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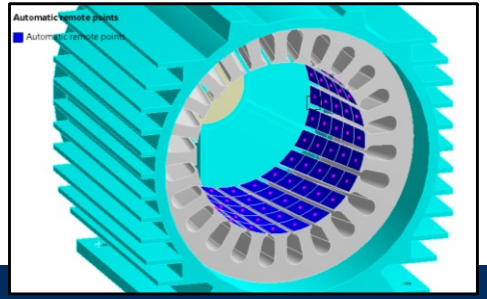
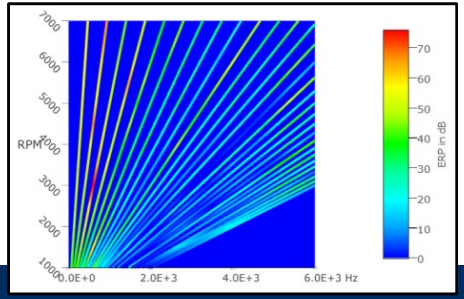




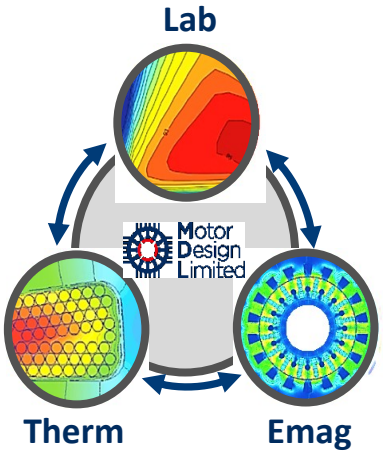
Vibration and Equivalent Radiated Power (ERP) of Electric Machines during Drive Simulation

Martin Hanke
Jürgen Wibbeler

KMK 2018, Ilmenau, March 15th – 16th

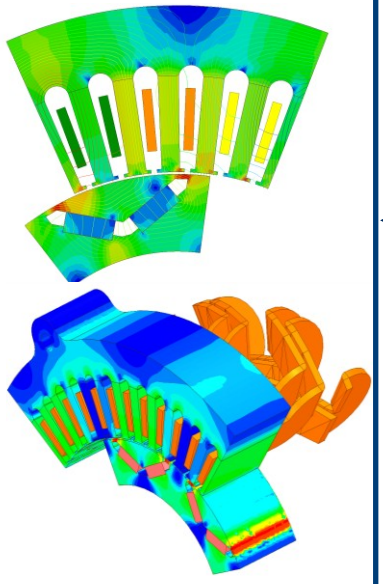
Electric Motor Design Platform & Workflow

Design
Efficient Motor Design Toolkit



Motor-CAD

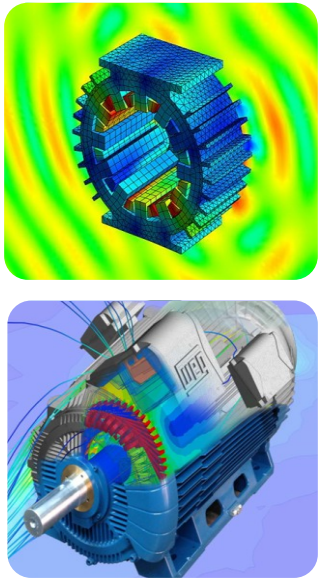
2D & 3D Analysis
Advanced Magnetics Modeling



Maxwell 2D & 3D

ANSYS

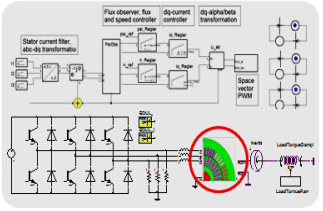
Coupled Analysis
NVH, Cooling…



Mechanical & CFD

ANSYS

System Validation
Control logic, software



Motor Design Limited
Concept Design

System Validation

3D Physical Validation

Simplorer

ANSYS

Electrical Drives as Noise Sources

Origin of Noise by Electrical Drives:

Magnetic Circuit

- Reluctance, geometry
- Magnetic saturation
- Current waveform, Inverters

Fluidics

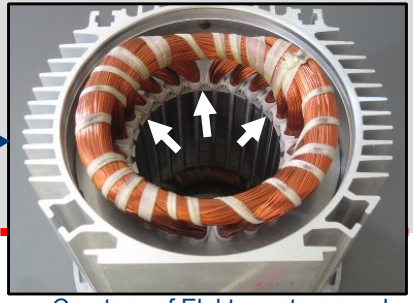
- Cooling

Drive Side

- Gearbox etc.

