

Waidhofen, 15.05.2025

Dr. Marius Franck, FEV Europe GmbH

MAGNA

ECS Simulation Conference 2025

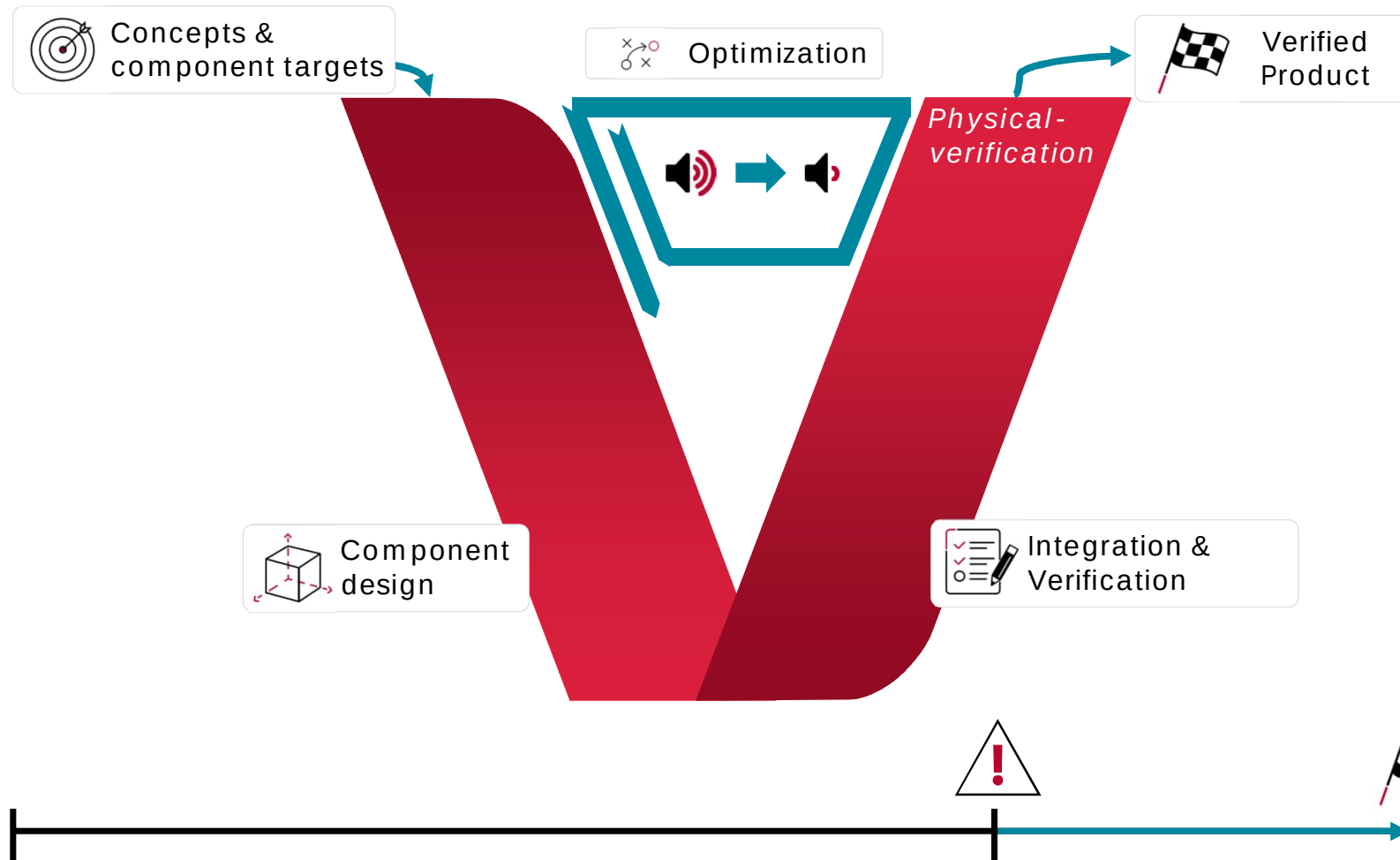


Analysis of Structural Dynamic Damping of Electric Machines

Modeling and Experimental Characterization



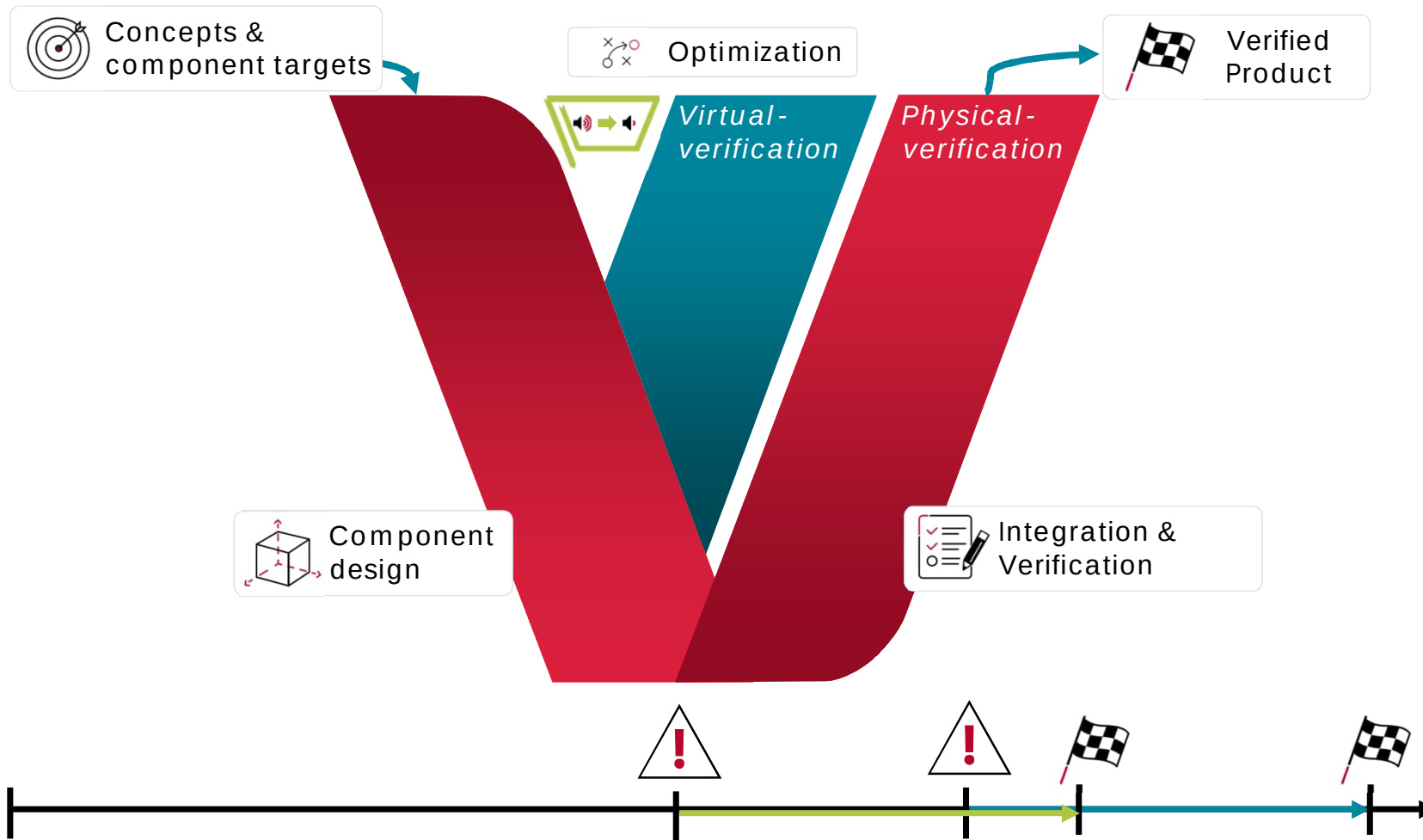
Late detection of acoustics problems causes delays and costs



