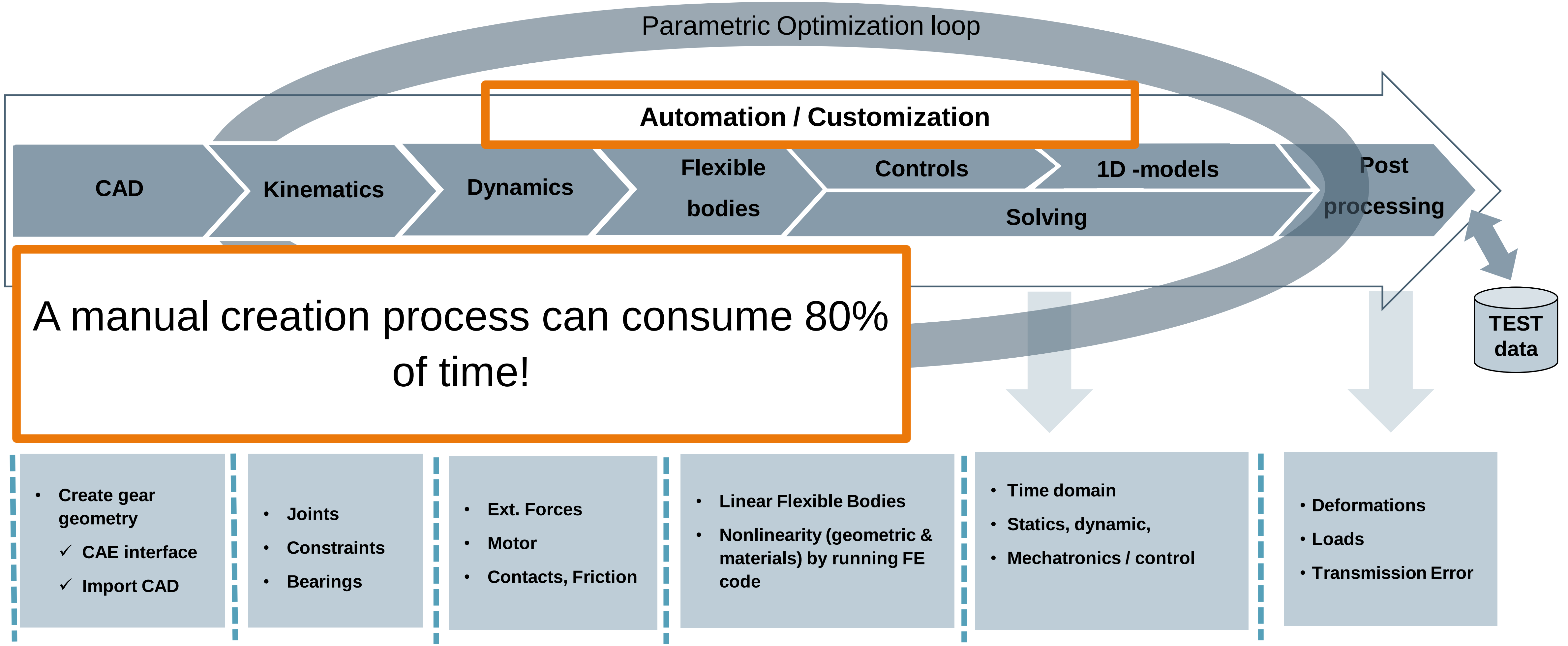
Mechatronic Systems	Flexible Bodies
• Integration with tools for robust design of complex non-linear multi-physics systems: control systems, sensors, electric motors, etc	• Predict mechanical system more accurately wrt displacements and loads • Gain insight in frequency response of a mechanism • Enable Noise, Vibration & Harshness (NVH) as well as Durability analyses



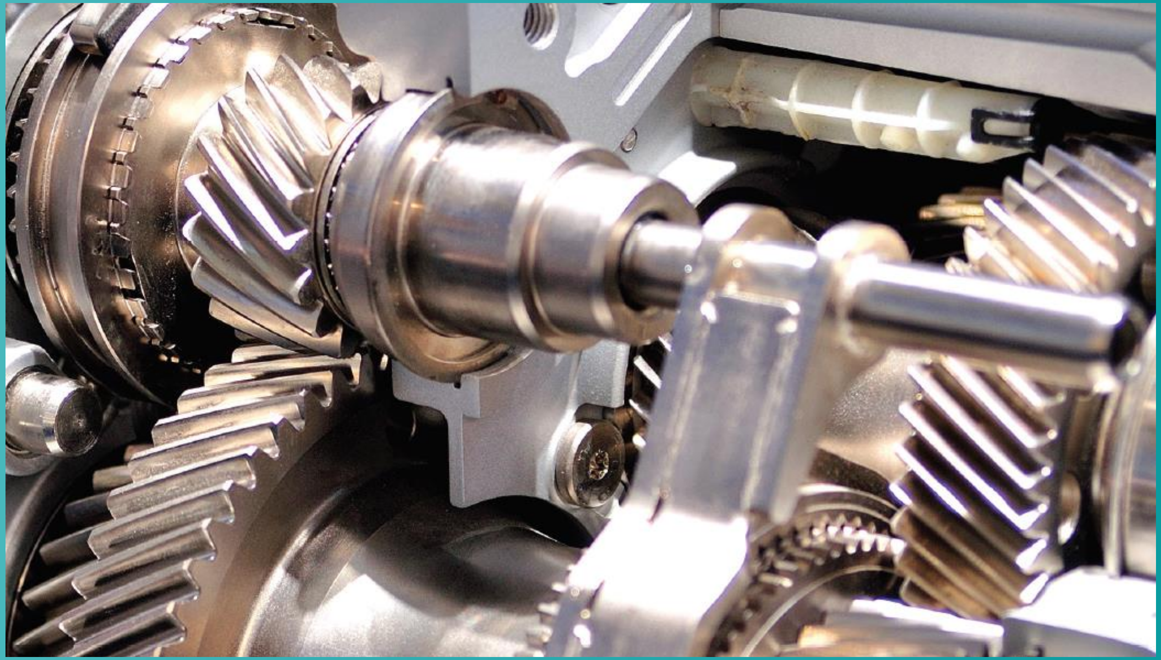




Multi-Body Simulation
Industry Modelling Practices



Multi-Body Simulation of Transmissions



Transmission Builder

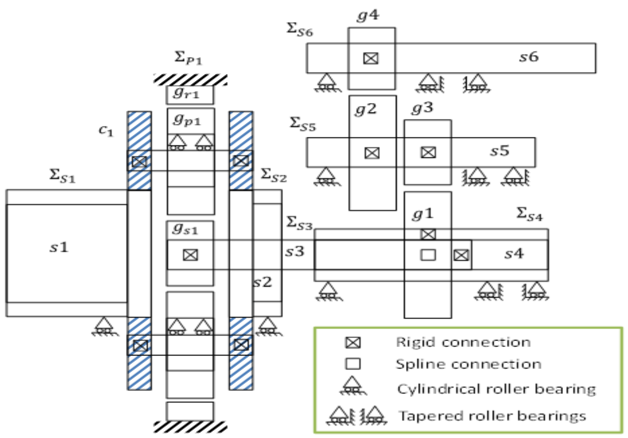
New Simulation Solution for Gears

Summary

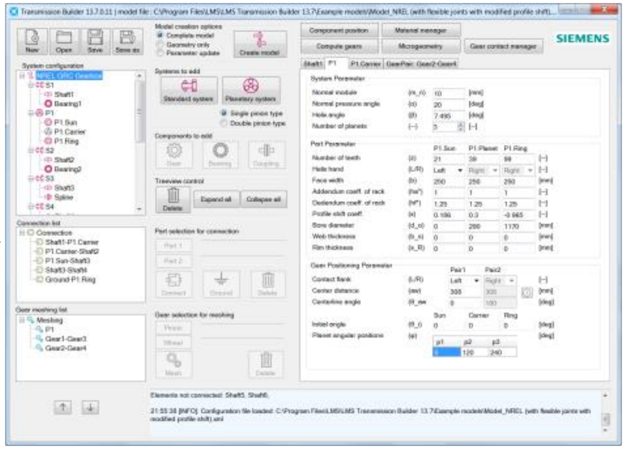
New Approach
Transmission Builder Vertical Application

Problem: Even experienced 3D-Multi Body Simulation experts can struggle to
1. Model complex parametric transmissions
2. Capture all relevant effects correctly and efficiently
3. Update and validate their models

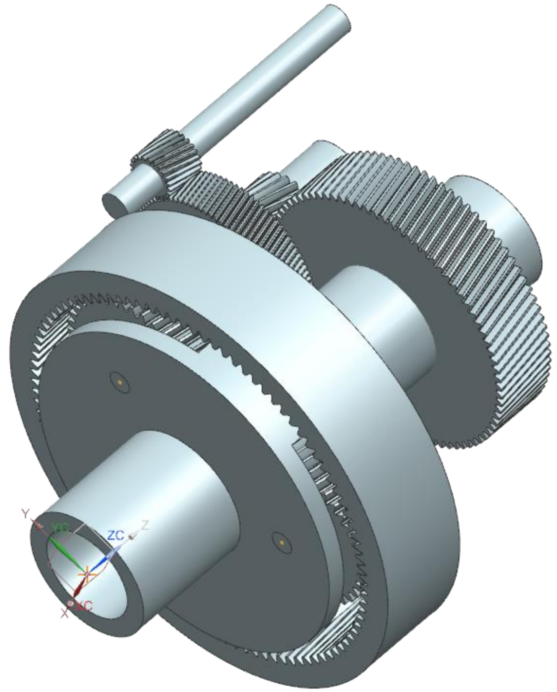
Solution: Transmission Builder → Up to 5x faster Model creation process



Gear train specification based on Industry standards



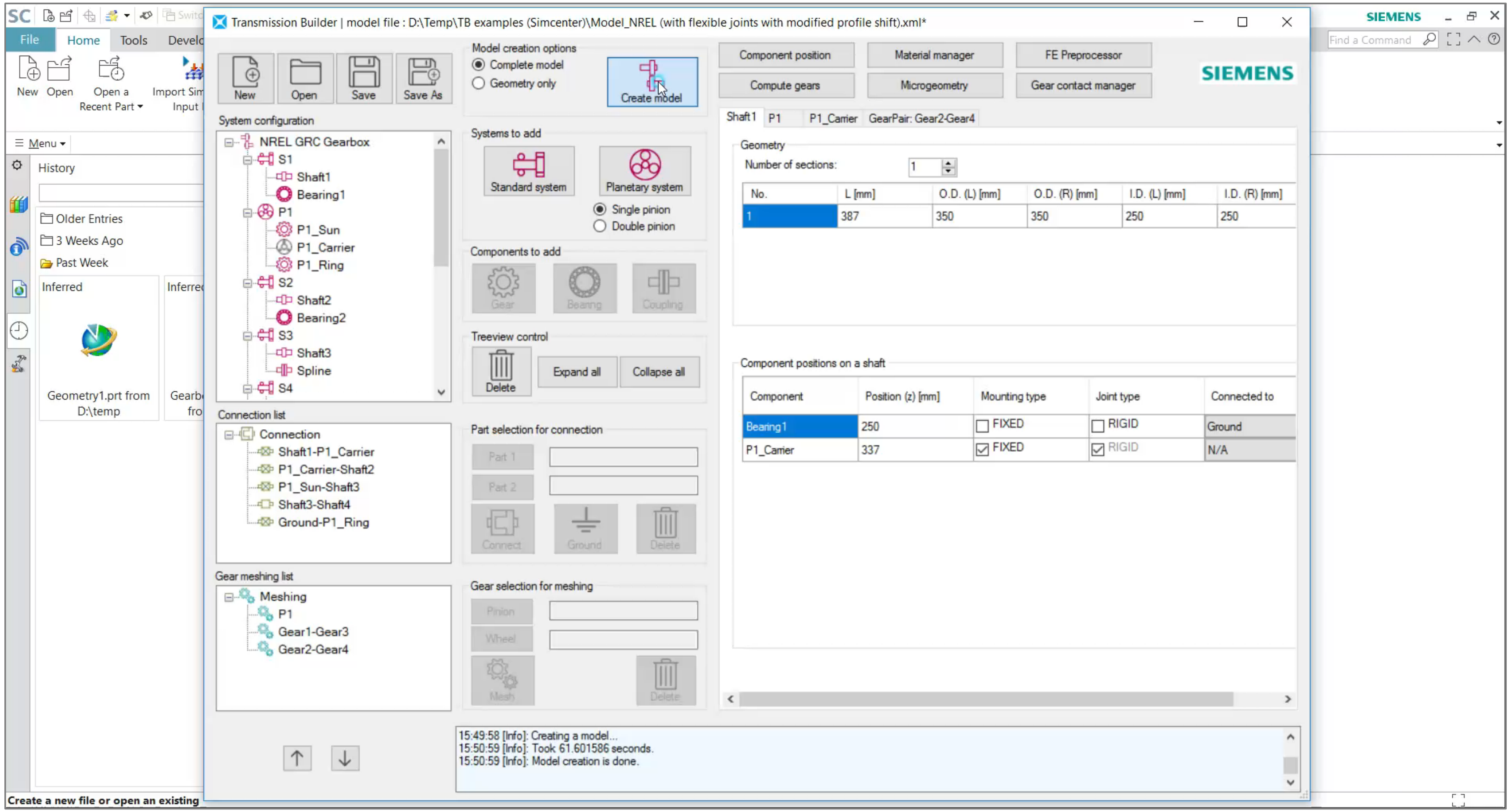
Simcenter Transmission Builder



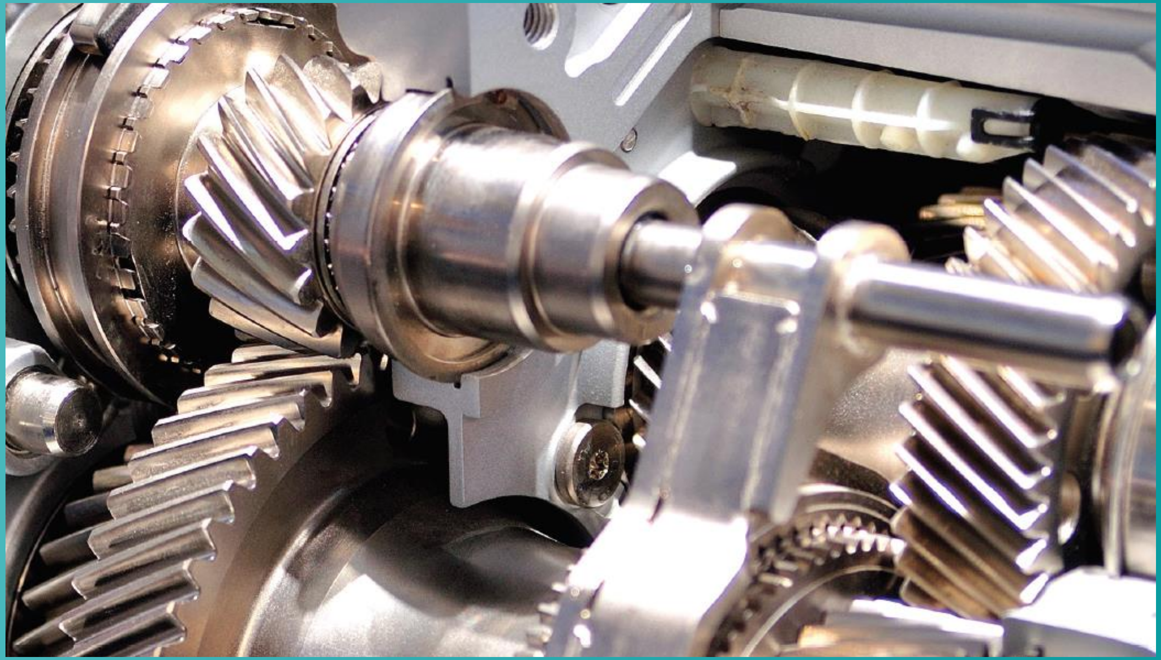
Multibody simulation model

Demonstration
Model Creation and Updating

1. Loading of pre-defined Transmission
2. Geometry creation
3. Creation of rigid bodies for gearwheels and shafts
4. Positioning and Joint-definition
5. Force element creation