➔ *Sources captured by the presented method*

Gap forces



Courtesy of Elektromotorenwerk Grünhain GmbH

CADFEM

ANSYS

Contents

- Concept of FEM-based Noise Computation
- Electromagnetic Analysis Using ANSYS Maxwell
  ➔ Computation of Magnetic Excitation Loads
- Dynamic Analysis Using *Electric Drive Acoustics inside ANSYS*
  ➔ Computation of Structural Vibration and Noise Level
- Load Application for Non-skewed and Skewed Motors
- Postprocessing of Equivalent Radiated Power (ERP)
- Summary

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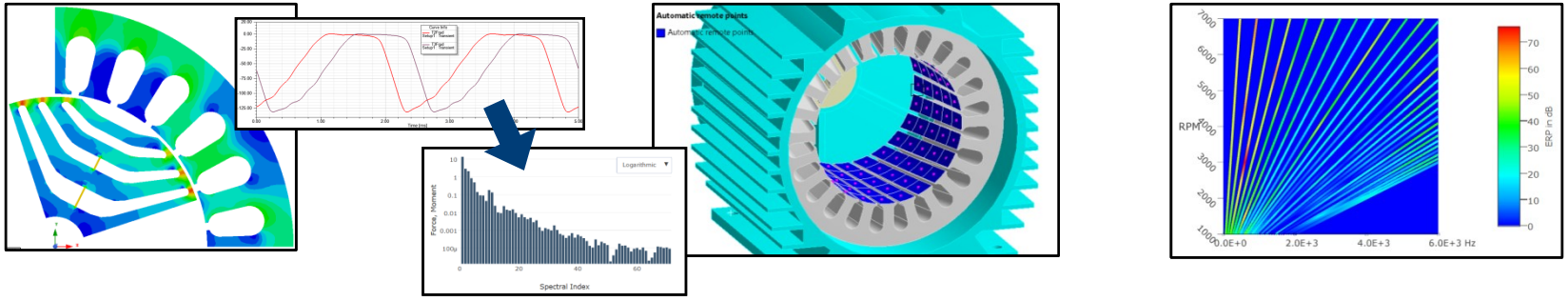
Concept of FEM-based Noise Computation

Concept of FEM-based Noise Computation

From Electromagnetic FEM-analysis to Equivalent Radiated Power (ERP):

Electro-magnetic Analysis → **DFT** → **Harmonic Vibration Analysis** → **Oscillation, ERP, Waterfall Plot**

Excitation Loads



→ Waterfall diagramm
➔ Simulation over speed range!

Concept of FEM-based Noise Computation

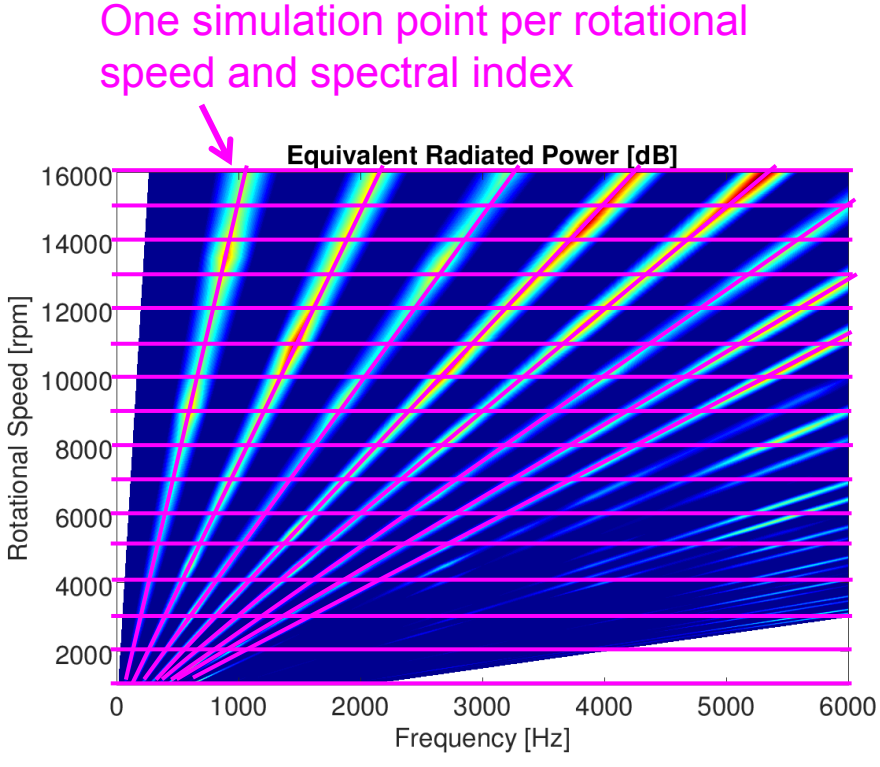
Waterfall (also Campbell) Diagram: Numerical Analysis vs. Measurement

Example: 40 rotational speed points
30 spectral lines

= 1200 simulation points!