Challenges

- In traditional V-model development, issues like acoustics often arise late in the verification phase
- Late detection of acoustic problems can significantly delay the project timeline
- Optimization at this stage is time-consuming and cost-intensive

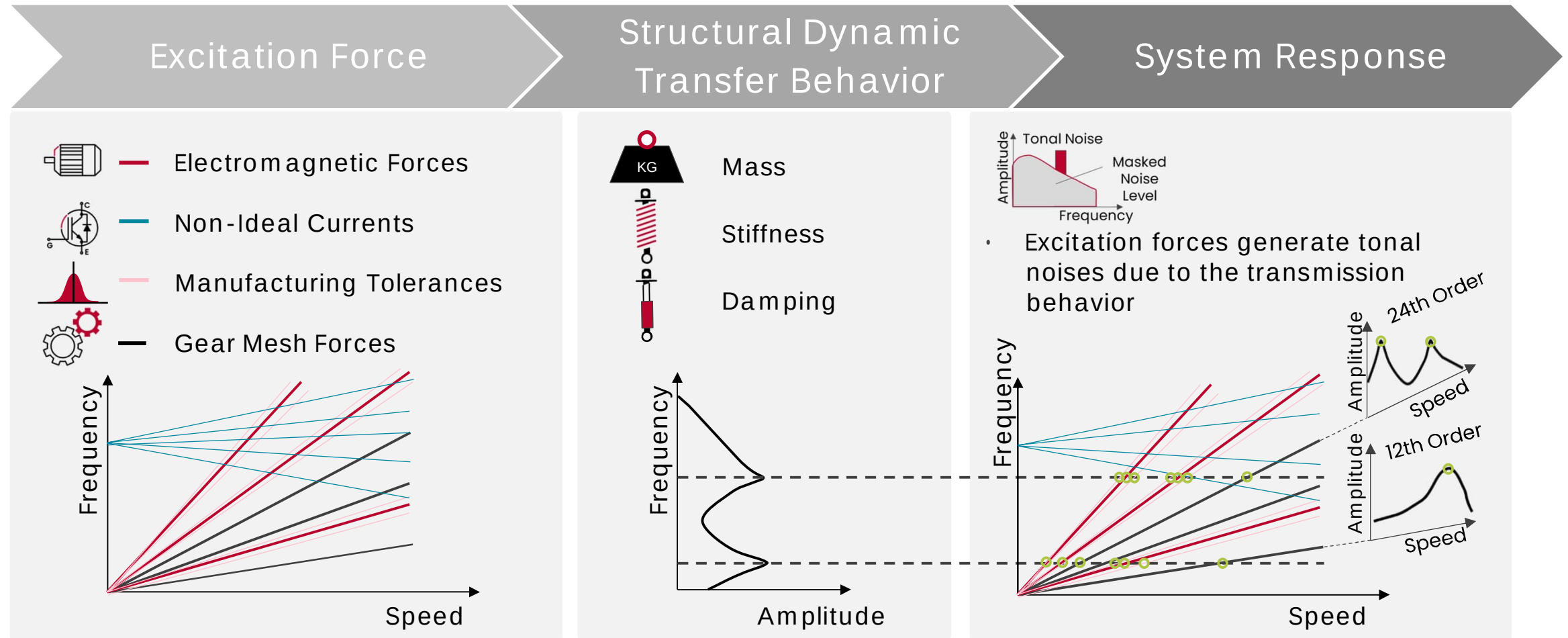
Mitigate acoustic risks early in the development process by virtual verification to reduce time and costs