Multi-Body Simulation of Transmissions

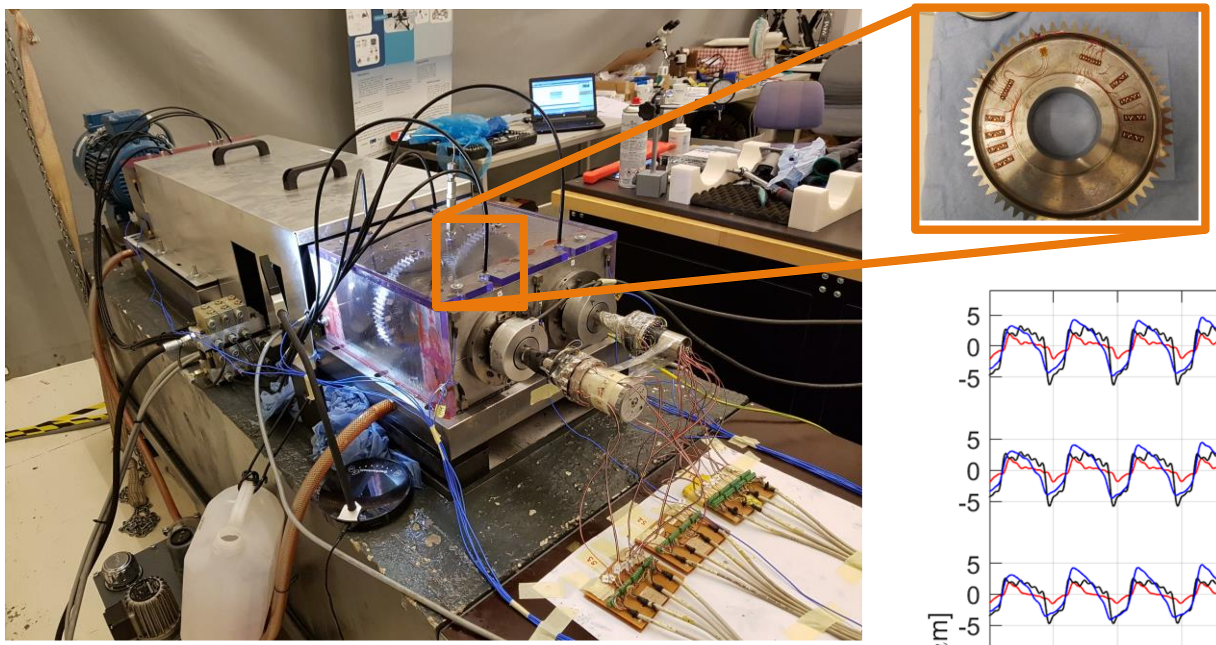


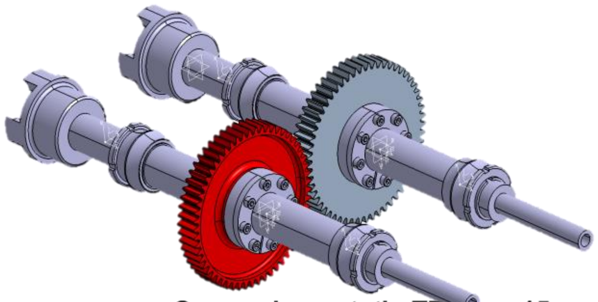
Transmission Builder

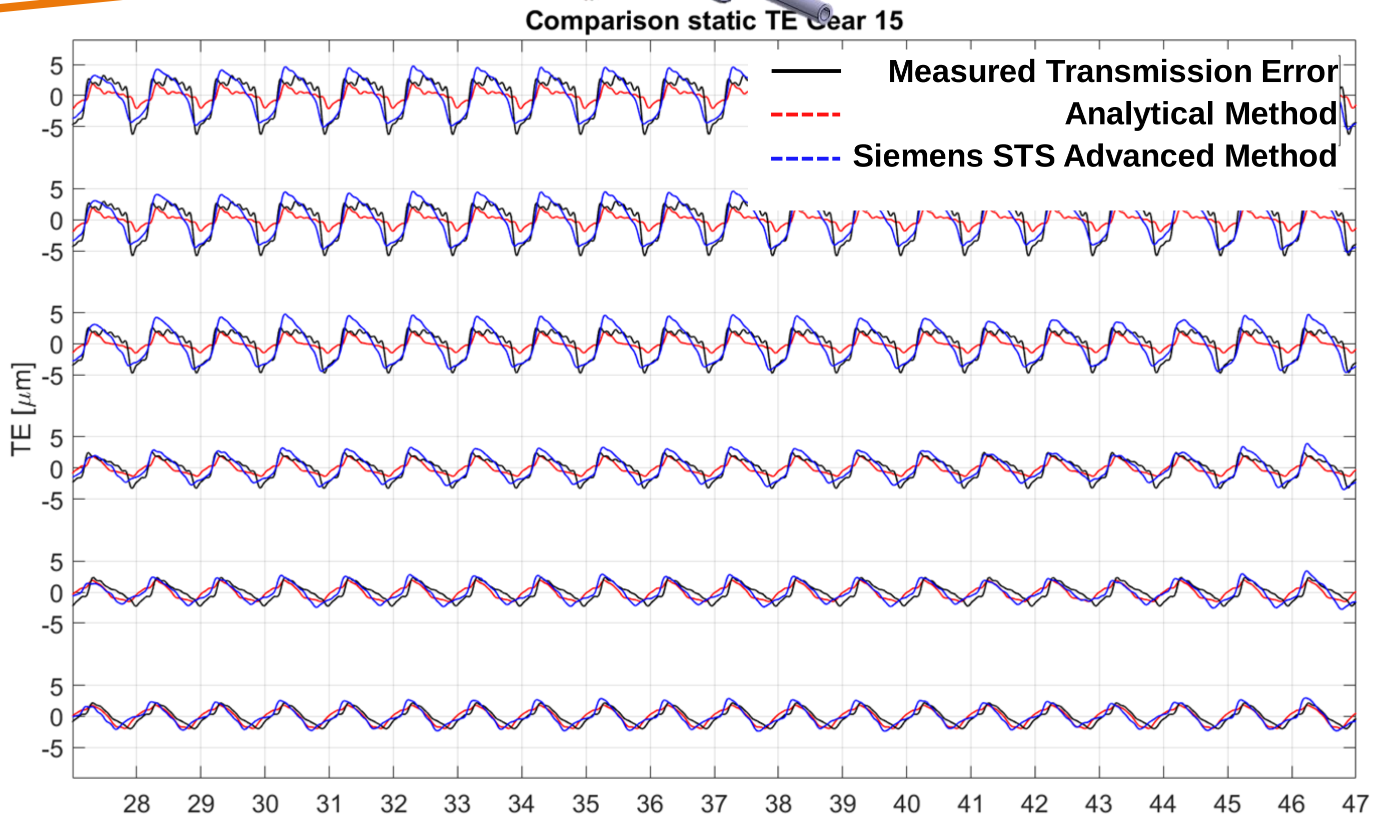
New Simulation Solution for Gears

Summary

New Solver Methodologies
Simulating and Validating







Validation cases ensure results as <u>accurate</u> as non-linear Finite Elements simulation

KU LEUVEN

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Dedicating Tooth Contact

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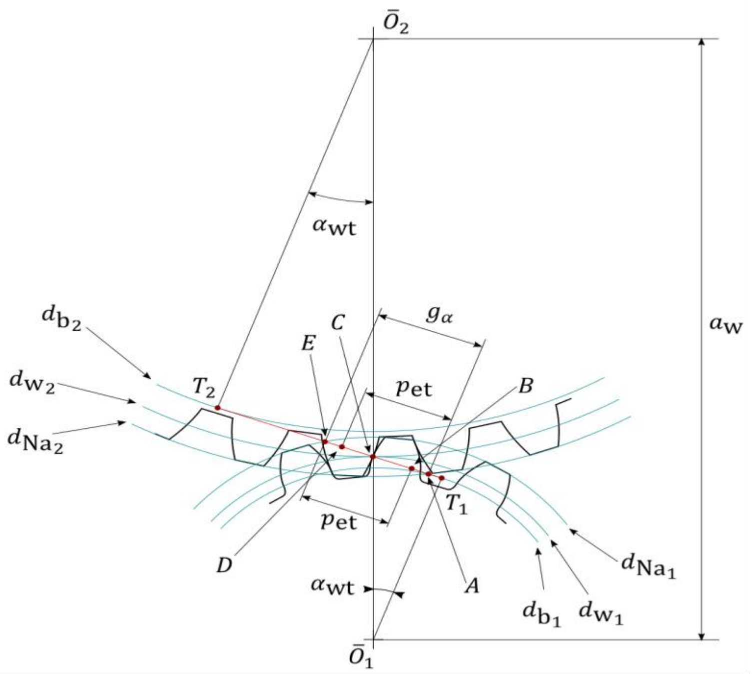
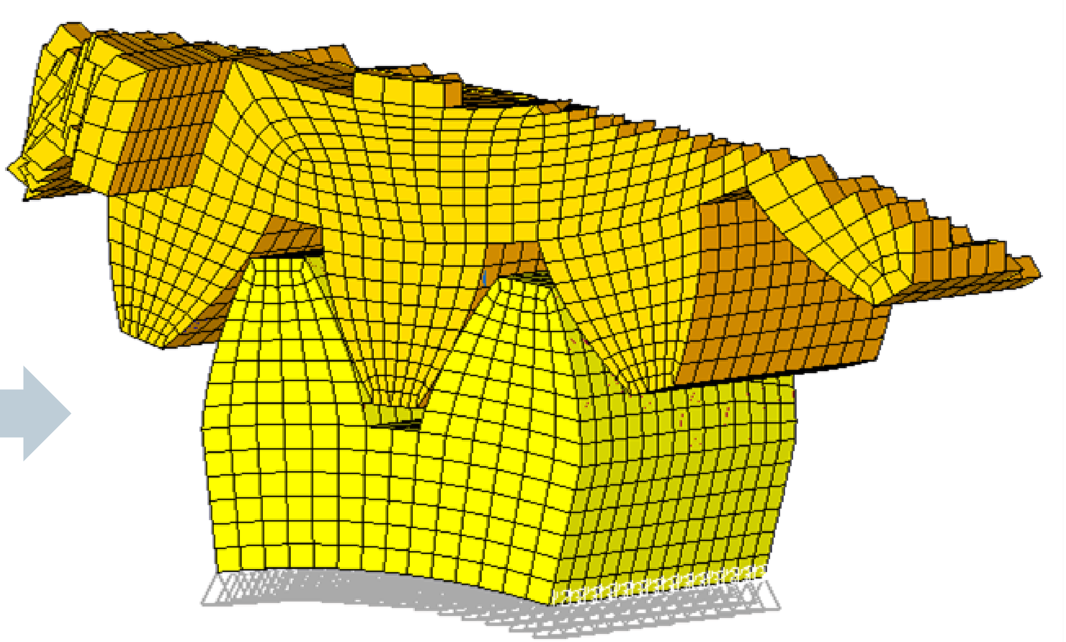
Exploiting intrinsic geometric properties of gears



+ Efficient
- Only for gears, not for arbitrary shapes
- No deformation included
  But, included as part of the Load Calculation

FE based contact detection

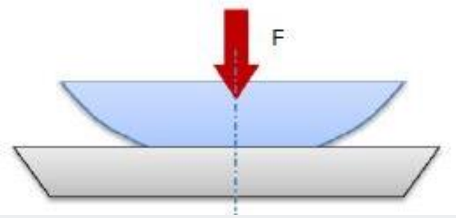


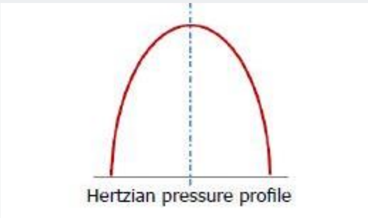
- "Brute force" → Slow
+ Any geometry
+ Deformation effects included

Gear Contact
Methodology Highlights

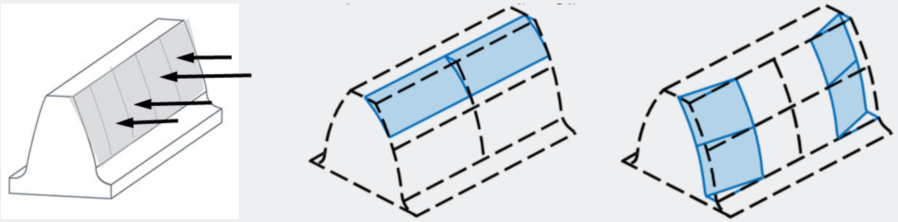
Modeling – FE Preprocessor

Local Deformation – Analytic Solution





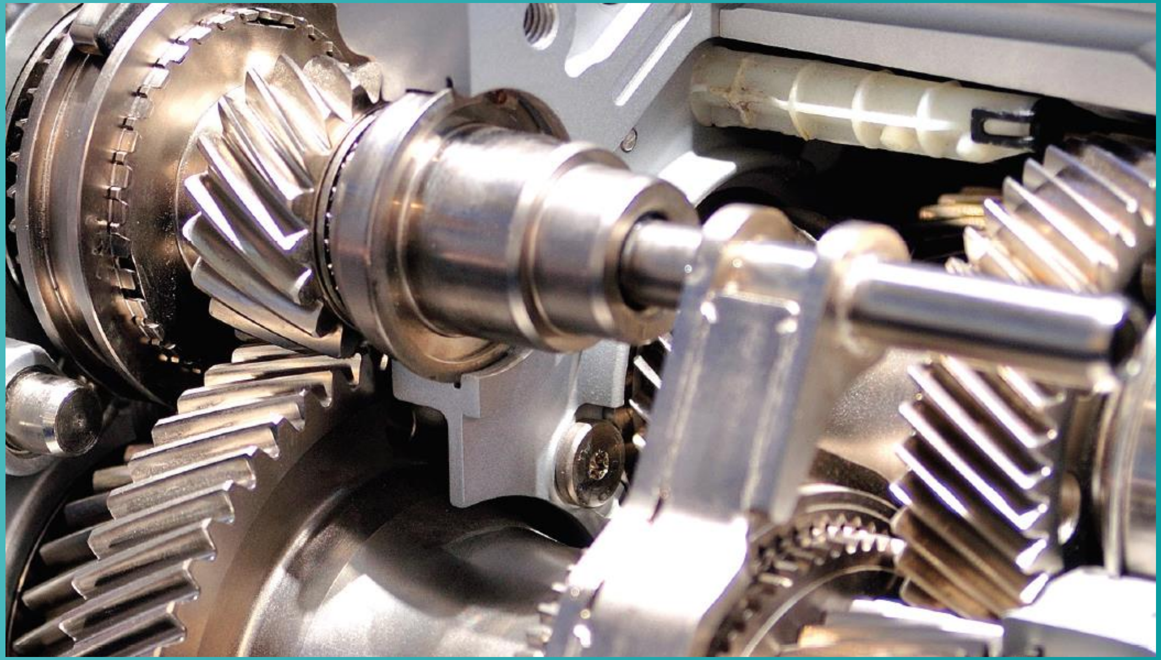
Slicing – Gear Force Distribution Along Line of Action