➔ FEM-methods with minimized computational effort:

- reduce electromagetic sim.
- speed up structural dynamics
- ERP instead of true acoustics



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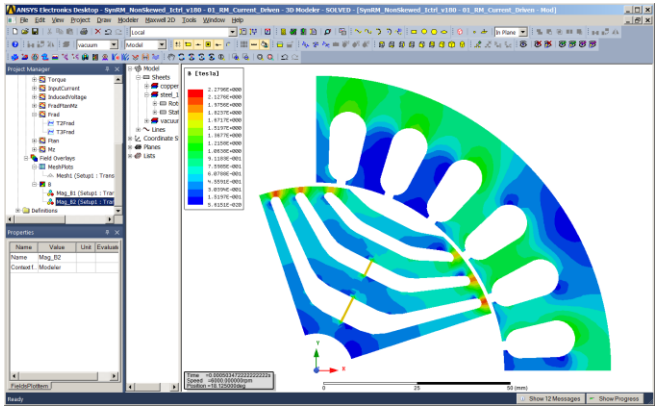
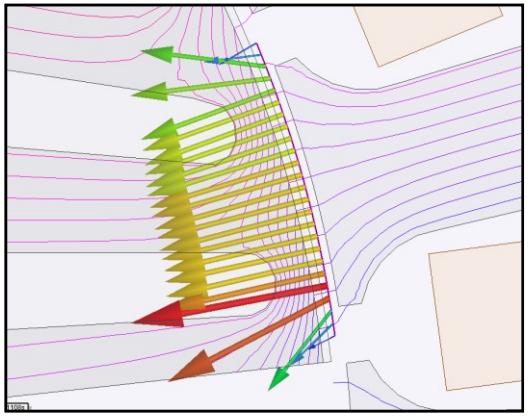
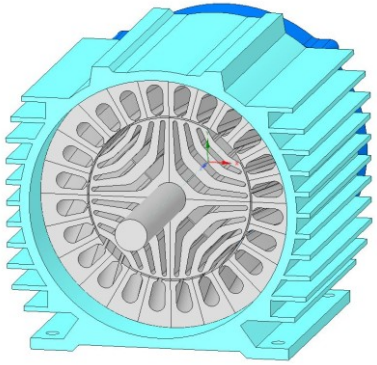
Electromagnetic Analysis Using ANSYS Maxwell

Magnetic Field Computation:







Force density distribution

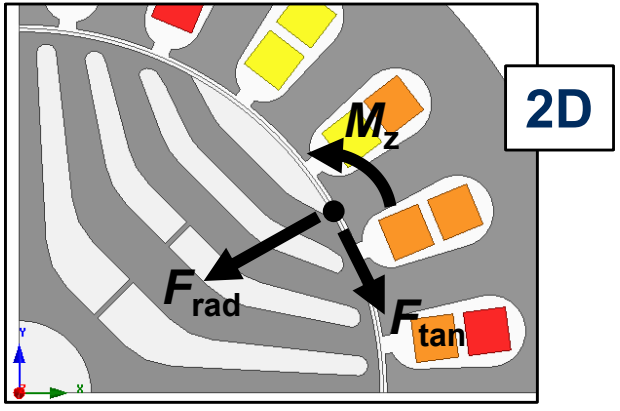
- Force density distribution by Maxwell Stress Tensor:

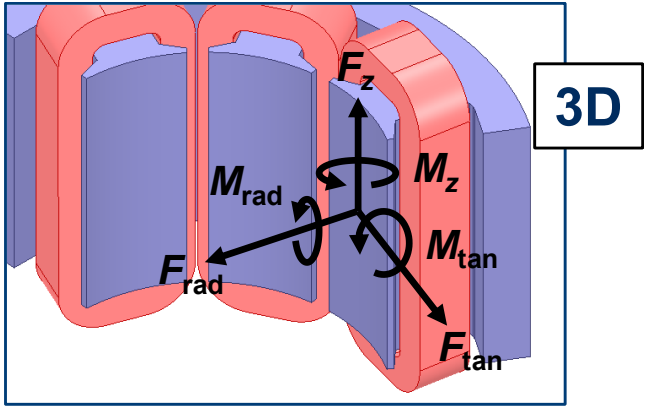
$$\sigma = \begin{pmatrix} (H_x \cdot B_x - \frac{1}{2}\vec{B}\cdot\vec{H}) & H_x \cdot B_y & H_x \cdot B_z \\ H_y \cdot B_x & (H_y \cdot B_y - \frac{1}{2}\vec{B}\cdot\vec{H}) & H_y \cdot B_z \\ H_z \cdot B_x & H_z \cdot B_y & (H_z \cdot B_z - \frac{1}{2}\vec{B}\cdot\vec{H}) \end{pmatrix}$$

$$\vec{f} = [\sigma]\cdot\vec{n} \quad \left[\frac{\mathrm{N}}{\mathrm{m}^2}\right]$$