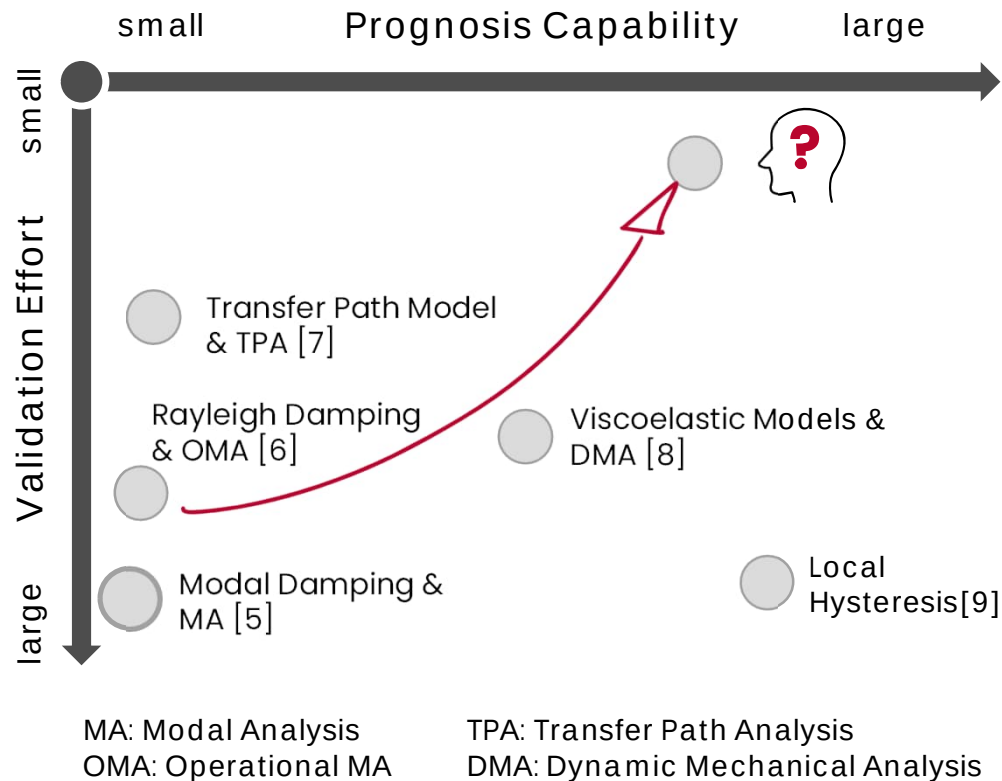
Development Goal

- Early integration of virtual acoustic analysis is crucial to avoid costly redesigns
- Emphasizes the need for front-loading simulation and validation activities

Tonal noises are caused by the interaction of the excitation forces and the transfer behavior



Reduce testing effort by advancing predictive damping models



- [5] Gerlach, M.: Einfluss von Wicklung und Isolierung auf das Schwingungsverhalten elektrischer Maschinen, Dissertation IAL Gottfried Wilhelm Leibniz Universität Hannover, 2023.
- [6] Mülder, C.: Systematische Bewertung der Akustik von getrieblosen Windenergieanlagen am Beispiel des Betriebsverhaltens des Generators, Bd. 48, Dissertation IEM RWTH Aachen, Shaker, 2022.
- [7] Franck, D.: Ein effizientes transientes Antriebsakustikmodell als Werkzeug zur Simulation und Analyse elektromagnetisch erregter Schwingungen, Bd. 23, Dissertation IEM RWTH Aachen, Shaker, 2016.
- [8] Schwarzer, M.: Structural Dynamic Modeling and Simulation of Acoustic Sound Emissions of Electric Traction Motors, Dissertation, TU Darmstadt, 2017.
- [9] Wischmann S., Berroth J., König F., Jacobs G.: "An Improved Method for FEM Modeling and Parameter Identification of Damping in Bolted Lap Joints Using Zero-Thickness Elements," 29th International Congress on Sound and Vibration, Prague, 2023.

Challenges

- Predictive capability of transfer behavior, especially damping, is currently insufficient
- Physical testing is required for model calibration
- Hybrid methods combining measurement and simulation are used for prediction
- Accurate damping prediction is not yet feasible with current methods

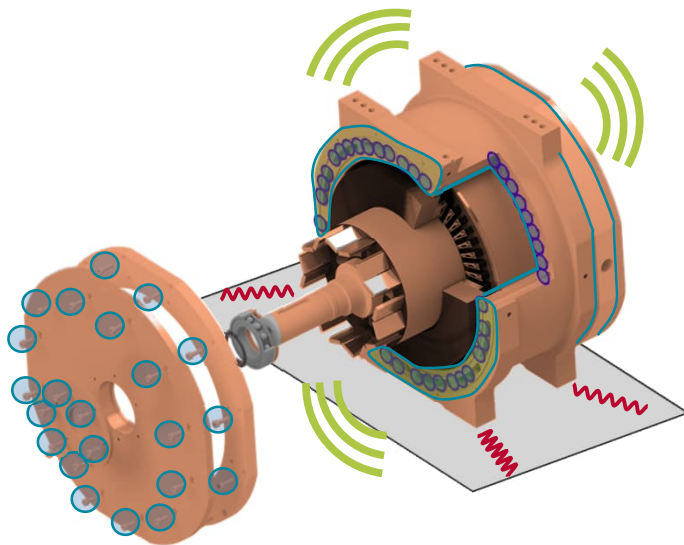
Objective

1. How can structural dynamic damping be efficiently predicted in the development process of an electric drive?
2. How can the experimental effort for validating acoustic models be reduced?



Integrated approach using local and global damping models

Damping in Electric Machines



Different Damping Phenoms must be considered:

Internal Damping



Material Damping



Joint Damping

External Damping



Fluid Damping



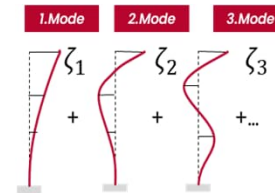
Airborne Radiation



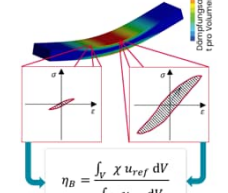
Structure Borne Radiation

Integrated Damping Model

Global Damping



Local Damping



Linearized Damping Model

- Combined local and global damping model, transformed to modal domain:

$$\zeta(r) = \frac{\sum_i \chi_{B,i} U_i(r) + \sum_j \chi_{F,j} U_j(r) + \sum_k \chi_{S,k} U_k(r)}{2U(r)}$$

Model-based optimization of measurement strategies in experimental modal analysis

Excitation

Excite all relevant frequencies
(Enhanced) Optimum Driving Point
Criterion (eODP)

Driving Points

$$\Phi^T \mathbf{E} = \begin{pmatrix} \vdots & \vdots & \vdots \\ \Phi_1^T & \Phi_2^T & \Phi_N^T \\ \vdots & \vdots & \vdots \end{pmatrix} \mathbf{E}$$

$$= \begin{pmatrix} \vdots & \vdots & \vdots \\ q_1 & q_2 & q_m \\ \vdots & \vdots & \vdots \end{pmatrix} \begin{pmatrix} \mathbf{r}_1 & \vdots & \vdots \\ \vdots & \ddots & \vdots \\ \vdots & \vdots & \mathbf{r}_n \end{pmatrix}$$