Key Features

- Includes Microgeometry Modifications and Misalignments in all DOF
- Automatically takes in to account coupling between slices and between teeth
- Accounts for actual gear body geometry with advanced stiffness formulation
- Evaluates tip contact (approximation)

Multi-Body Simulation of Transmissions



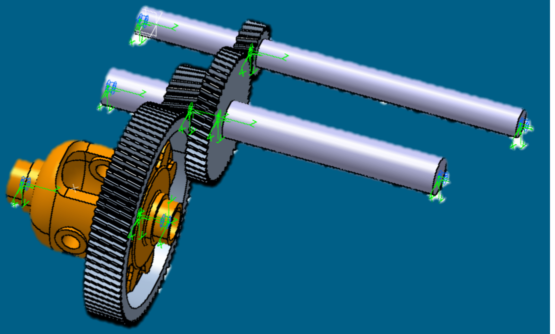
Transmission Builder

New Simulation Solution for Gears

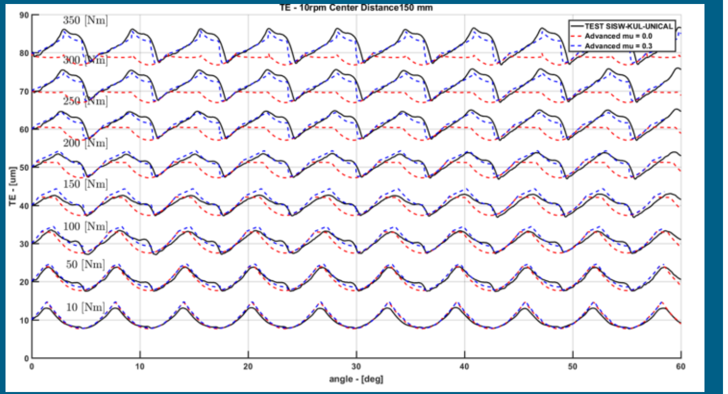
Summary

Multi-Body Simulation of Transmissions
Summary

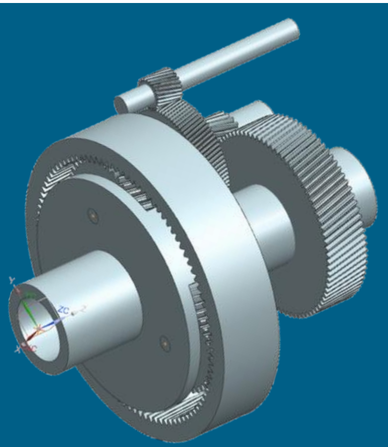
Gear simulation as accurate as FE while extremely fast



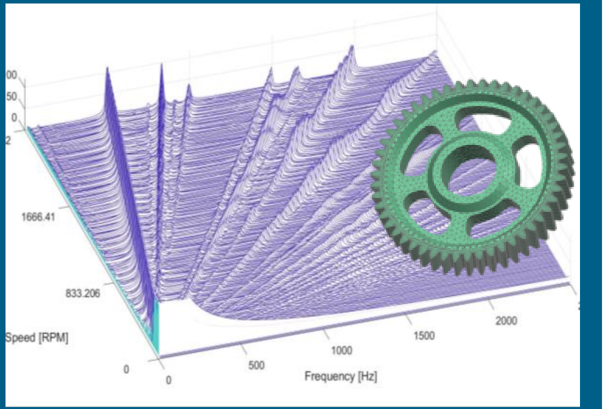
Validated methodology



Automated creation of transmission models

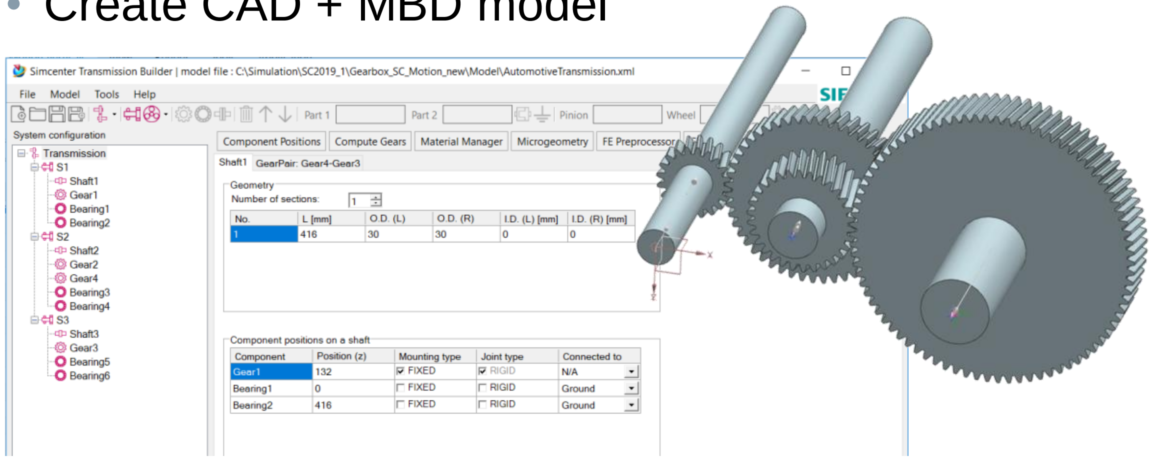


Superior insight in transmission vibrations

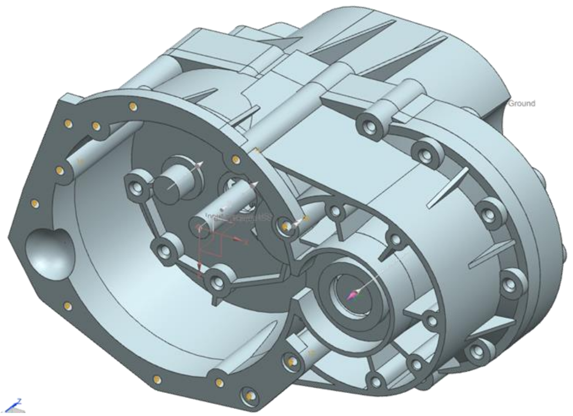


Simcenter 3D Motion
Simulate Transmission

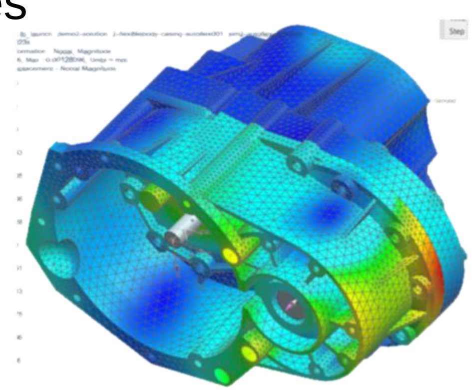
- Create CAD + MBD model



- Connect and position housing

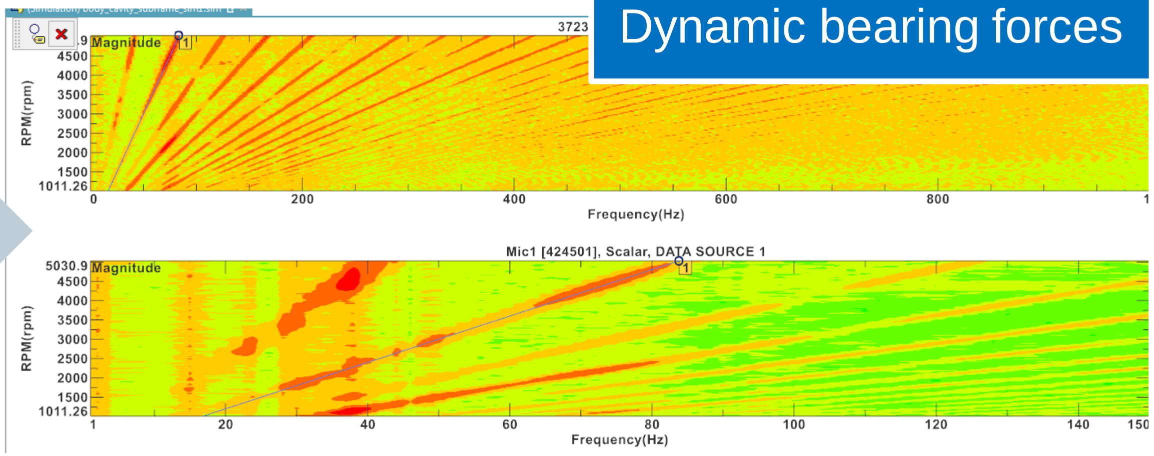


- Add flexible modes (Autoflex)
- Set up load cases



Simulate

Dynamic bearing forces



Acoustic Simulation of Transmissions

Transmission Engineering Process

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Typical process for NVH analysis

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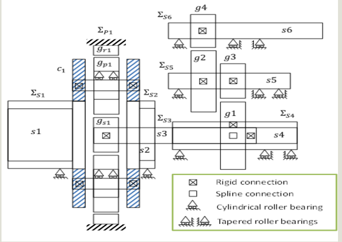

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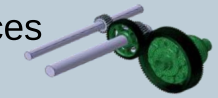

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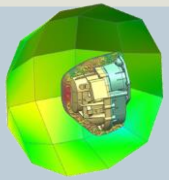
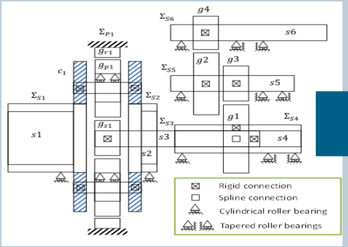
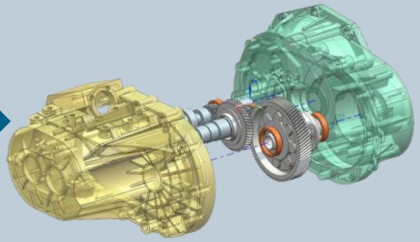
- Gear rattle



Positioning, dimensions…

More efficient process in Simcenter 3D





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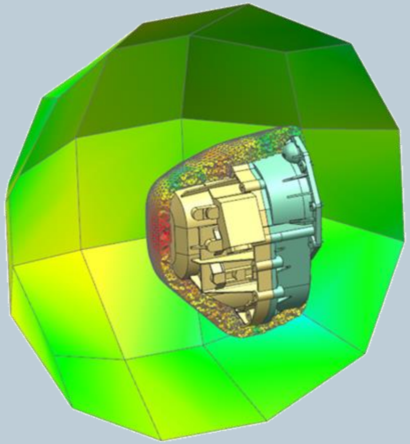
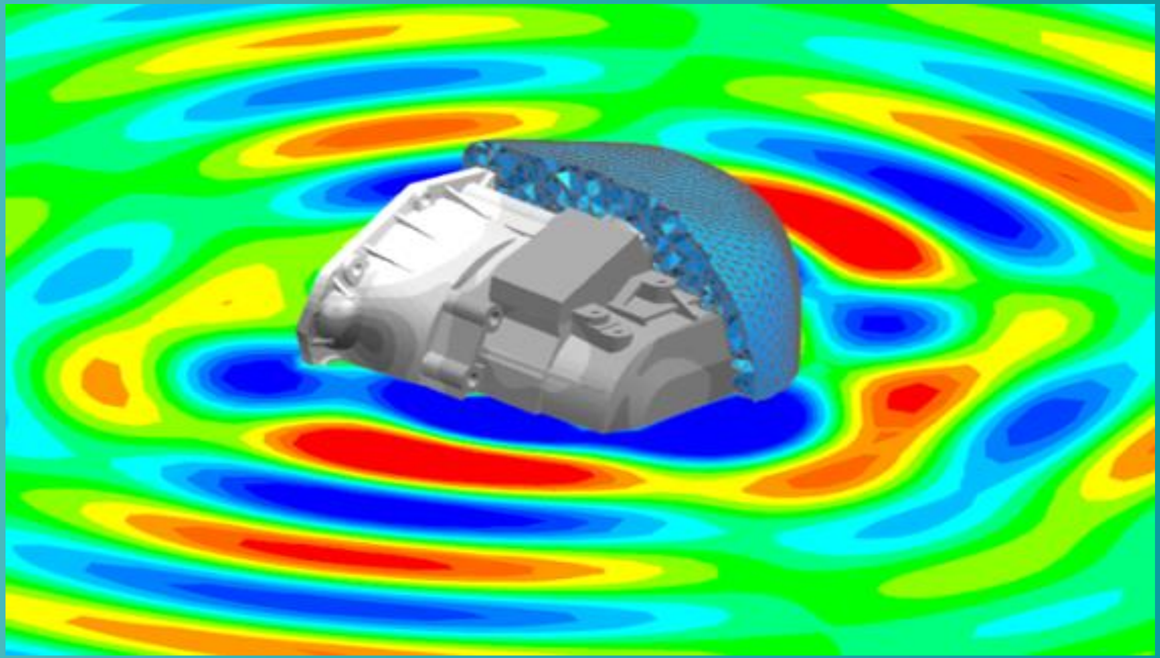