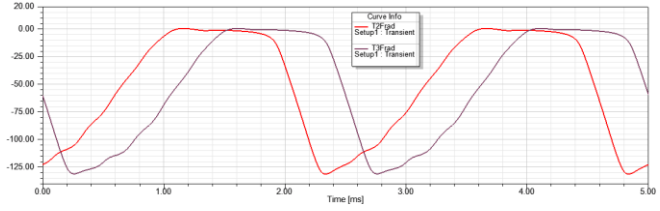
$\vec{n}$ … normal vector

Excitation Loads at Stator (Time Domain):



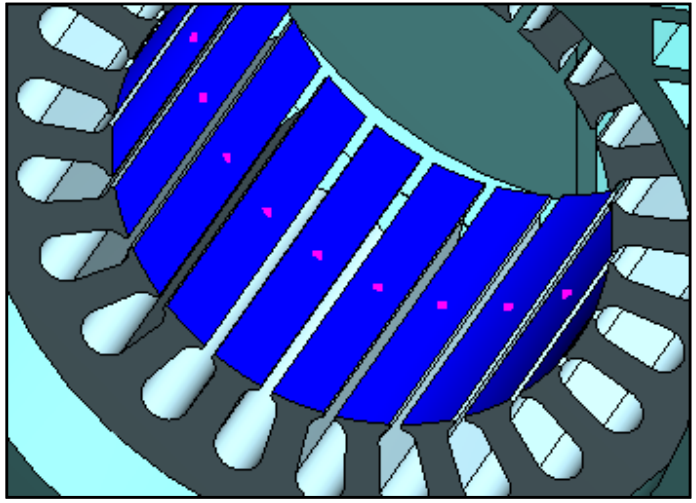


- Force/moment components condensed to load centroids at stator teeth:

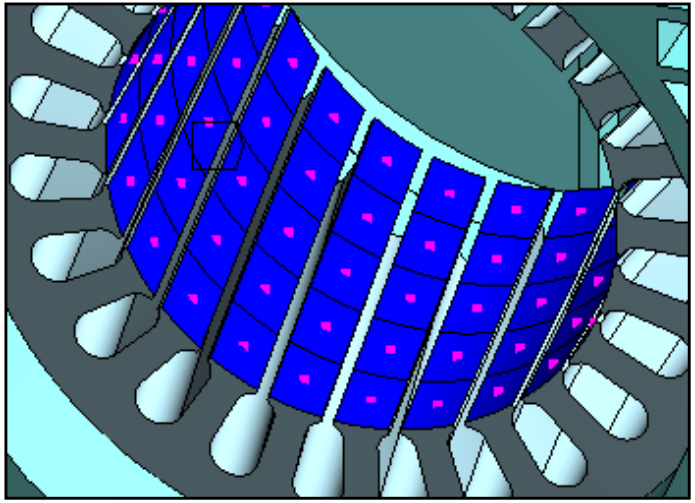


Treatment of Motors with Skewing:

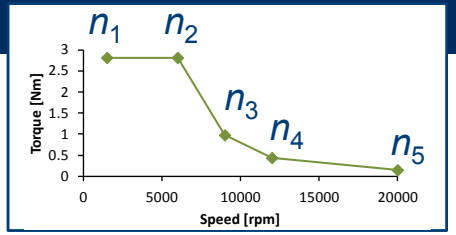
➔ Axial subdivision into planes
(i.e. both in EM and structural FE-models)