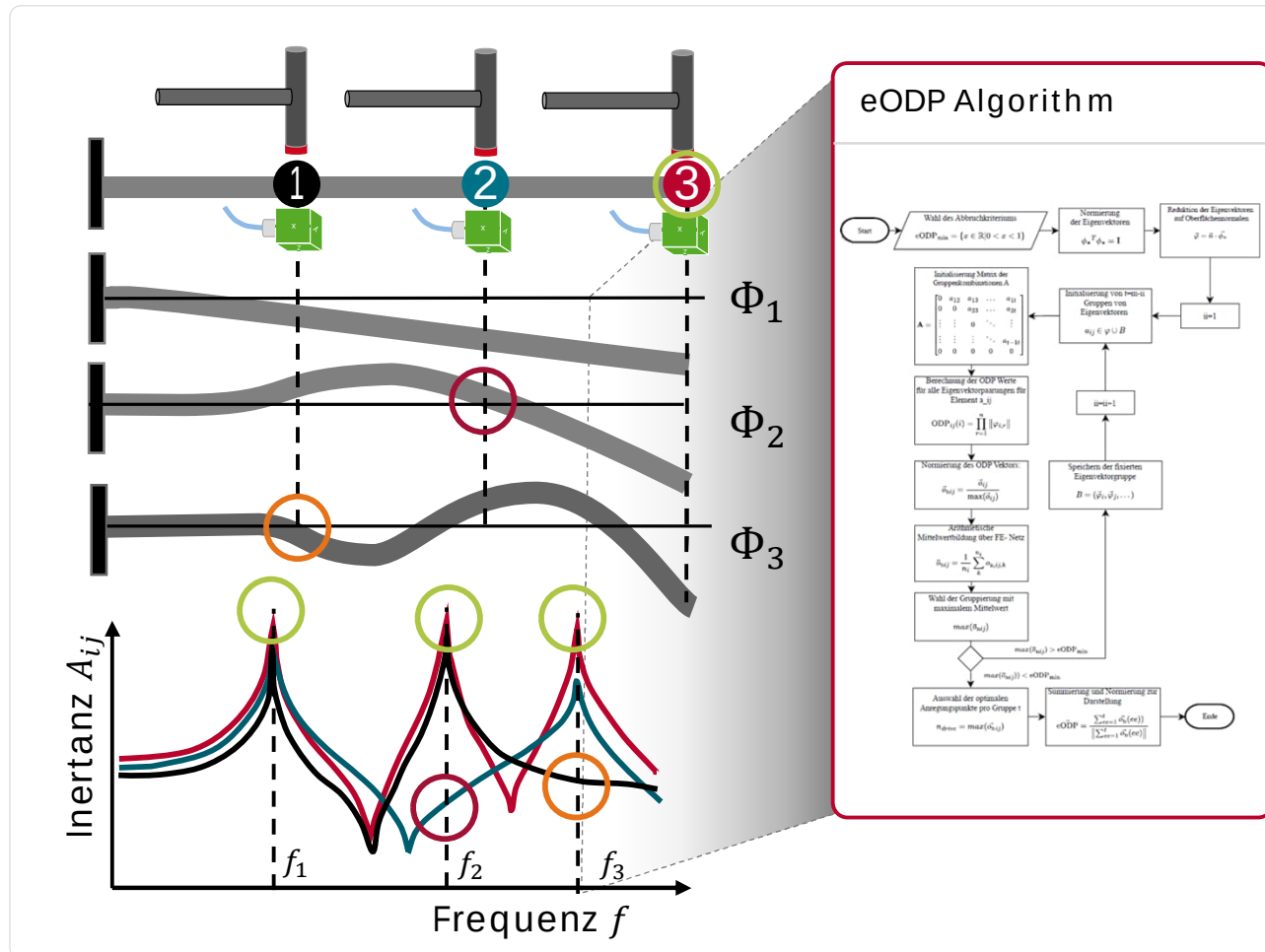
Anregungs- position	1.Mode	2.Mode	3.Mode
zentrisch	Auslenkung: maximal	Auslenkung: null	Auslenkung: null
Anregungs- position	1.Mode	2.Mode	3.Mode
exzentrisch	Auslenkung: mittel	Auslenkung: mittel	Auslenkung: mittel

Measurement Points

Response

Unique reconstruction of the
mode shapes using the
QR-decomposition of the
Eigenvector matrix

Optimizing driving points in systems with high modal density



Enhanced Optimal Driving Point Criterion



- Advancement of the classic Optimum Driving Point (ODP) Criterion [16] for structures with high modal density

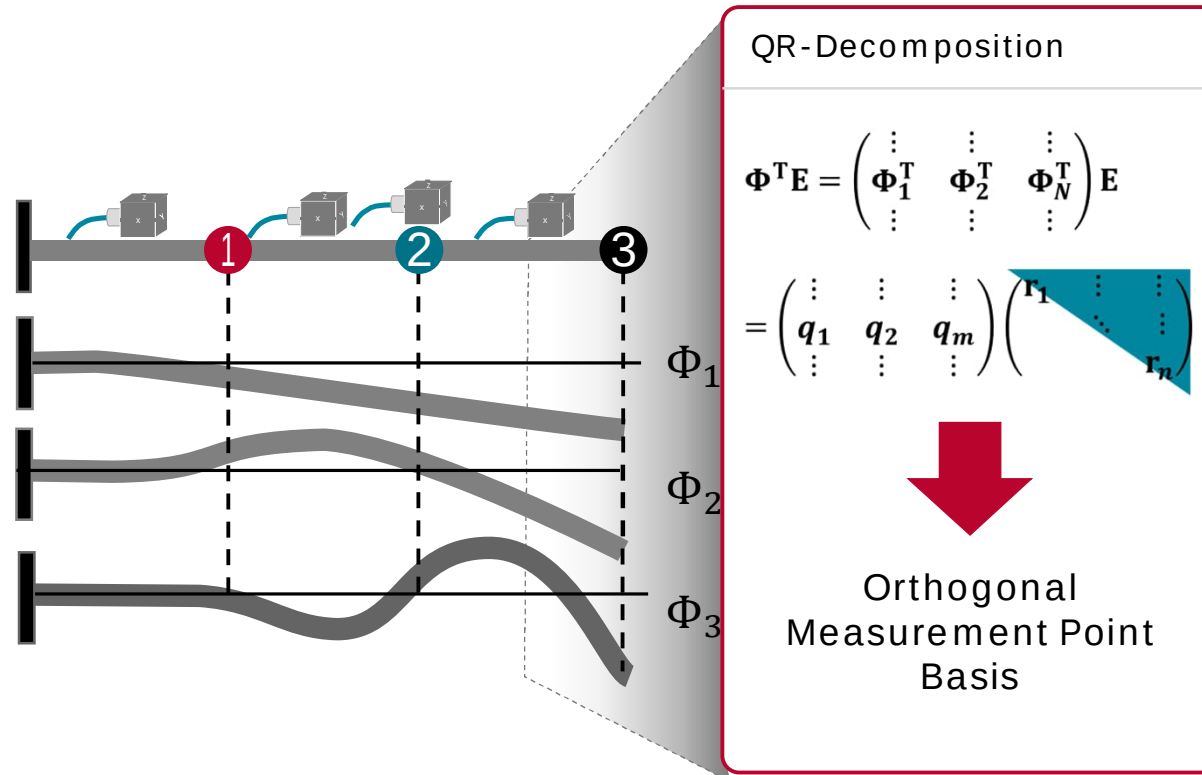
Approach

- Basis are the linearized Eigenvectors of the Geometry
- Iterative selection of excitation points for different eigenvector groups
- Identification of multiple excitation points optimized for higher frequency ranges

[16] Imamovic, N. "Validation of large structural dynamics models using modal test data". Ph.D. thesis, Imperial College of Science, Technology & Medicine, University of London, 1988.