Acoustic Simulation of Transmissions



Acoustic Simulation

Post-Processing

Summary

Acoustic Process Overview

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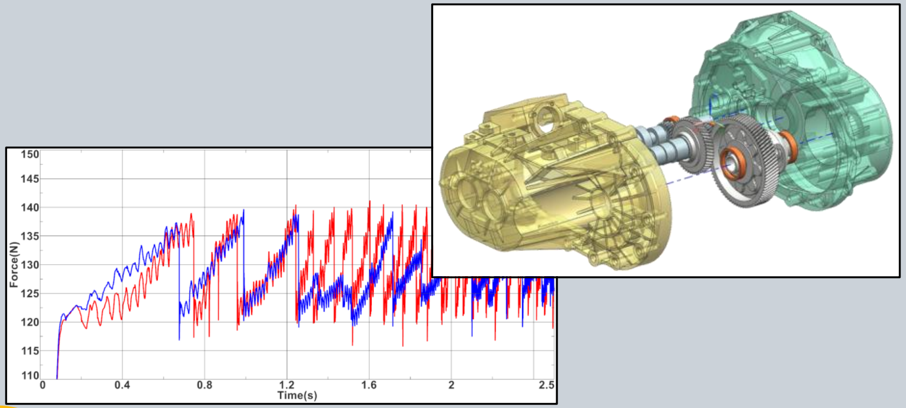
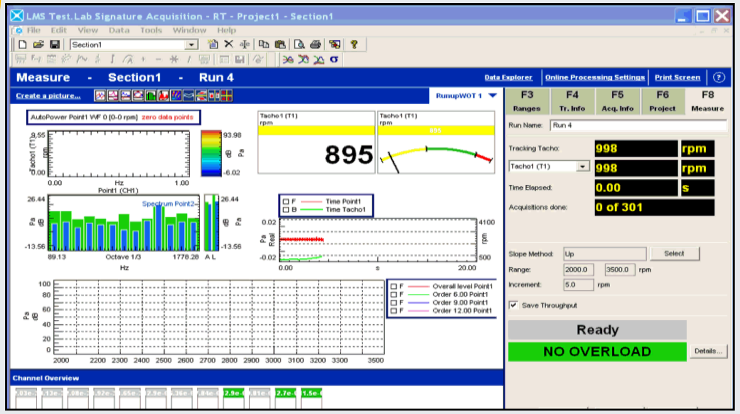


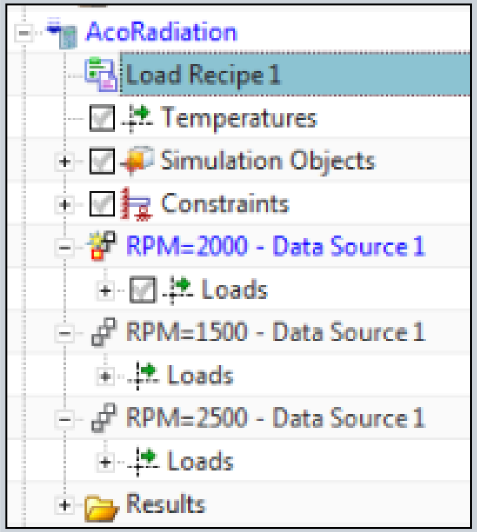
Multi-body simulation results

OR

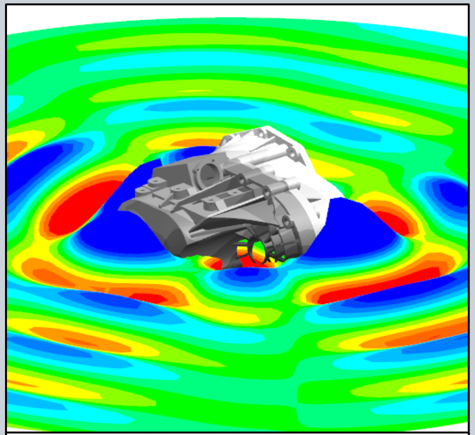


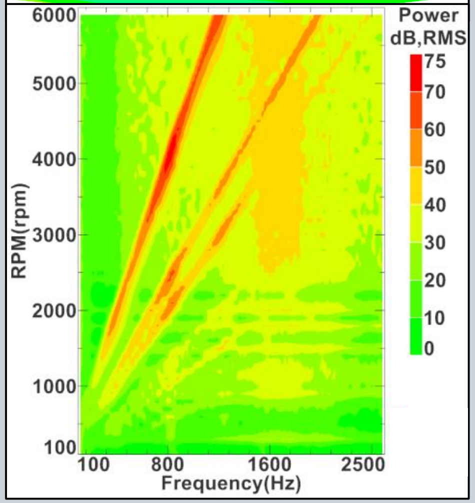
Measured data

Data processing and mapping



Load Recipe
Time series
Frequency spectra
Waterfalls
Orders





Noise Prediction

Acoustic Process Overview
From Motion to Acoustics

Benefits
- Quick switch between Motion and Acoustics solutions
- Efficient data processing (fast pre-solver)
- Automatic data mapping
- Pre-processing time reduction

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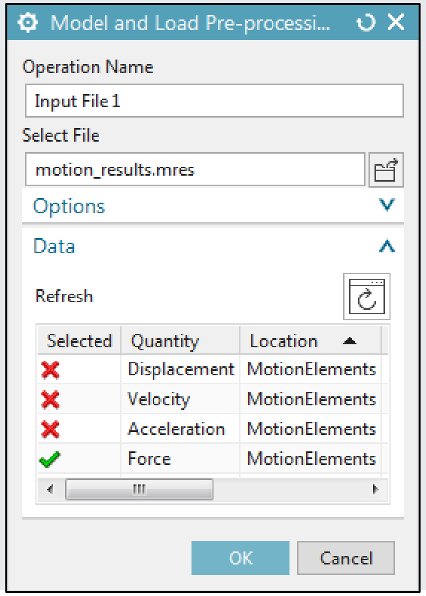
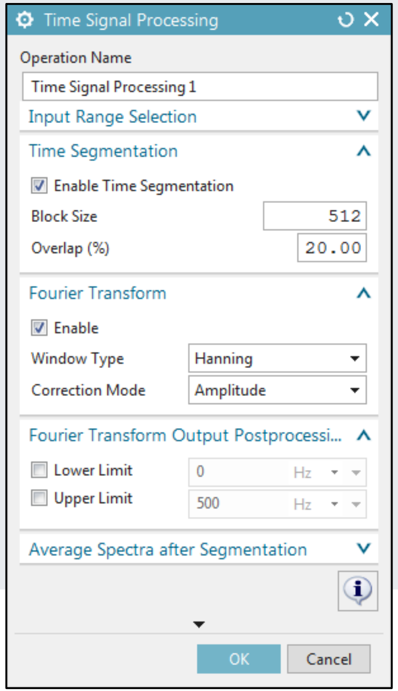
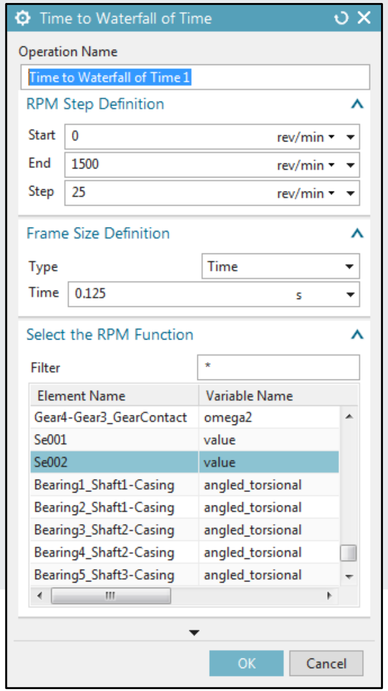
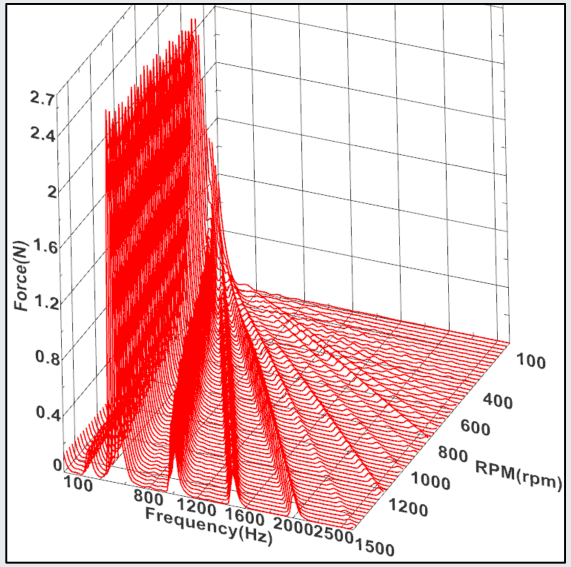
Input Loads	Time Data to Waterfall of Time Data	FFT	Post-Processing
• Multi-body simulation results • Data selection *(forces, vibrations)* • **Automatic mapping**	• Multiple RPM • RPM function • Frame size definition	• Time range selection • Time segmentation • Fourier transform *(windowing, frequency range, averaging)*	• Waterfalls • Functions • Order-cut analysis









Acoustic Process Overview

Acoustic Simulation

Benefits

- Efficient model set-up
- Efficient, accurate solutions
- Quick solution update
- Deep insight into results

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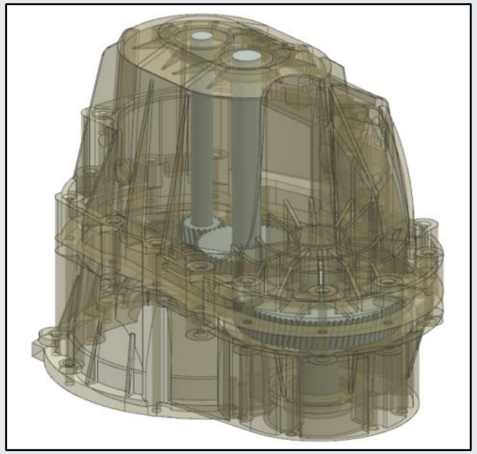
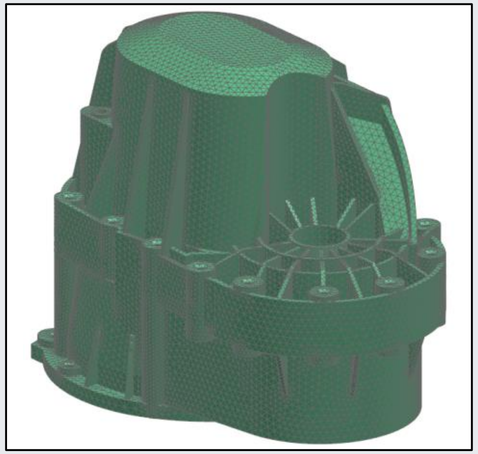
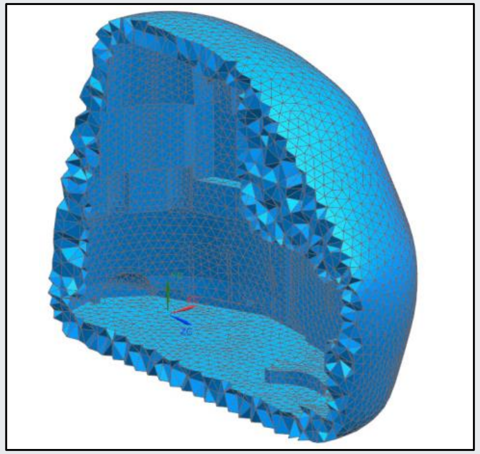
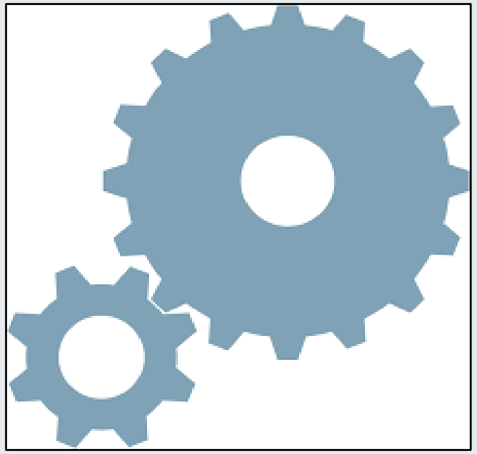
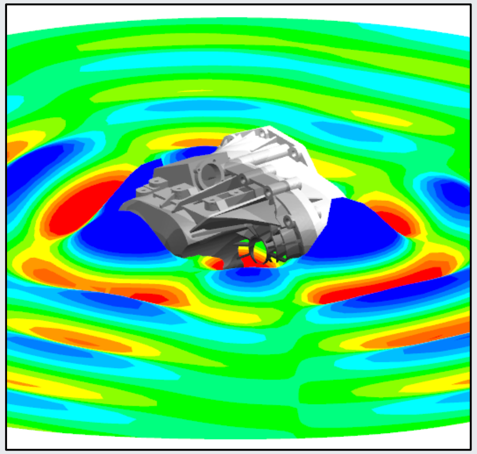
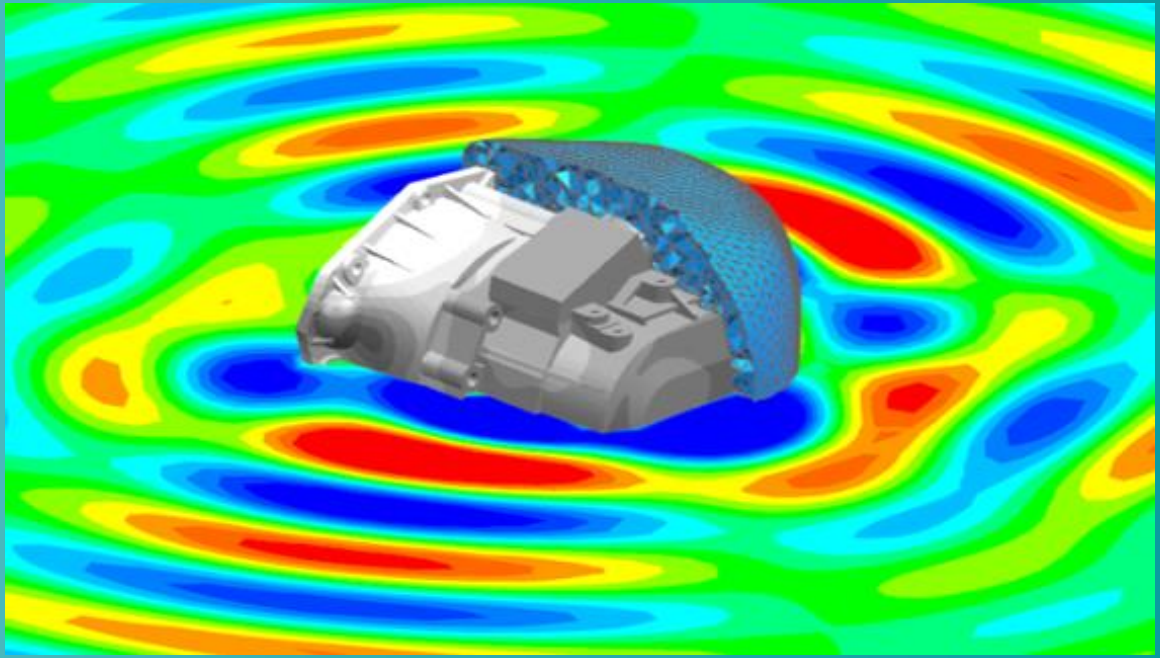
Geometry Preparation	Meshing and Assembly	Structural/Acoustic Pre-Processing	Solver	Post-Processing
• Holes closing • Blends removal • Parts assembly	• Mesh mating • Bolt pre-stress • Structural meshing • Acoustic meshing	• Loading from multi-body analysis • Fluid-Structure Interface • Output requests	• Simcenter Nastran Vibro-Acoustics *(FEM AML, FEMAO, ATV)*	• Structural results • Acoustic results • Contribution analysis *(modes, panels, grids)*
				