Non-skewed



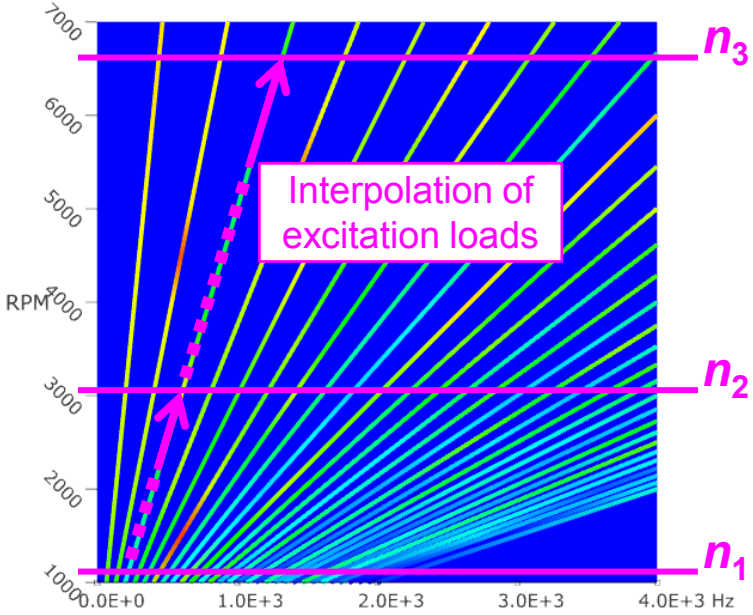
Skewed

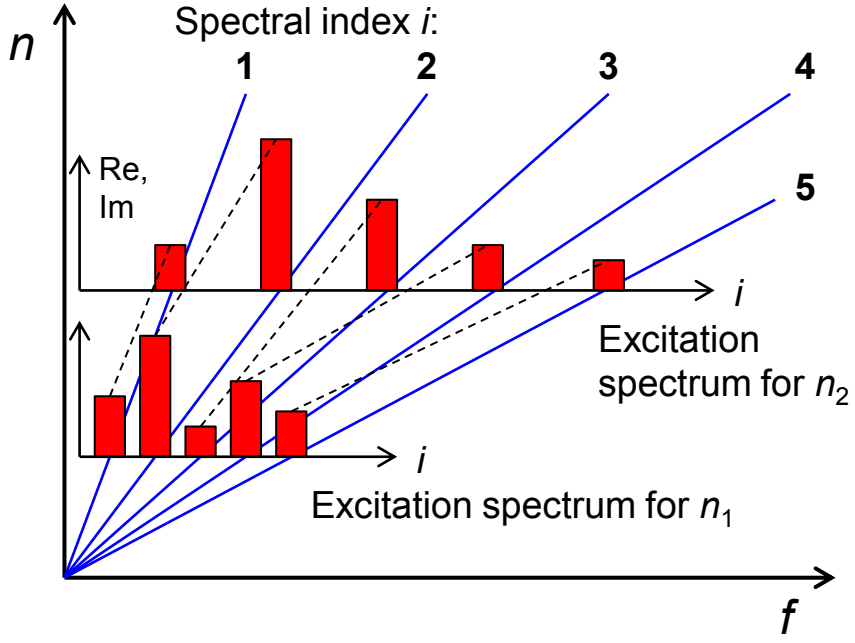


Motor characteristics

Calculation for Selected Rotational Speed Points:

➔ Reduction of EM-simulations by interpolation





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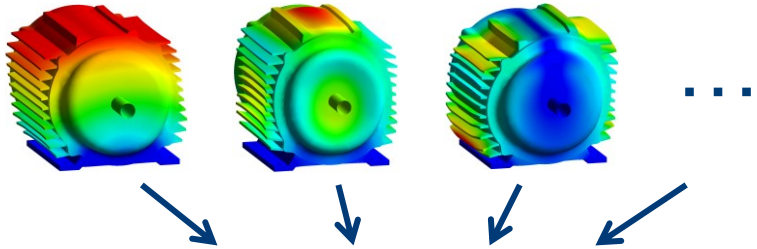
Dynamic Analysis Using

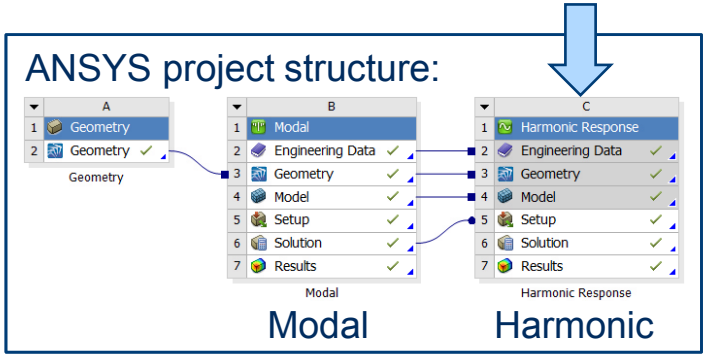
Electric Drive Acoustics inside ANSYS

Harmonic Analysis Based on Mode Superposition:

- Total oscillation as linear combination of eigenmodes



$$u(n,\mathrm{i}\omega) = \sum_{m=1}^{M} c_m(n,\mathrm{i}\omega)\cdot u_m$$

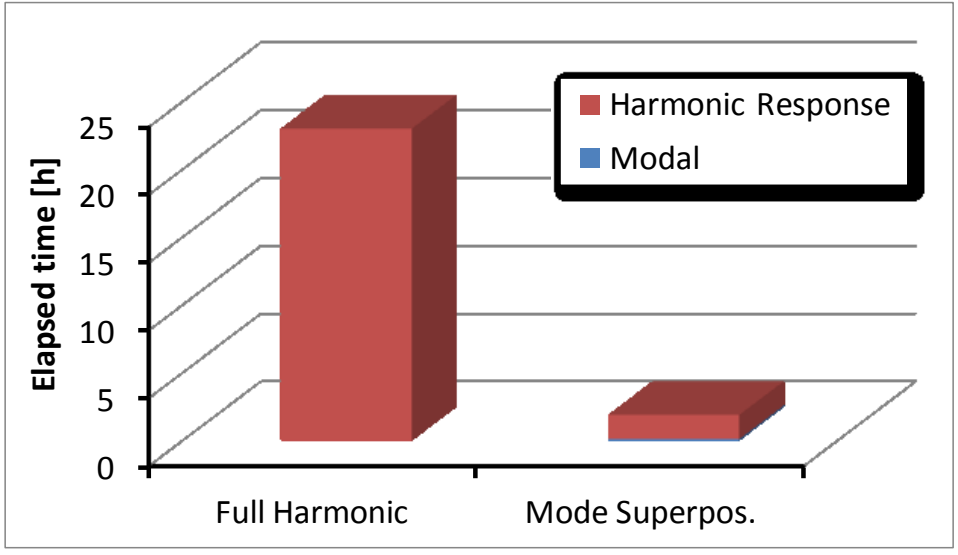


u … complex amplitude at arbitrary location
u_m … displacement of eigenvector m at loc.
n … rotational speed, ω…frequency
M … total included eigenmodes