[17] M. Franck, S. Mönninghoff, D. Butterweck, K. Hameyer, "Methodik zur Bestimmung von optimalen Messpunkten bei der strukturdynamischen Vermessung elektrischer Maschinen", e&i, Ausgabe 138, 2021.

Efficient response location selection using Eigenvector decomposition



Optimal Sensor Locations Selection

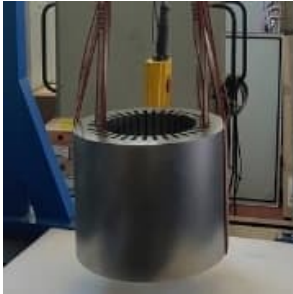
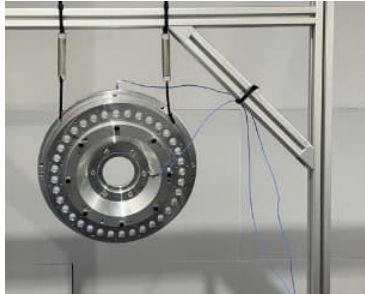


- Identify a minimal set of measurement points that allows for unique reconstruction of eigenvectors

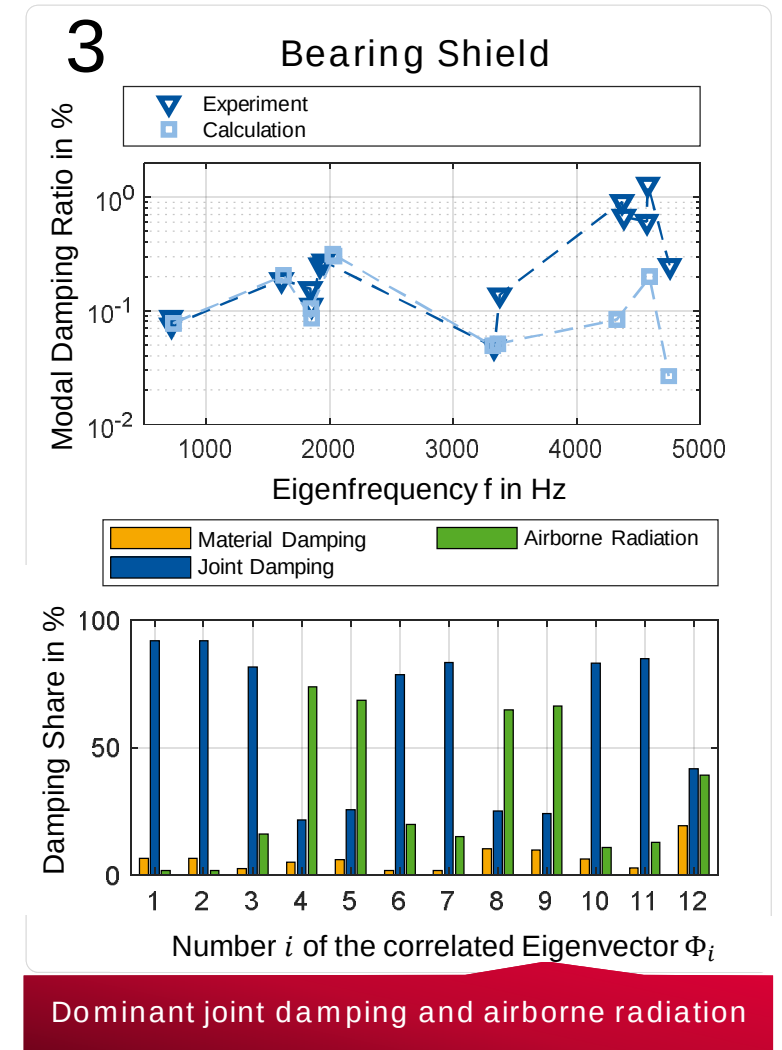
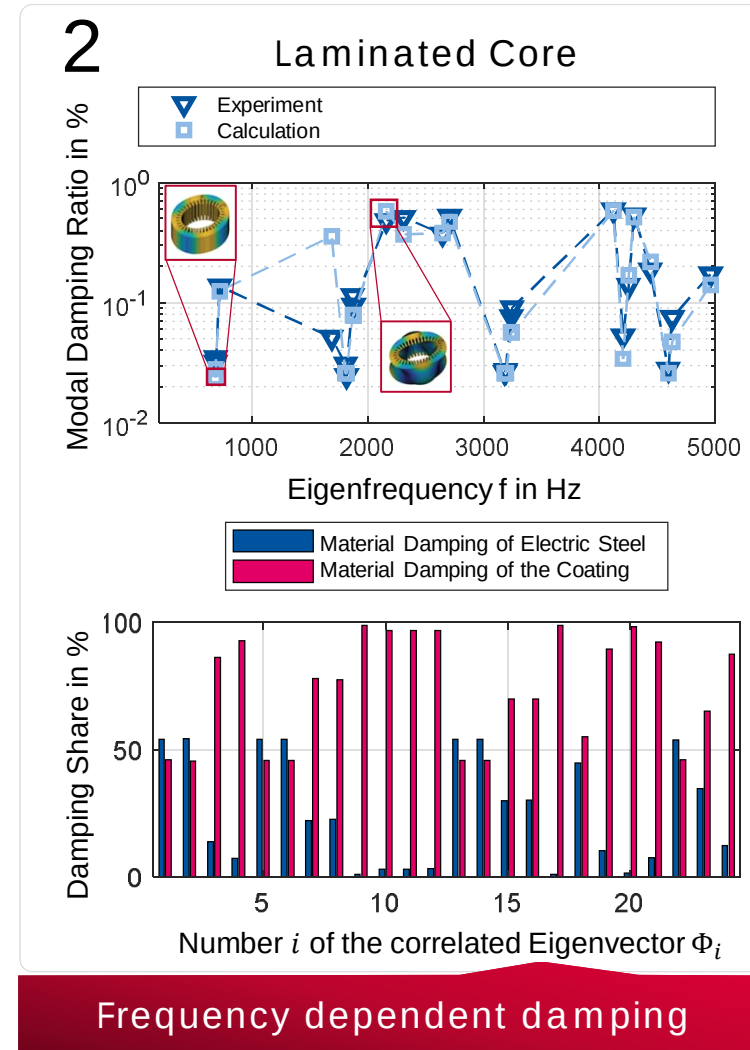
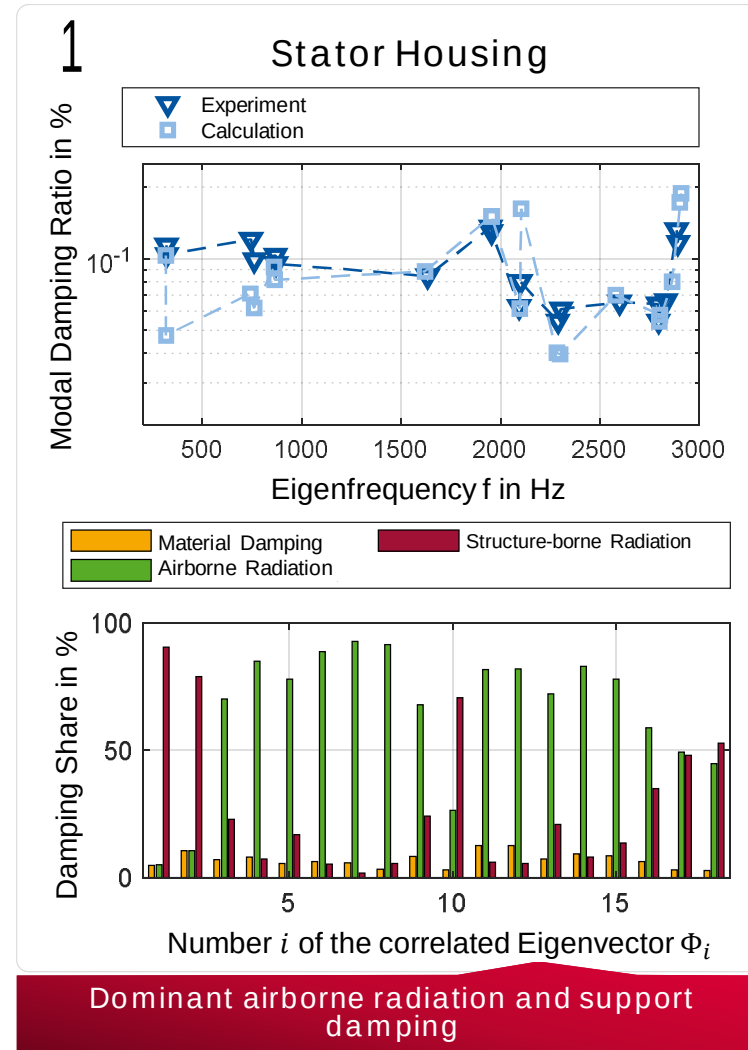
Approach