What-If, Optimization, Feedback to Designer

Acoustic Simulation of Transmissions



Acoustic Simulation

Post-Processing

Summary

Acoustic Simulation
Model Preparation – Meshes

Benefits

- Easy, fast, efficient model set-up
- Quick switch between CAD and FEM environments
- Quick update with associativity of meshes to CAD
- Flexible modelling through assembly

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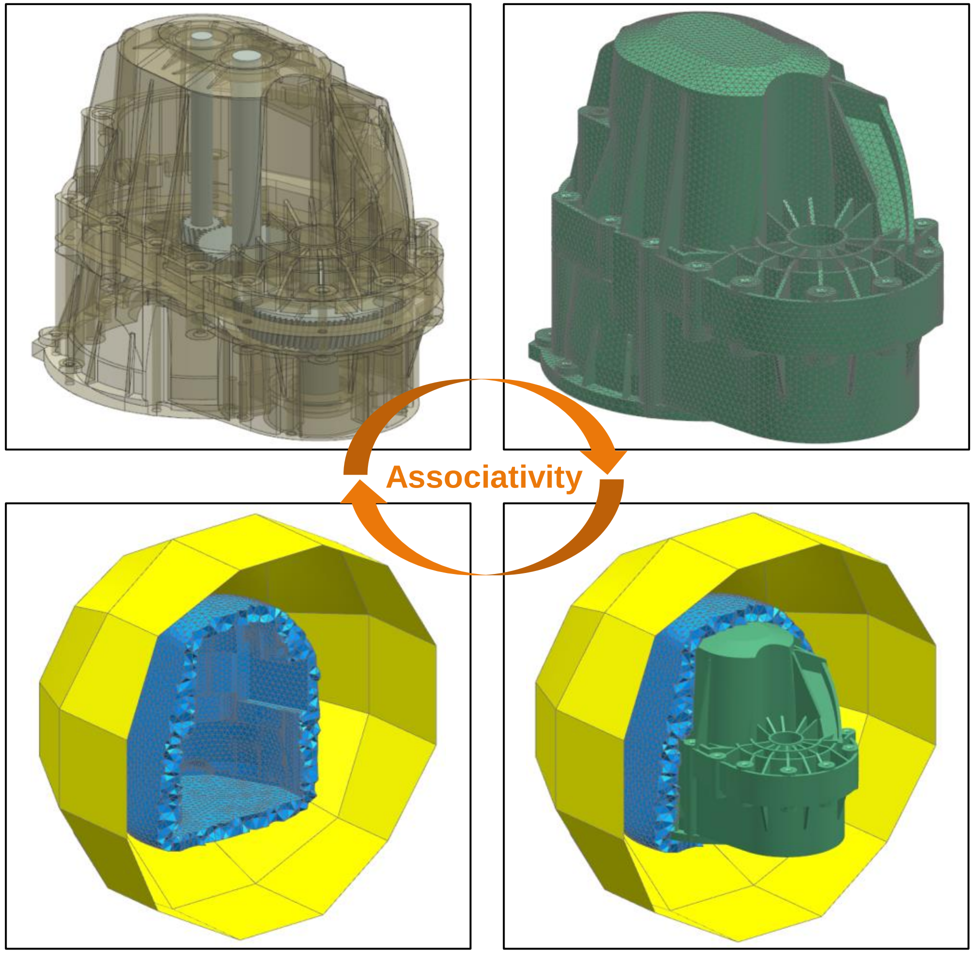
From multi-body analysis

- CAD geometry
- Structural mesh of body
  → Used to compute structural modes included in Motion model when accounting for flexibility of body

Specific to acoustic analysis

- Acoustic mesh around body for exterior noise radiation
  → Geometry cleaning (ribs removal, holes filling)
  → Surface and convex meshing
  → 3D elements filling
- Microphone mesh for acoustic response

Assembly of structural and acoustic meshes



Acoustic Simulation
Model Preparation – Loads and Boundary Conditions

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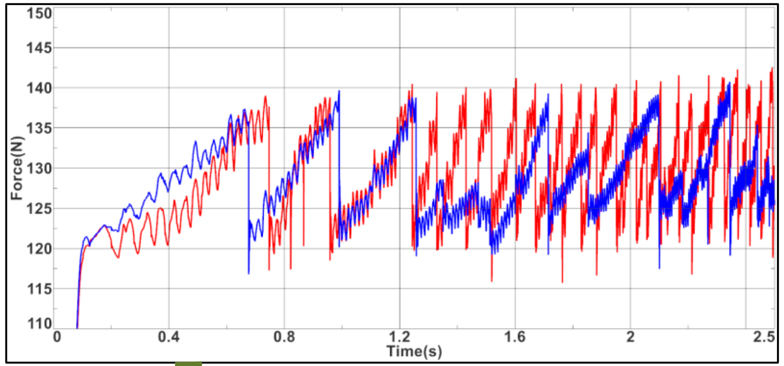
Structural constraints and loads

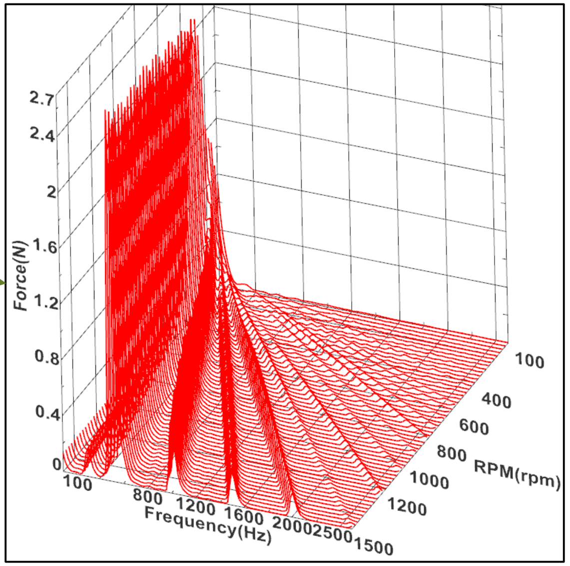
- Fixed constraints
- Multi-body forces applied at center of bearings
  → Automatic mapping
  → Data processing (time to waterfall of time data, FFT)



Acoustic boundary conditions

- AML (Automatically Matched Layer)
  → Non-reflecting boundary condition to absorb outgoing acoustic waves

**Time data
To
Waterfall of
Frequency data**



Fluid-structure interface

- Weak or strong coupling

Benefits

- **Easy, fast, efficient model set-up**
- **Quick switch between FEM and SIM environments**
- **Quick solution update with associativity of loads and boundary conditions to CAD**

Acoustic Simulation
Solver Technologies – FEM AML

AML (Automatically Matched Layer)

- Automatic creation of PML (Perfectly Matched Layer) at solver level
  → Full absorption of outwards-traveling waves
  - First, accurate results in “physical” (red) FEM domain
  - Then, accurate results outside the FEM domain (green), through post-processing
- PML layer very close to radiator

Benefits

- **No manual creation of extra absorbing layer**
- **Optimal absorption**
- **Lean FEM model**
- **Fast computation**

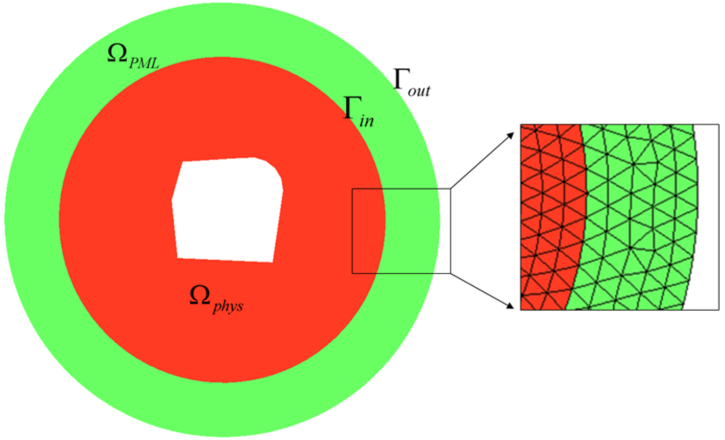
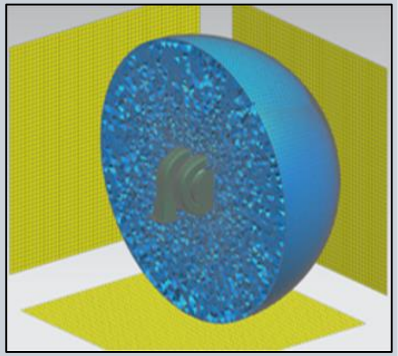
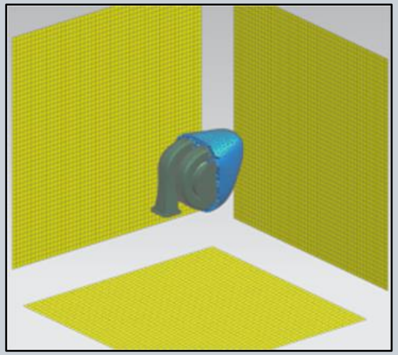


Figure 7: PML elements layer around a bounded spherical FEM model

$$\forall x \in \Omega_{PML} : x \rightarrow \hat{x} = x + \frac{f(x)\vec{n}(x)}{jk}$$

$$p(x) = \int_{\Gamma_{in}} G(x,y)\frac{\partial p(y)}{\partial n} + p(y)\frac{\partial G(x,y)}{\partial n}\, d\Gamma_{in}$$

	ρc	AML
		
Size	~ 190k nodes	~ 14k nodes
Time	x s/freq.	$x/20$ s/freq.

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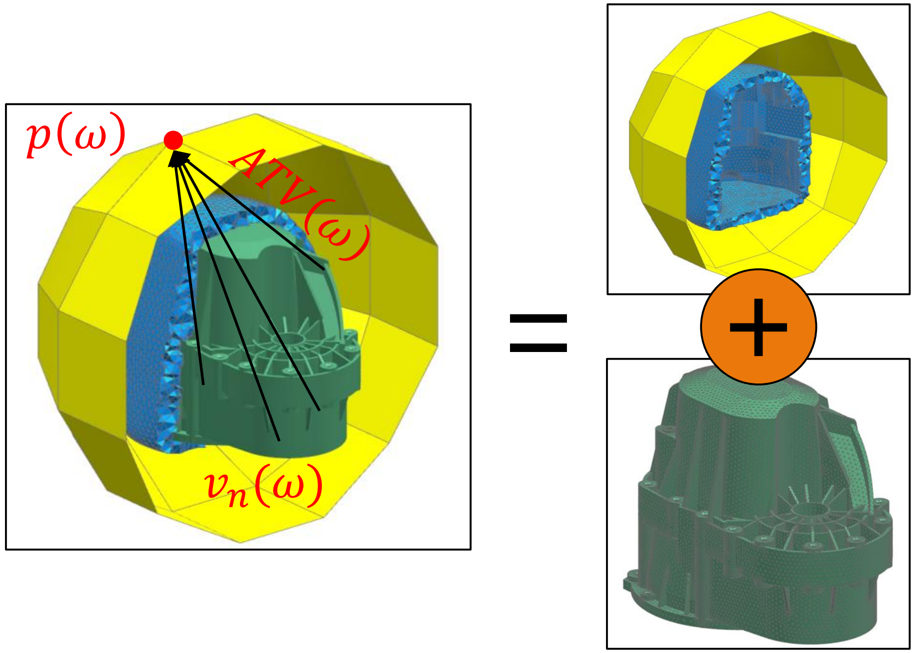
ATV (Acoustic Transfer Vector)

- **Single** computation of acoustic transfer vector between vibrating surface and microphones

$$\{p(\omega)\} = [ATV(\omega)] \times \{v_n(\omega)\}$$

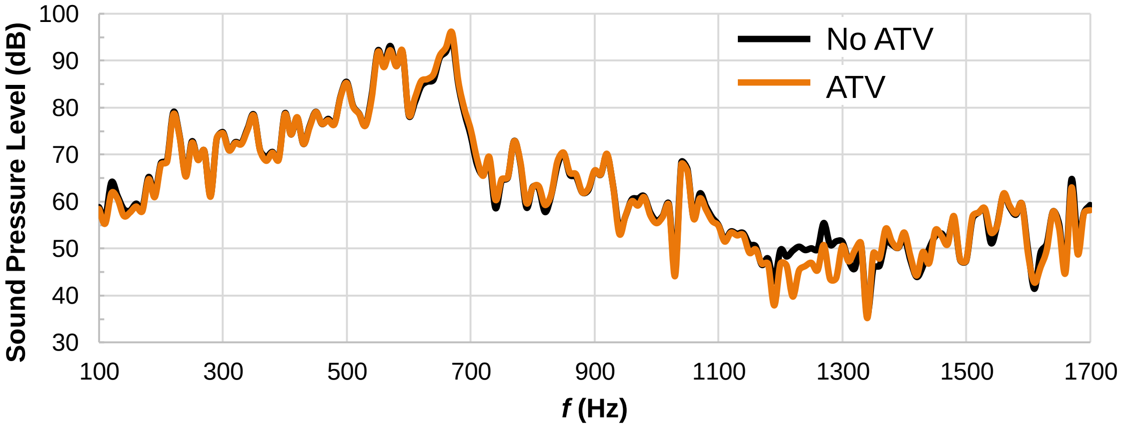
- Independence of ATV from load conditions (RPM, order)
- For exterior radiation, smooth ATV functions in frequency



Benefits

- **Large frequency steps for ATV computation, and interpolation for acoustic response**
- **Fast multi-RPM analysis**

	FEM	ATV Response
Frequency	100-1700 Hz	100-1700 Hz
Time	22 min	3 min



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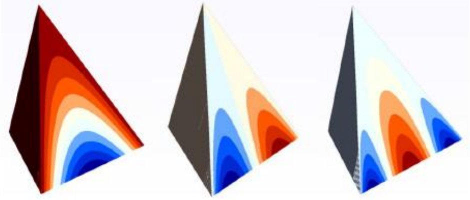
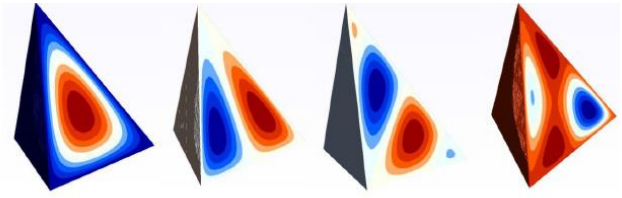
FEMAO (FEM Adaptive Order)