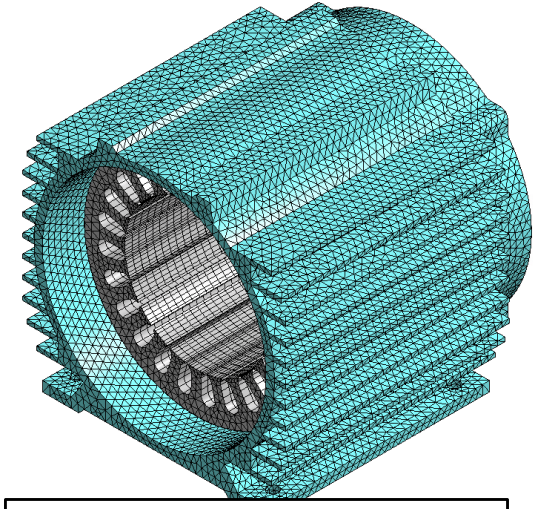
- Primary result: complex modal amplitudes c_m ("modal coordinates")

Dynamic Analysis Using *Electric Drive Acoustics inside ANSYS*

Comparison:



➔ Speed-up due to computation in the low-dimensional space of modal coordinates c_m

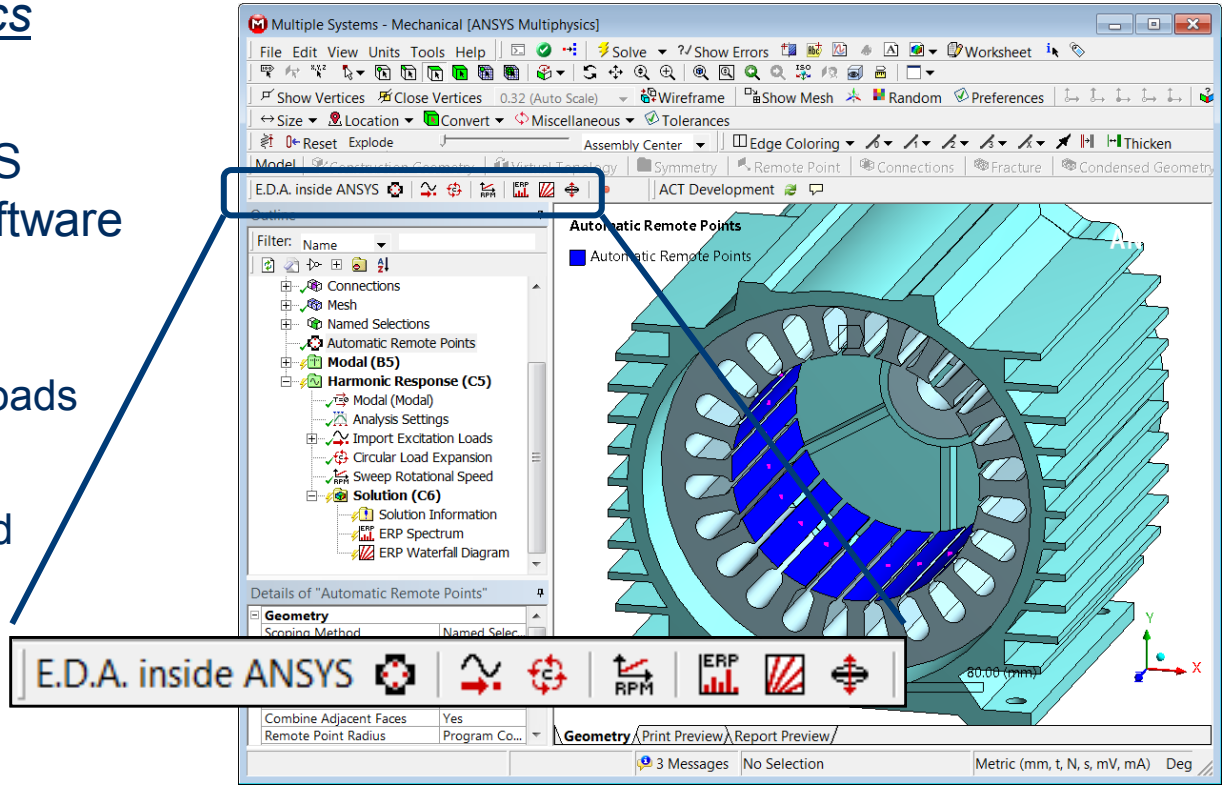


Example model:
- ≈ 123.000 finite elements
- ≈ 260.000 nodes
- ≈ 770.000 unknowns
- 200 eigenmodes
- 40 x 30 frequency points