- Apply QR-decomposition to the transposed eigenvector matrix Φ^T
- The first n columns of matrix Q form an orthogonal basis
- This basis is selected as the optimal measurement point distribution in the measurement

Validation of developed methods on key e-machine components

Subject	1 Stator Housing	2 Laminated Core	3 Bearing Shield	4 E-Machine
				
	Excitation:  Modal hammer	Excitation:  Modal hammer	Excitation:  Modal hammer	Excitation:  Auto-Modal hammer
	Response:  Acceleration sensors	Response:  Acceleration sensors	Response:  Acceleration sensors	Response:  Robot 3D-LDV
Effects	 Material damping	 Material damping	 Material damping	 Material damping
	 Air-borne-sound radiation		 Contact-surface damping	 Contact-surface damping
	 Structure-borne-sound radiation		 Air-borne-sound radiation	 Air-borne-sound radiation

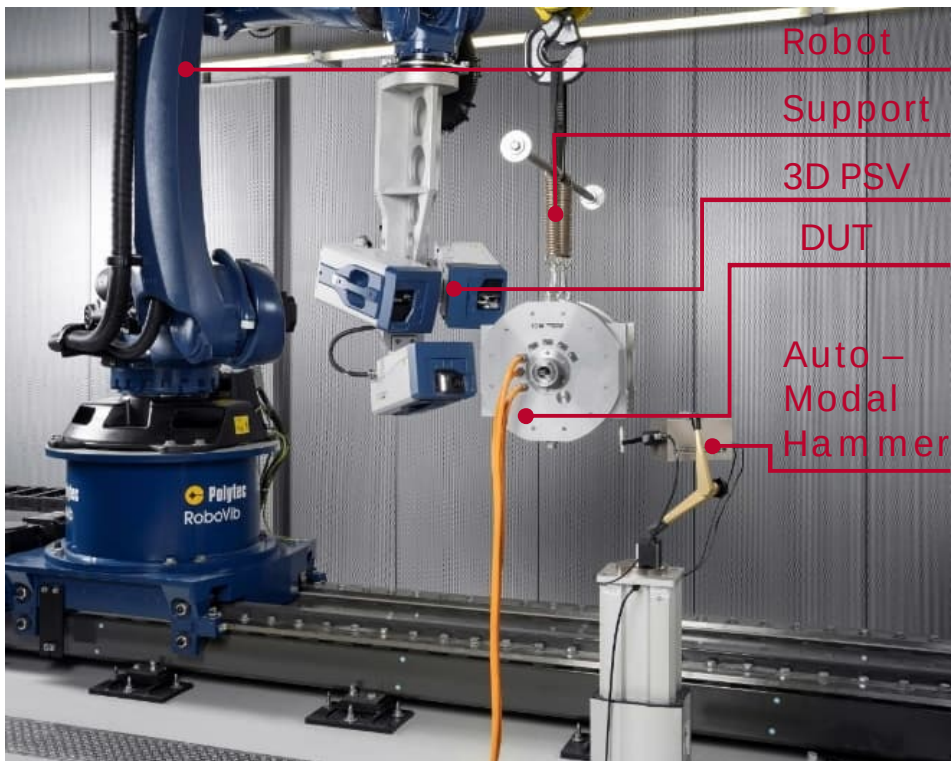
Assessing model accuracy in predicting component damping