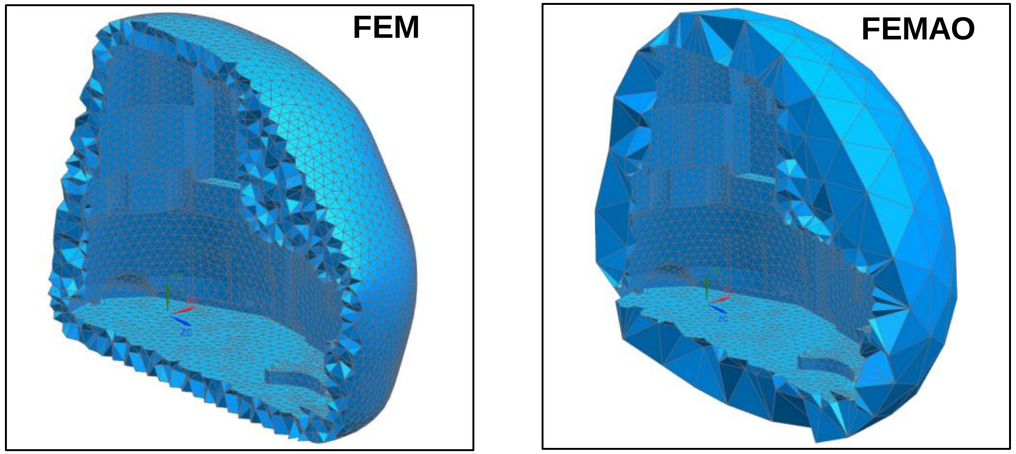
- High-order FEM with adaptive order refinement
- Hierarchical high-order shape functions
- Auto-adapting fluid element order at each frequency (dependent on f, local c_0, local h), to maintain accuracy



Edge Shape Functions

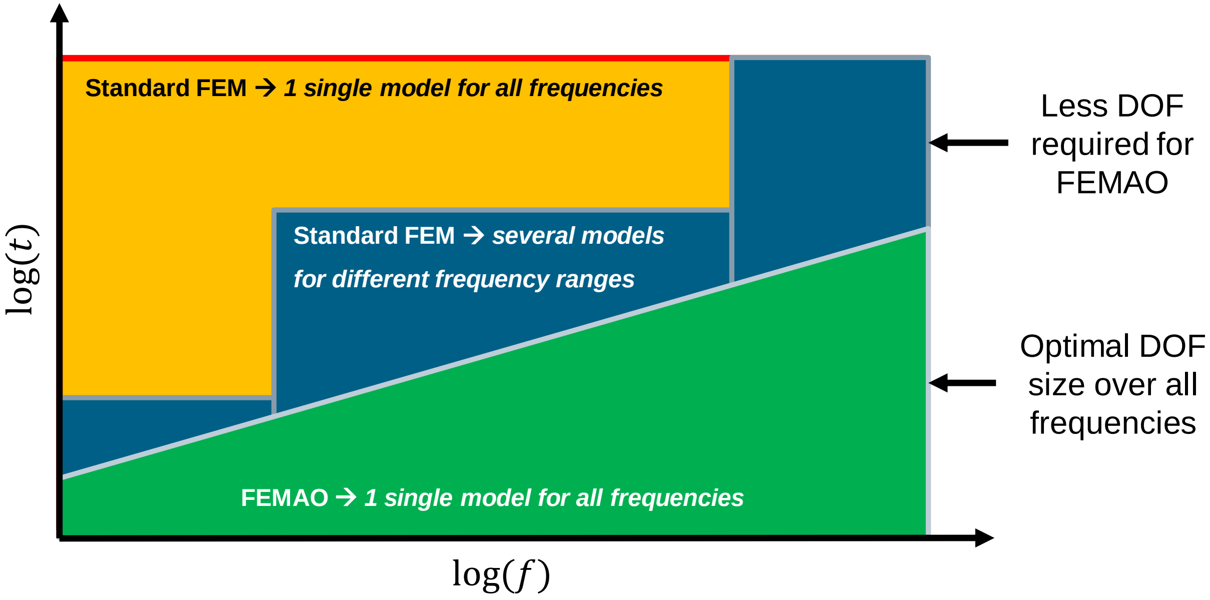


Face Shape Functions



Benefits

- **Lean single coarse acoustic mesh**
- **Optimal model size at each frequency**
- **Huge gains vs standard FEM**
  - **Faster at lower frequencies**
  - **More efficient at higher frequencies**
  - **2 to 10 x faster**



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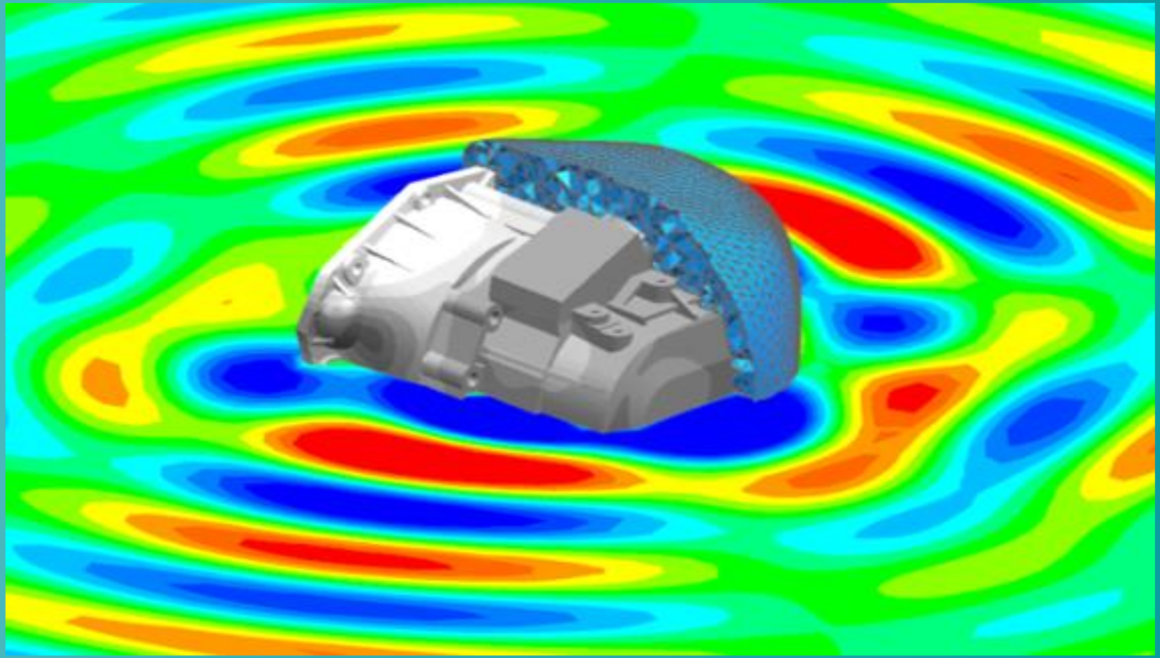
Acoustic Simulation of Transmissions



Acoustic Simulation

Post-Processing

Summary

Bearing Forces
Frequency Domain

Benefits

- Deeper insight on input forces
- Quick solution update for comparative studies involving design/modelling changes

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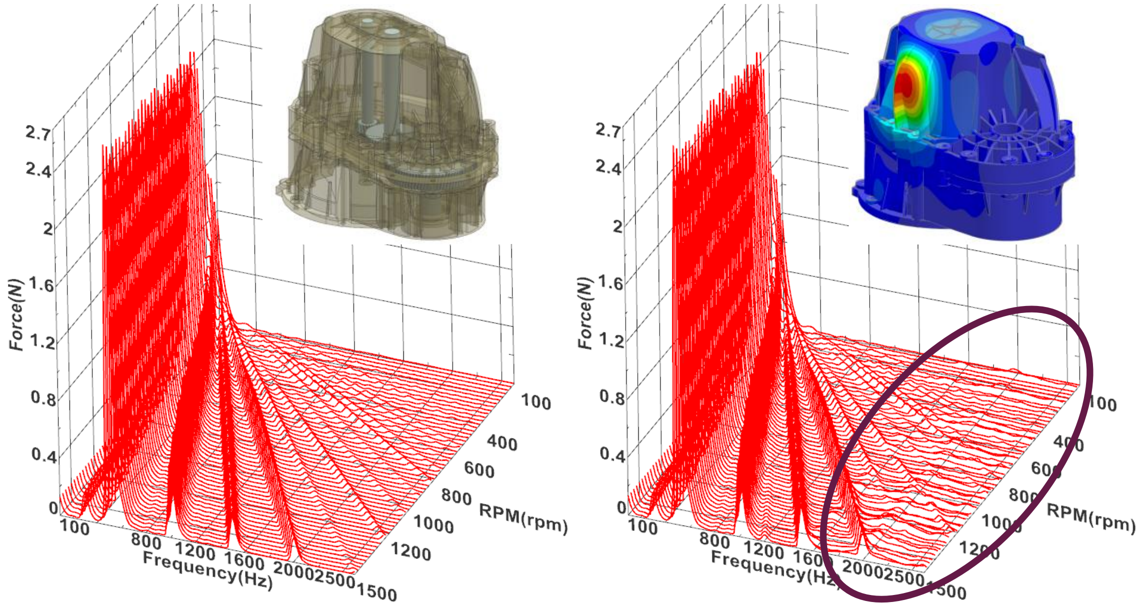
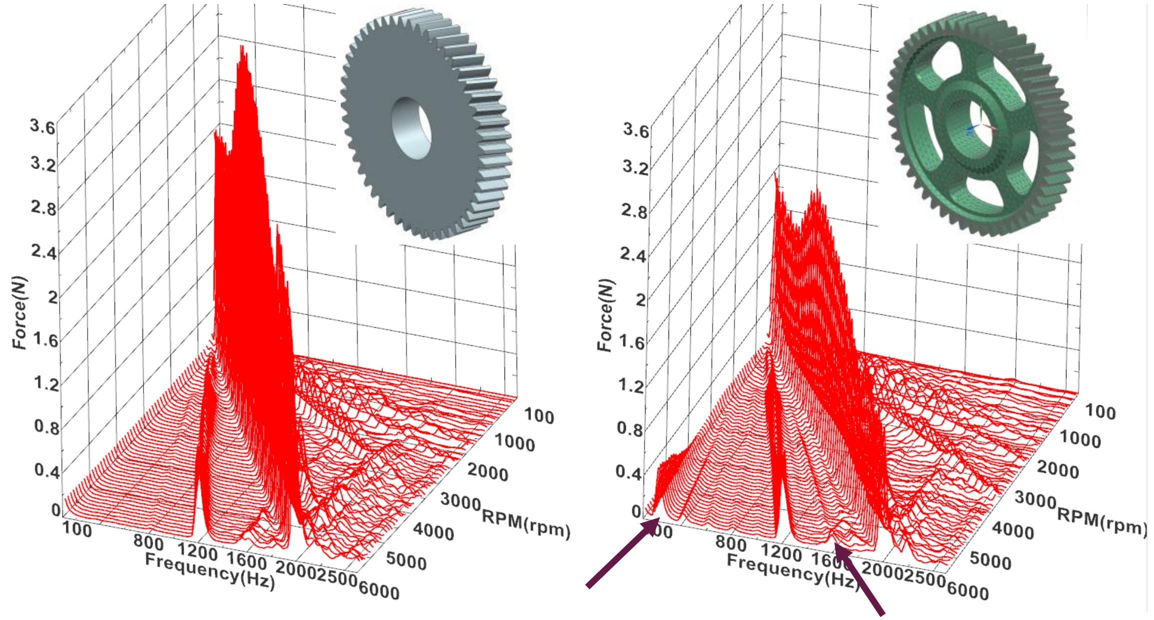
Rigid body vs Flexible body



Plain gears vs Lightweight gears (flexible body)



- No significant difference at low frequencies
- Above 1400 Hz, more frequency content due to structural modes of flexible housing structure

- Low harmonic at 200 Hz (6000 RPM), due to gear stiffness variation with holes in lightweight gear
- Side band due to tooth stiffness variation (amplitude effect due to coupling with holes)

Radiated Acoustic Power
Functions

Benefits
- Efficient post-processing for results analysis
- Quick solution update for comparative studies involving design/modelling changes

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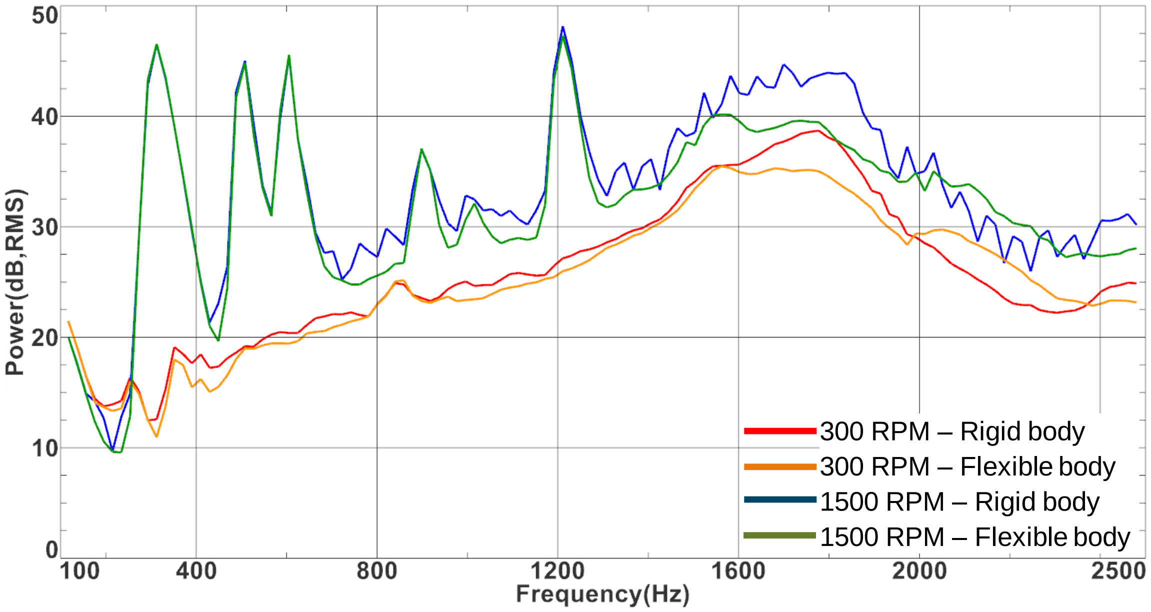
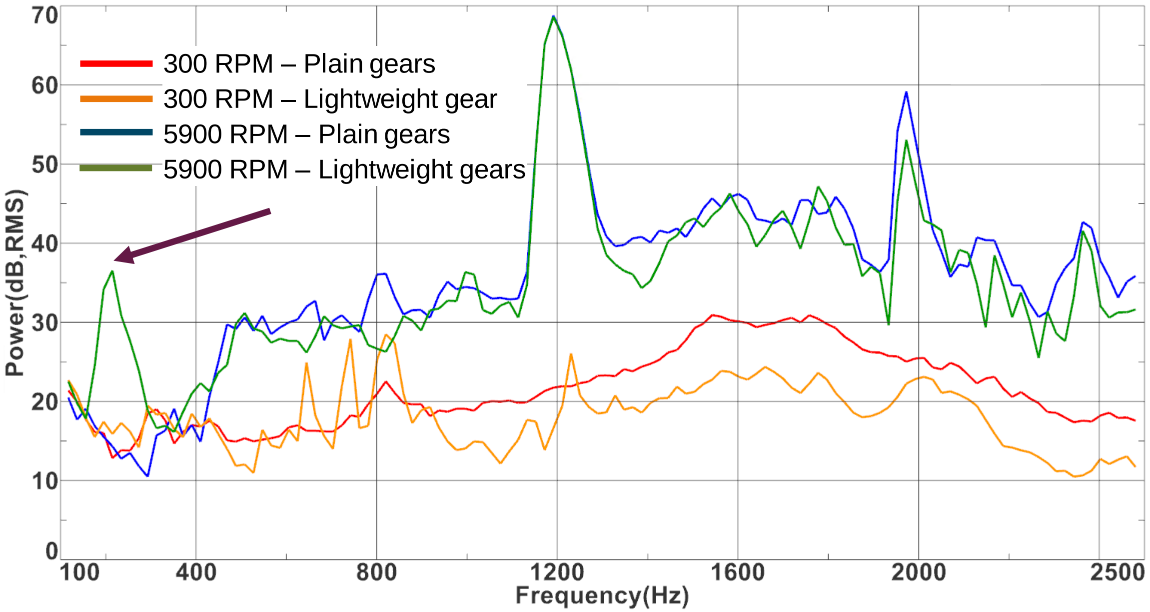
Rigid body vs Flexible body