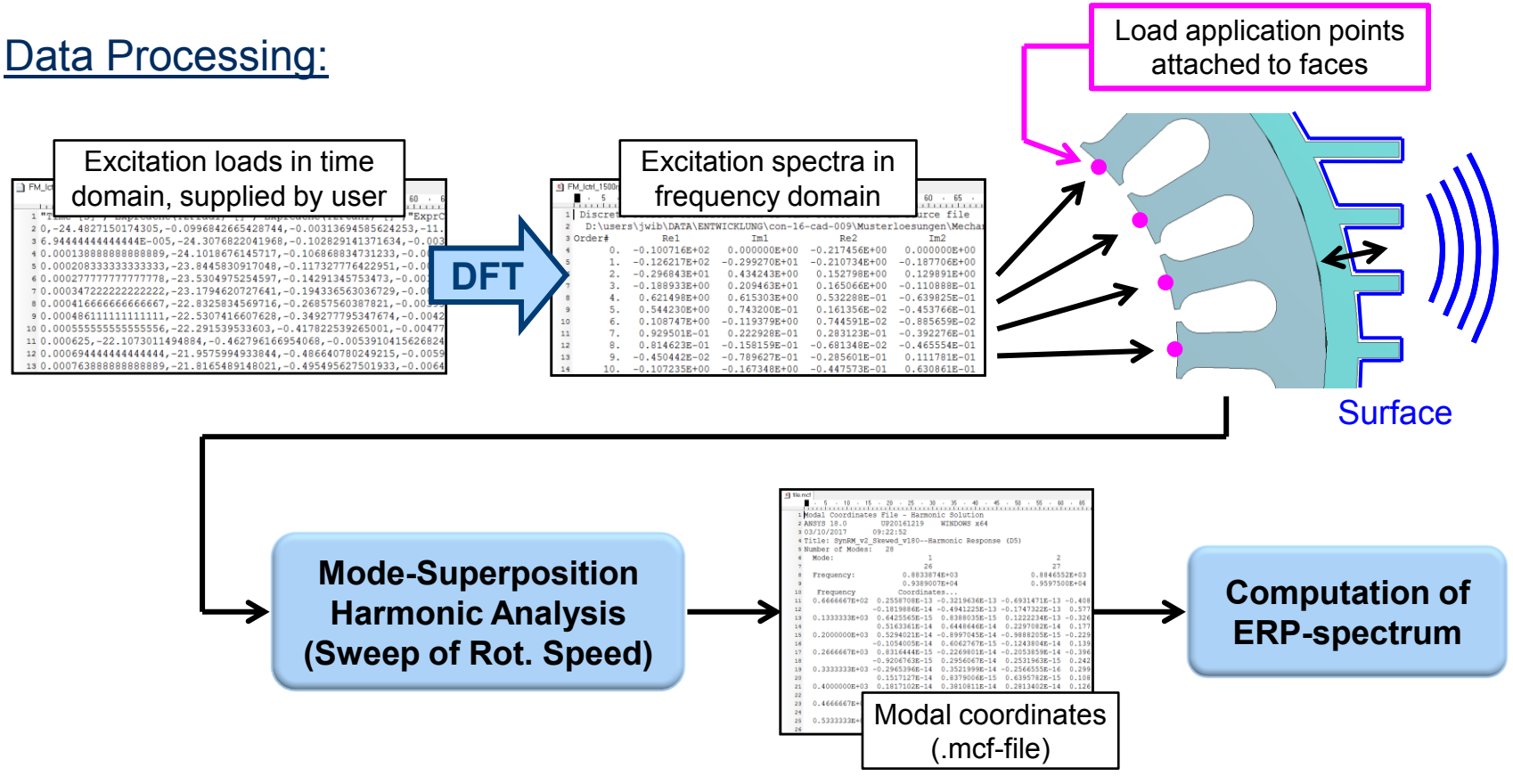
Dynamic Analysis Using *Electric Drive Acoustics inside ANSYS*

Electric Drive Acoustics inside ANSYS:

- Extension for ANSYS Mechanical FEM-software
- Supports
  - import of excitation loads
  - harmonic simulation, sweep through speed range
  - ERP computation and display



Data Processing:



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Postprocessing of Equivalent Radiated Power (ERP)

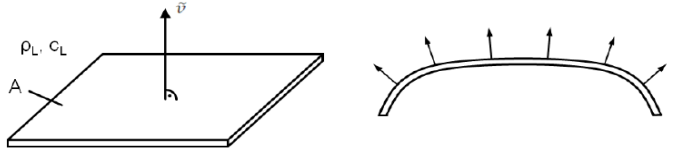
Postprocessing of Equivalent Radiated Power (ERP)

Equivalent Radiated Power (ERP):

- Integrated structural velocity on selected surface *A* (surface normal component v_n)

$$P_{\mathrm{ERP}} = \frac{1}{2} c \cdot \rho \cdot \iint \hat{v}_{\mathrm{n}}^2 \, \mathrm{d}A$$

- No true acoustic field calculation
  ➔ Fast!