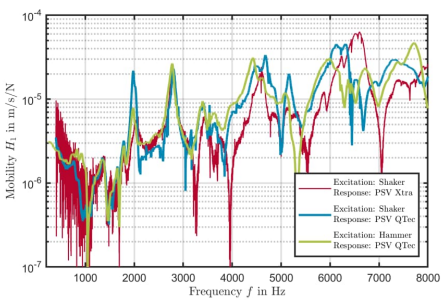
Efficient validation on system-level by advanced 3D-Laser-Doppler-Vibrometry



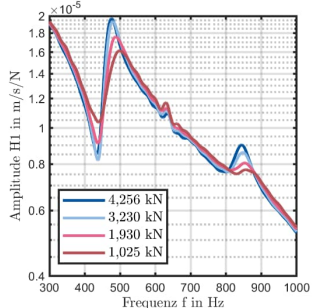
Robot-assisted 3D Scanning Laser-Doppler Vibrometer



Signal Quality Enhancement



Linearization

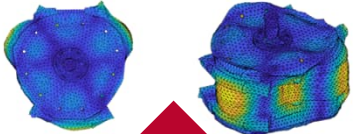


Mode Shape Analysis

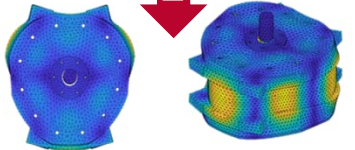


Automated Correlation

Measurement



Simulation



FEV

Polytec
RoboVib

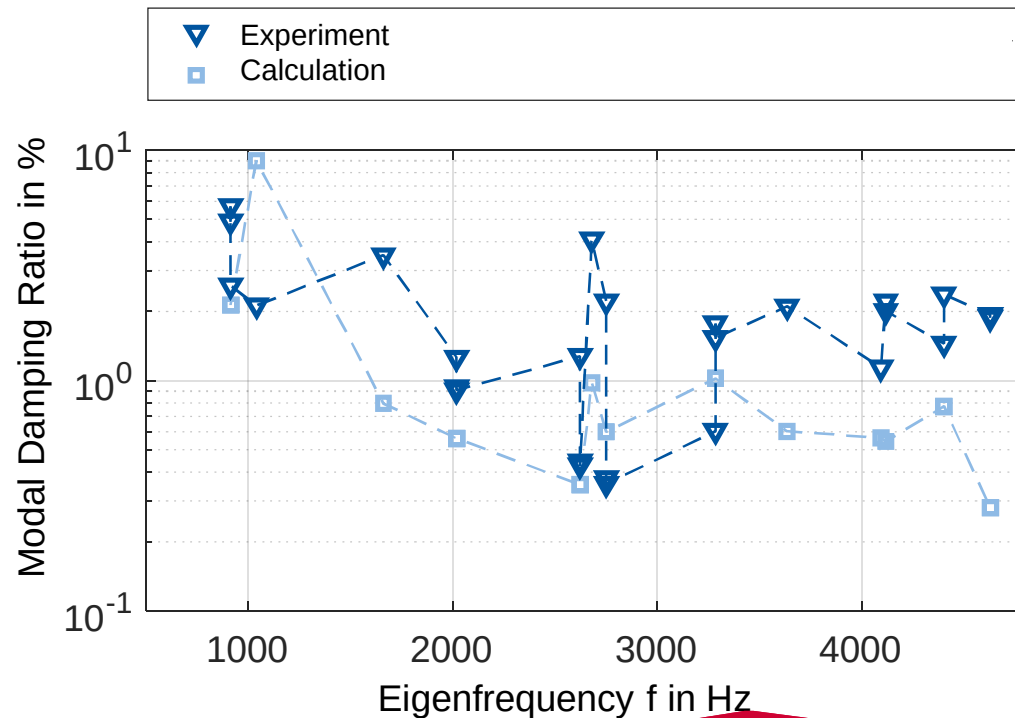
TIME LAPS

FULLY AUTOMATED
MODAL ANALYSIS



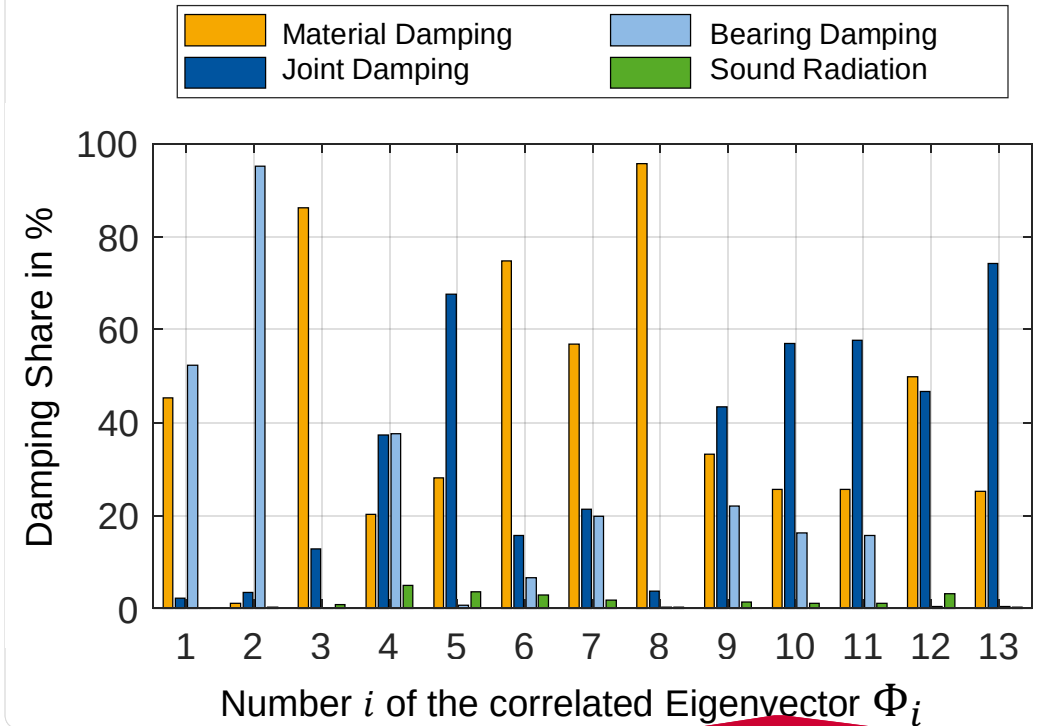
Assessing model accuracy in predicting system-level damping