Plain gears vs Lightweight gears (flexible body)



- Low frequencies
  - Reduced impact of flexibility
- High frequencies
  - Larger impact of flexibility

- Low RPM
  - Significant impact of lightweight gears
- High RPM
  - Extra frequency content at low frequencies

Order-Cut Analysis
Rigid Body vs Flexible Body

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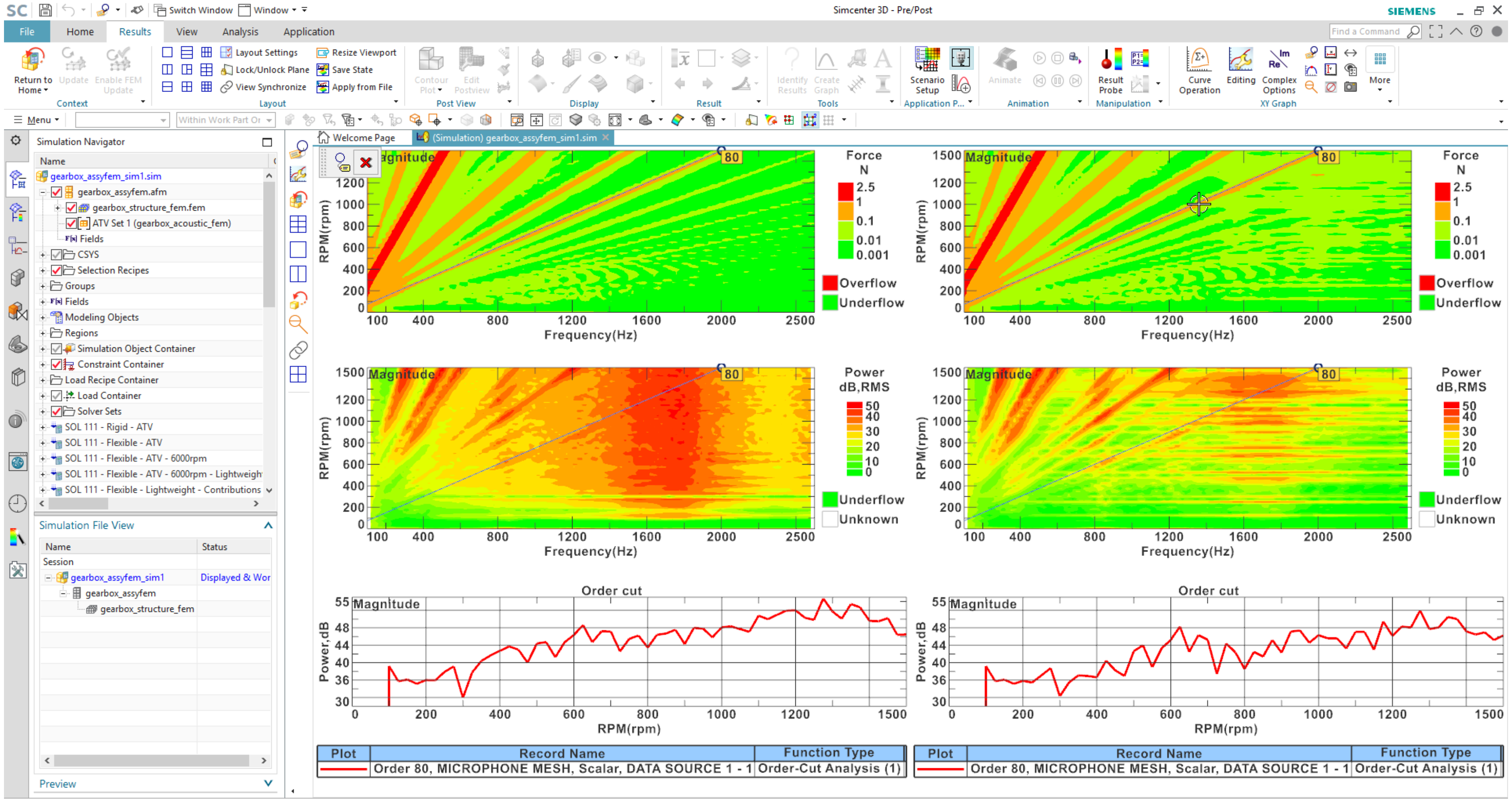
Benefits

- **Efficient post-processing for results analysis**
- **Global overview on correspondence between source (dynamic forces) and receiver (acoustic power)**



Order-Cut Analysis
Plain Gears vs Lightweight Gears

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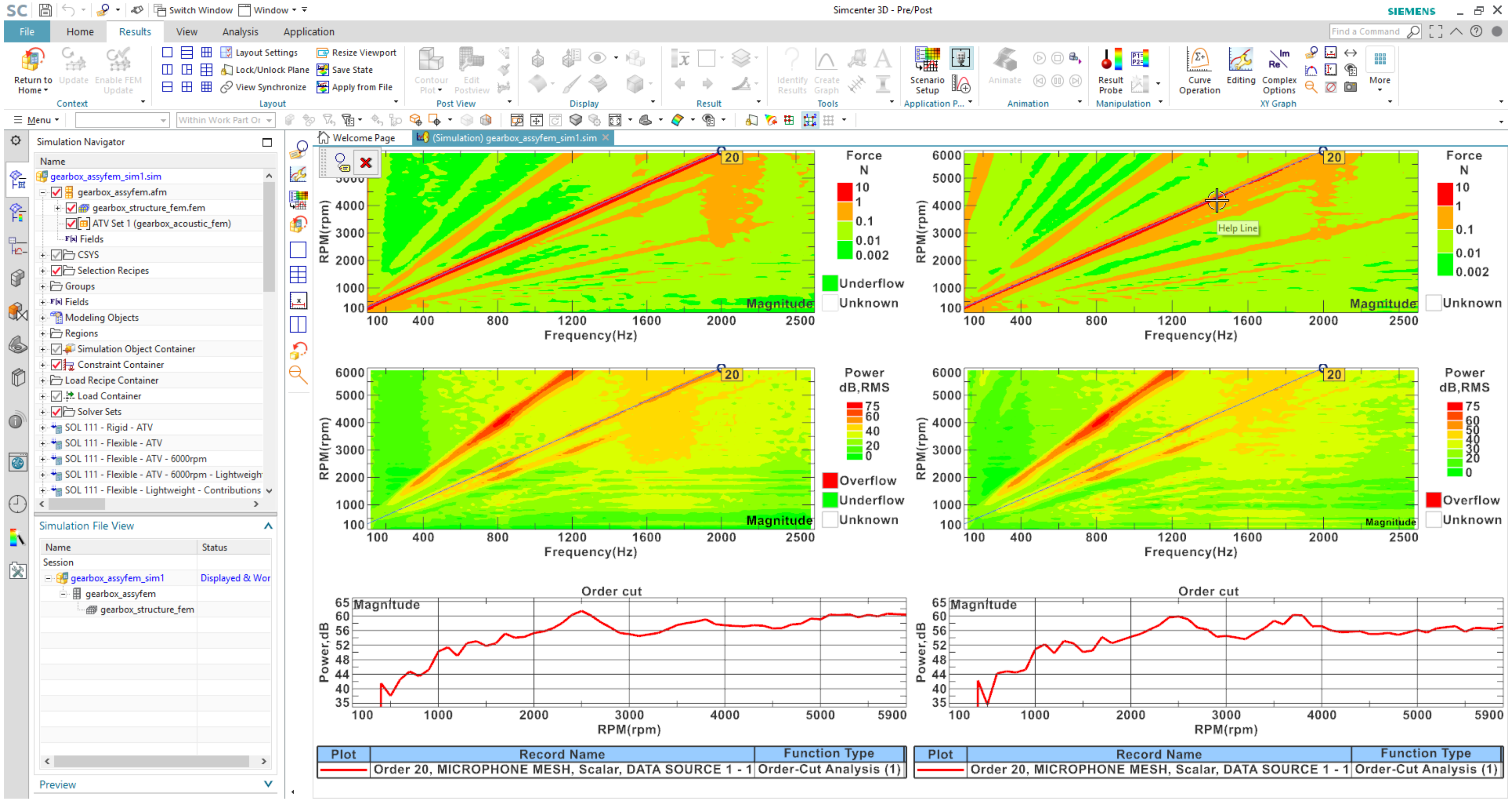
Benefits

- Efficient post-processing for results analysis
- Global overview on correspondence between source (dynamic forces) and receiver (acoustic power)

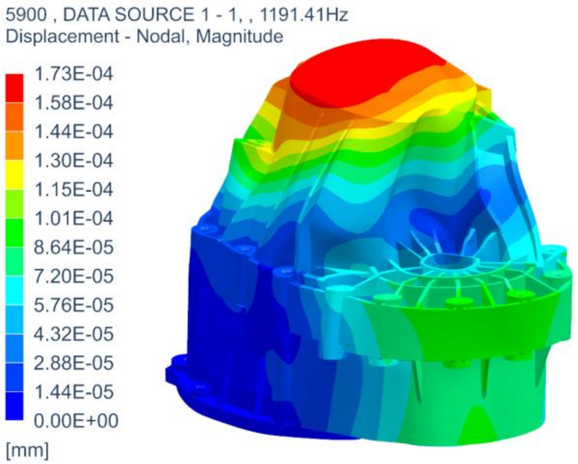


Contribution Analysis
Examples

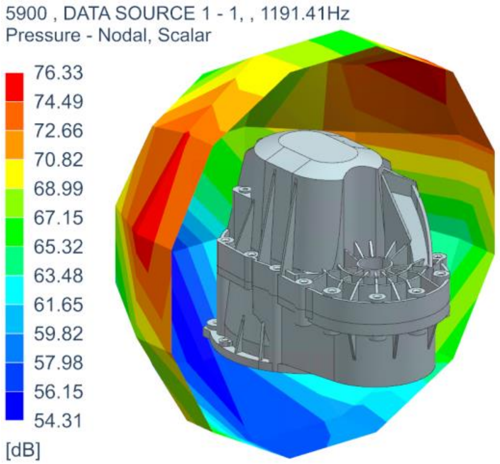
Multiple results types: structural displacements and modes, equivalent radiated power, acoustic pressure and power, panel contributions to pressure and power, grid contributions, etc

Benefits

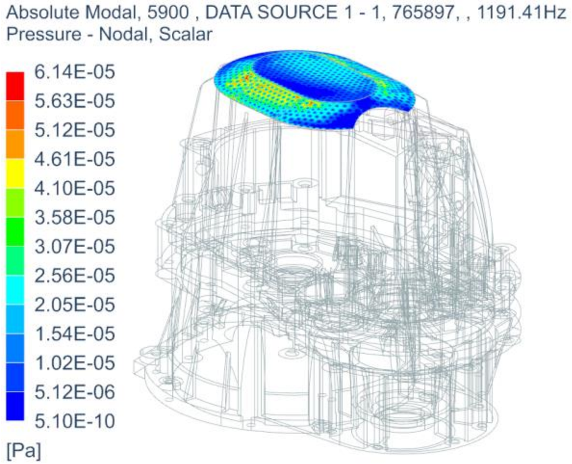
- **Efficient post-processing for results analysis**
- **Deep understanding of model behavior through multiple results types**



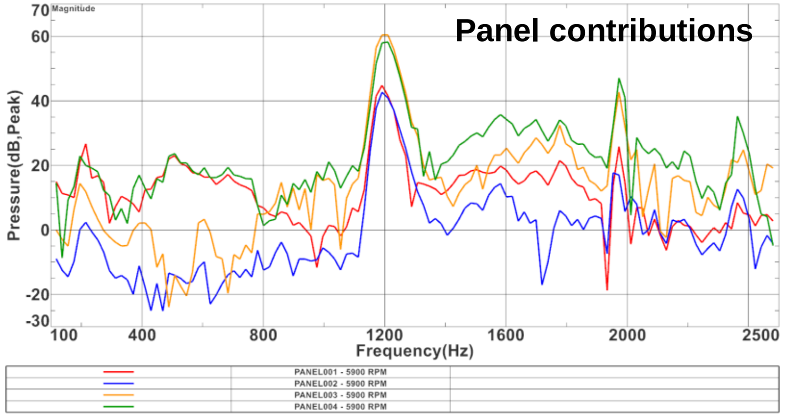
Structural displacements



Acoustic pressure



Grid contributions



Panel contributions

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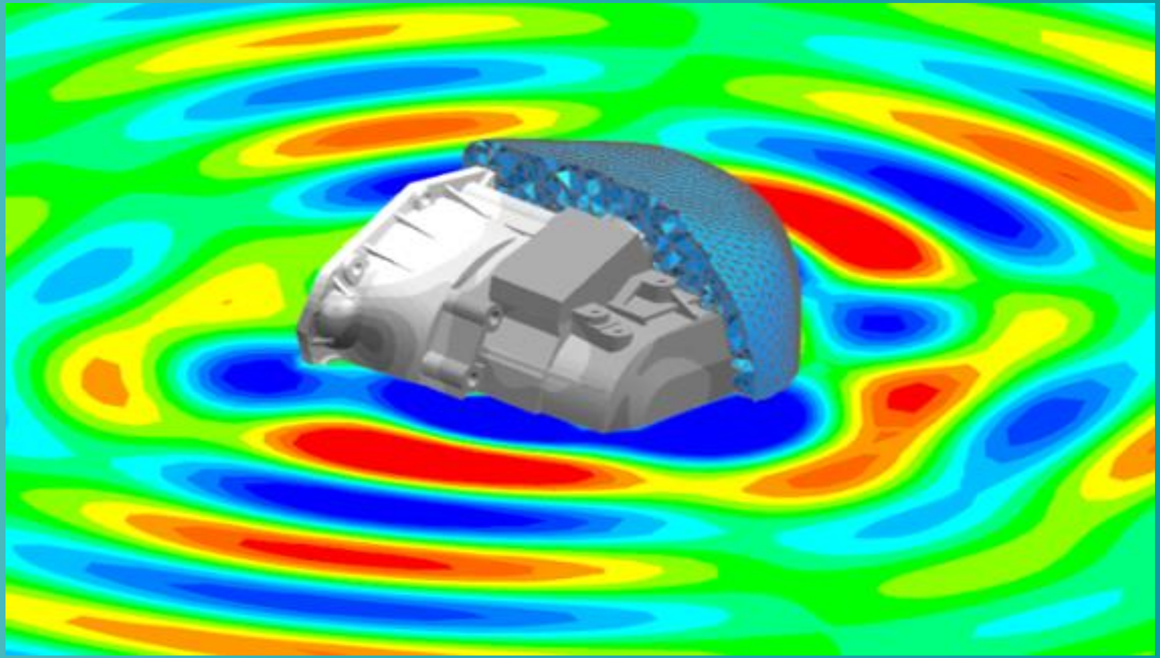
Acoustic Simulation of Transmissions