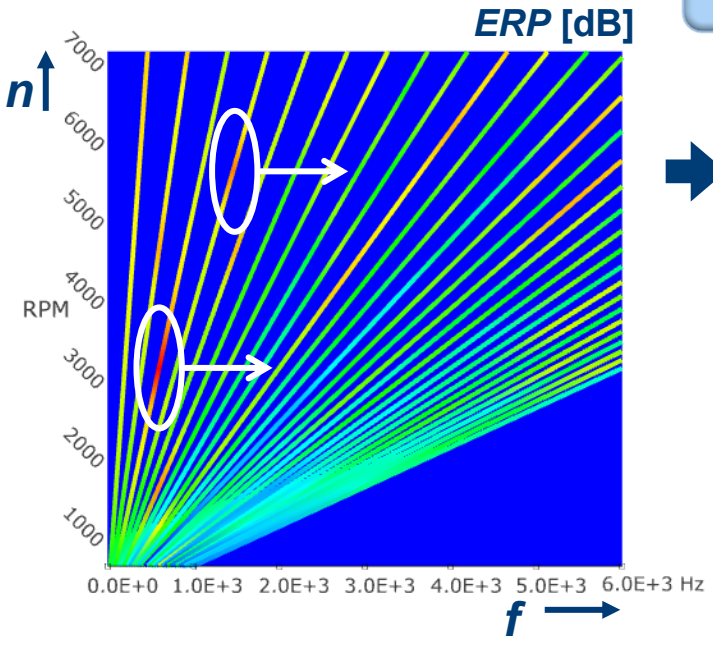
- Direct computation from mode shapes and modal coordinate results
  ➔ Additional speed-up

- Natural deviation from true radiated power
  ➔ Use air-borne acoustic field analysis *at selected operating points only*.

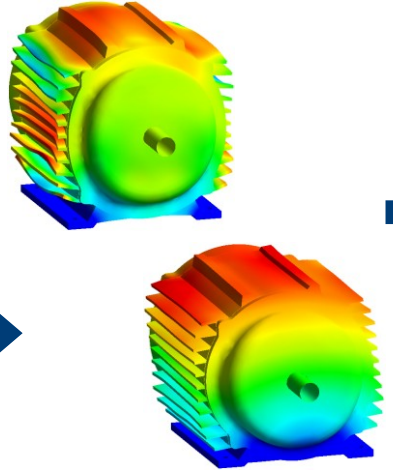
Postprocessing of Equivalent Radiated Power (ERP)

Complementing by Optional Acoustic Field Simulations:

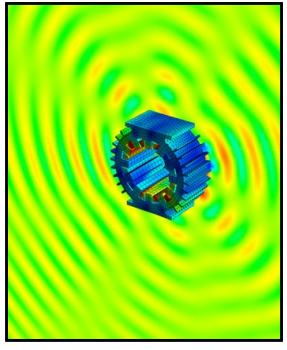
Identify critical OPs



Get vibration shapes for critical OPs only



Analyse true radiation by acoustic field simulation



(by dedicated tools for air-borne acoustics)

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Summary

Summary

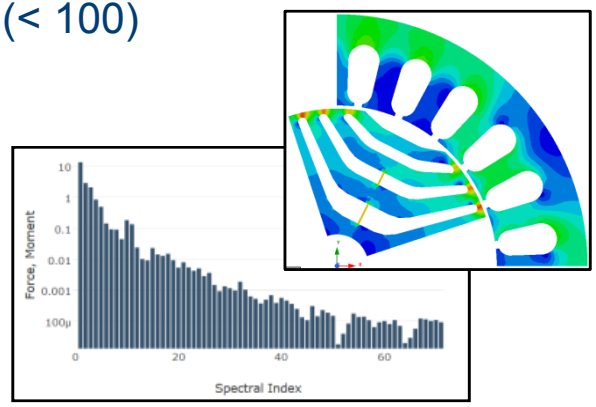
- FEM-based method for ERP-computation and display in a Waterfall plot
- Employs several methods to speed up the process
- Continuous workflow with prepared easy-to-use functions
- Implemented for ANSYS Mechanical FEM-software (*Electric Drive Acoustics inside ANSYS*)
- Enables fast design analysis and comparison during virtual prototyping

Why do we need significant speed-up?

Synchronous motor:

➔ short, well defined periodic interval

➔ few spectral components within excitations (< 100)



Induction motor:

➔ long, slip-dependent periodic interval

➔ dense spectrum containing several 100 lines

!