Acoustic Simulation

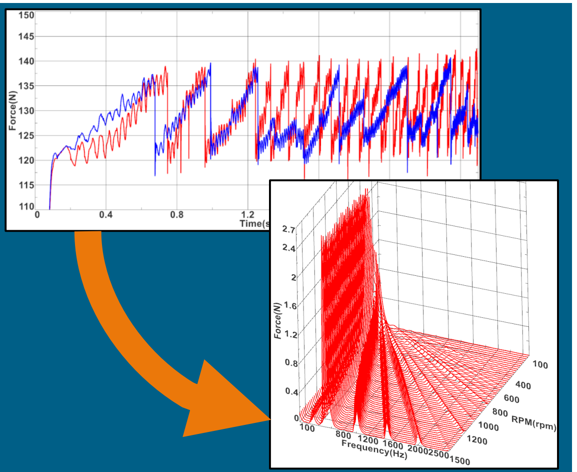
Post-Processing

Summary

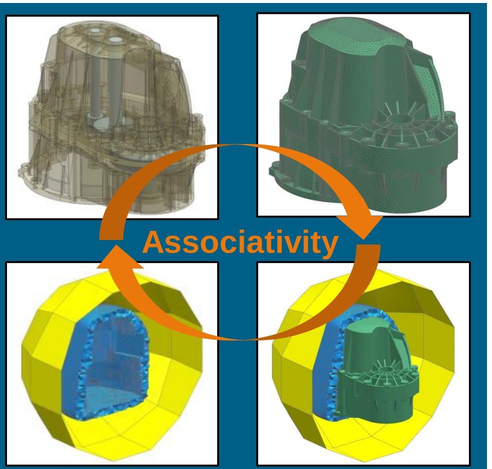
Acoustic Simulation of Transmissions

Summary

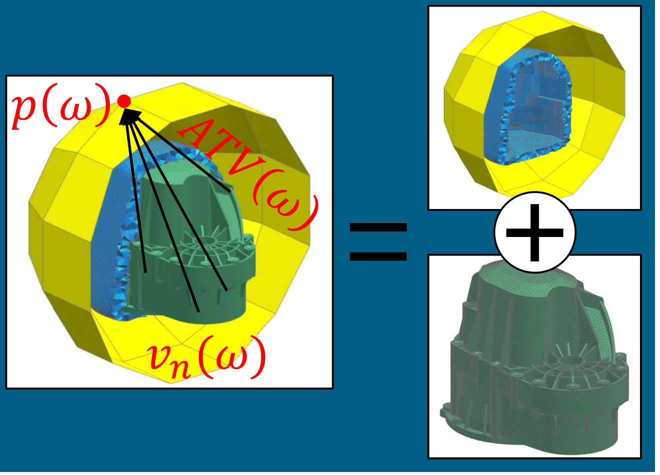
More efficient link of gear forces from Motion to Acoustics



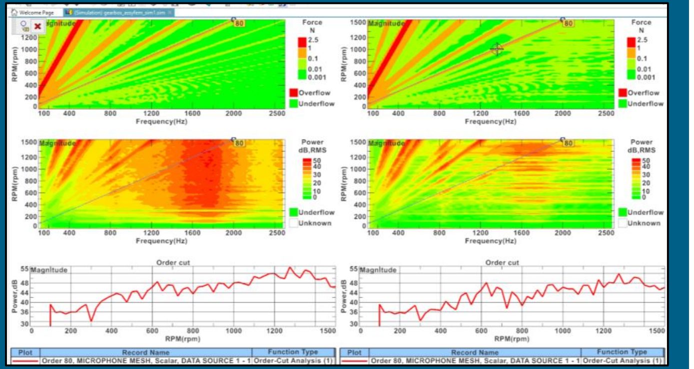
Efficient model set-up with CAD associativity for quick solution update



Fast and accurate solver technologies

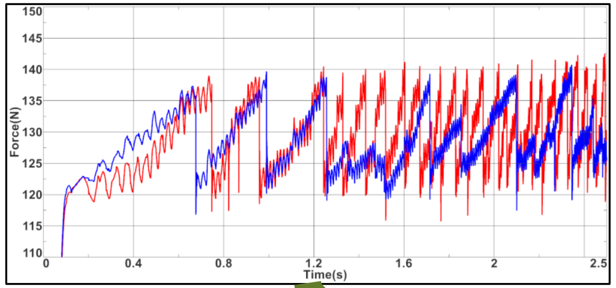


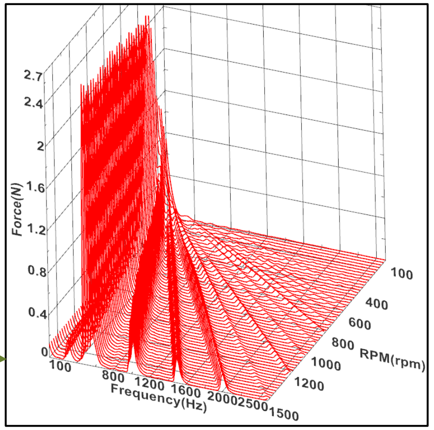
Superior insight in vibro-acoustic response



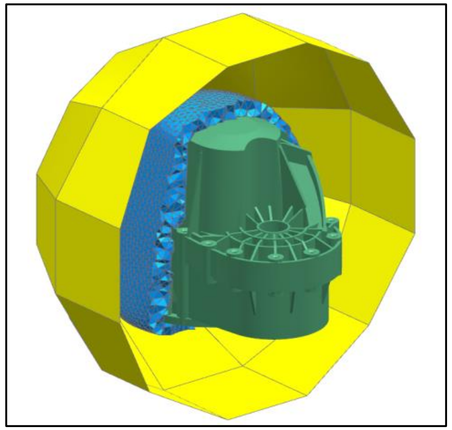
Simcenter 3D Acoustics
Simulate Transmission

- Transfer bearing forces into frequency domain

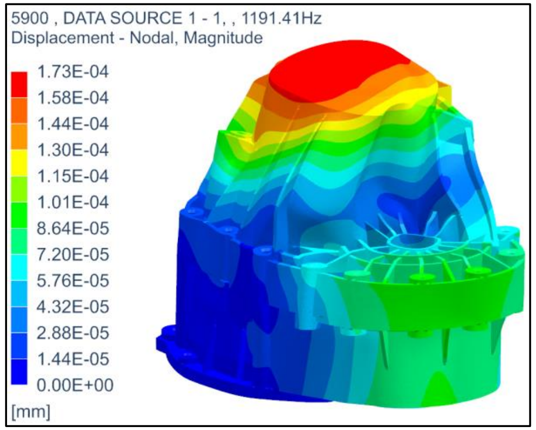




- Set-up vibro-acoustic model

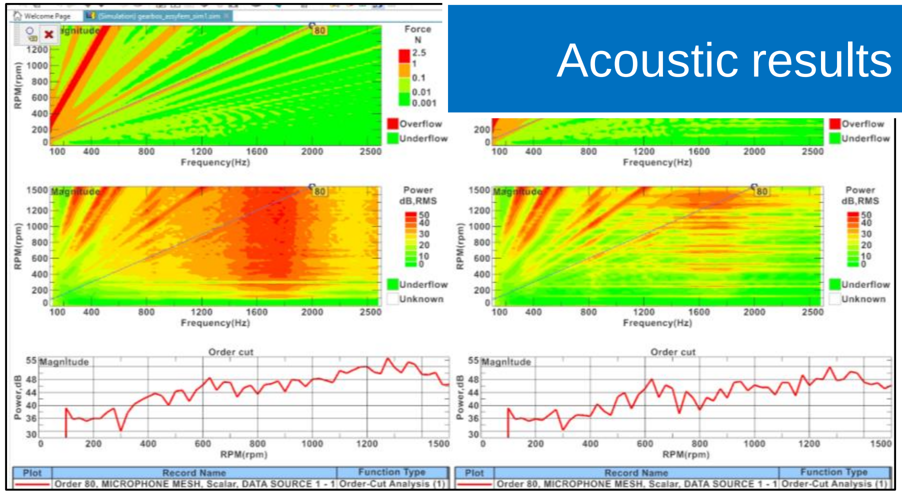


- Map bearing forces onto vibro-acoustic model



Simulate

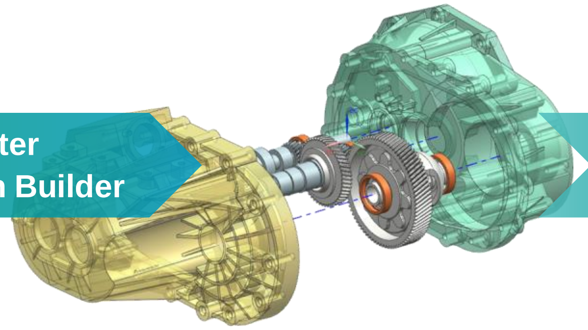
Acoustic results



Conclusion

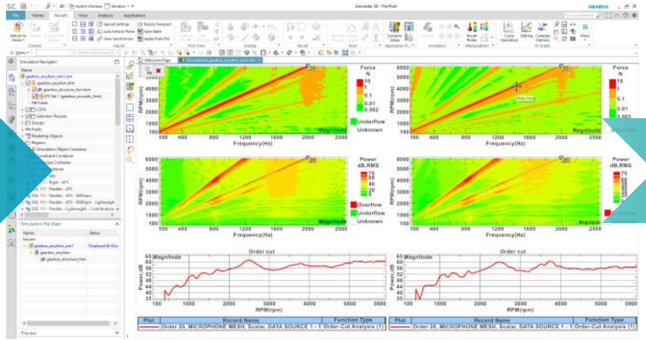
Predict and Reduce Gear Whine Noise 5 Times Faster

Generate transmission gearbox models automatically and boost vibro-acoustic performance

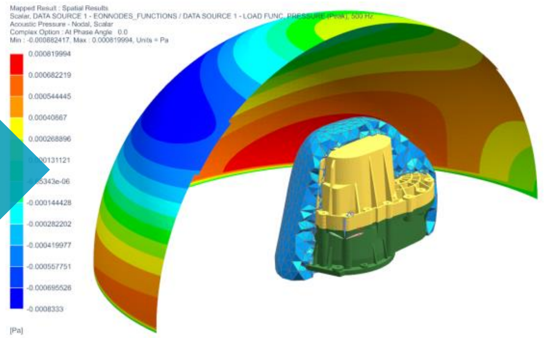


Simcenter Transmission Builder

Motion Simulation



Acoustic Simulation



Automation removes 80% of workload for transmission model generation

New gear solver increases efficiency and accuracy

Automatic motion-to-acoustics link simplifies pre-processing

Fast acoustic solver gives superior insight to response

Hyundai Motor Company
Gear Whine Analysis of Drivetrains Using Simcenter Simulation & Services

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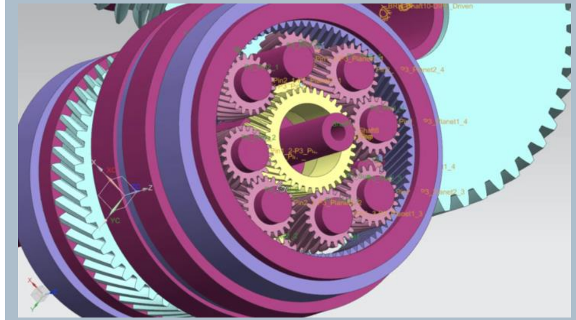
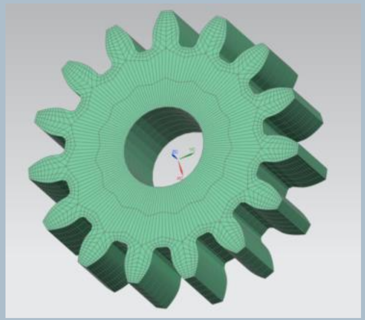
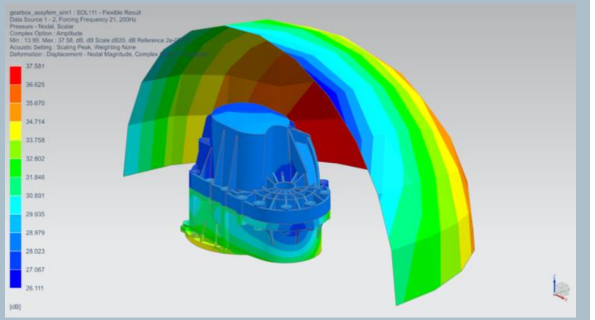
- **Predictive simulation for system level NVH and gear whine**
- **Bring 3D simulation to the next level of usability, towards an holistic generative approach for drivetrain design and NVH**

Easy workflow from design specifications NVH gear whine analysis







Automatic CAD and multibody creation	**Accurate** FE-based gear elements	**Multi-disciplinary** CAD-FEM Multibody- Acoustic

- Simcenter 3D Motion and Transmission Builder for system level NVH in multibody
- Simcenter Engineering and Consulting for solving complex engineering issues

"Simcenter Engineering and Consulting services helped us use the right analysis tools to cover the entire gear transmission analysis […] The Simcenter 3D Transmission Builder software tool is well suited for our engineering purposes"

Mr. Horim Yang, Senior Research Engineer

https://youtu.be/bBM5TPP6iBg