Damping Correlation



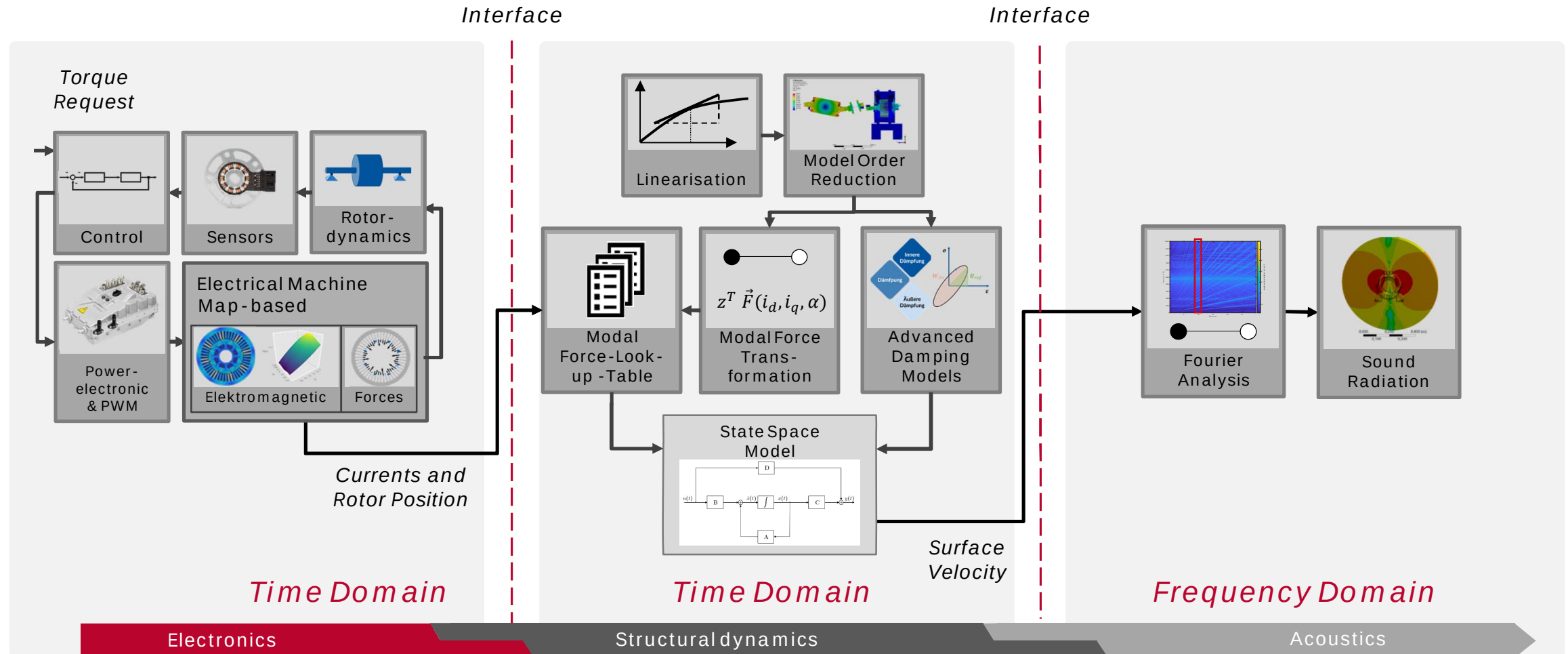
Predictable trend in frequency-dependent damping

Damping Decomposition Analysis



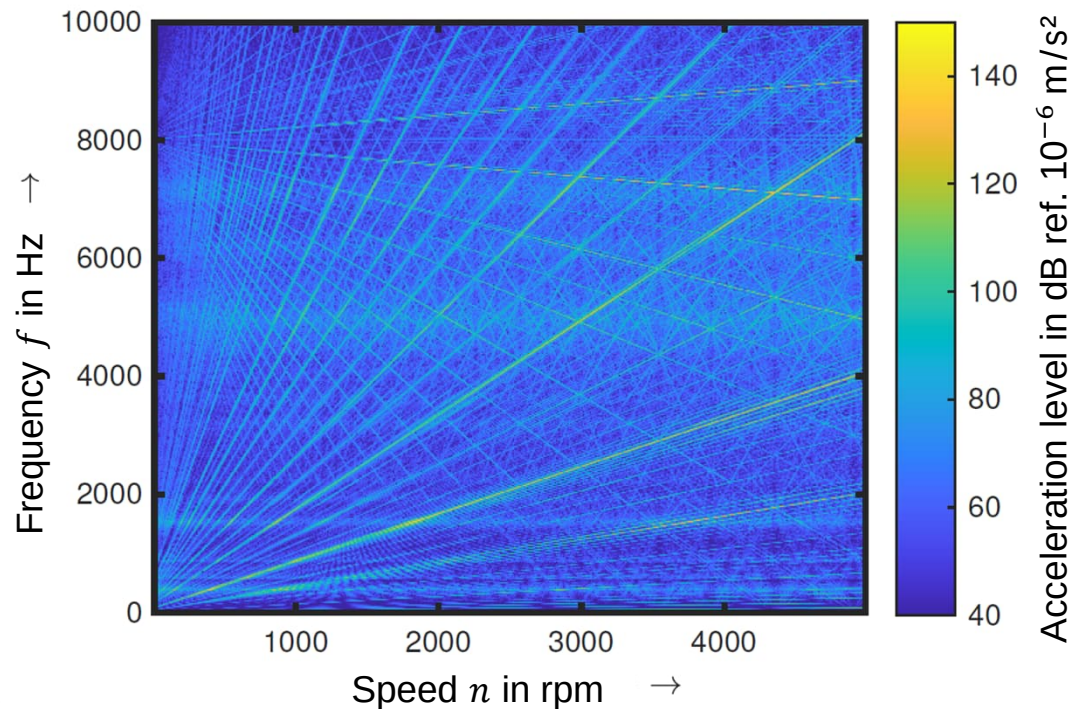
Dominant damping sources:
material, bearings, and joints

Integration of the damping model in an efficient transient CO-simulation for e-machine acoustics

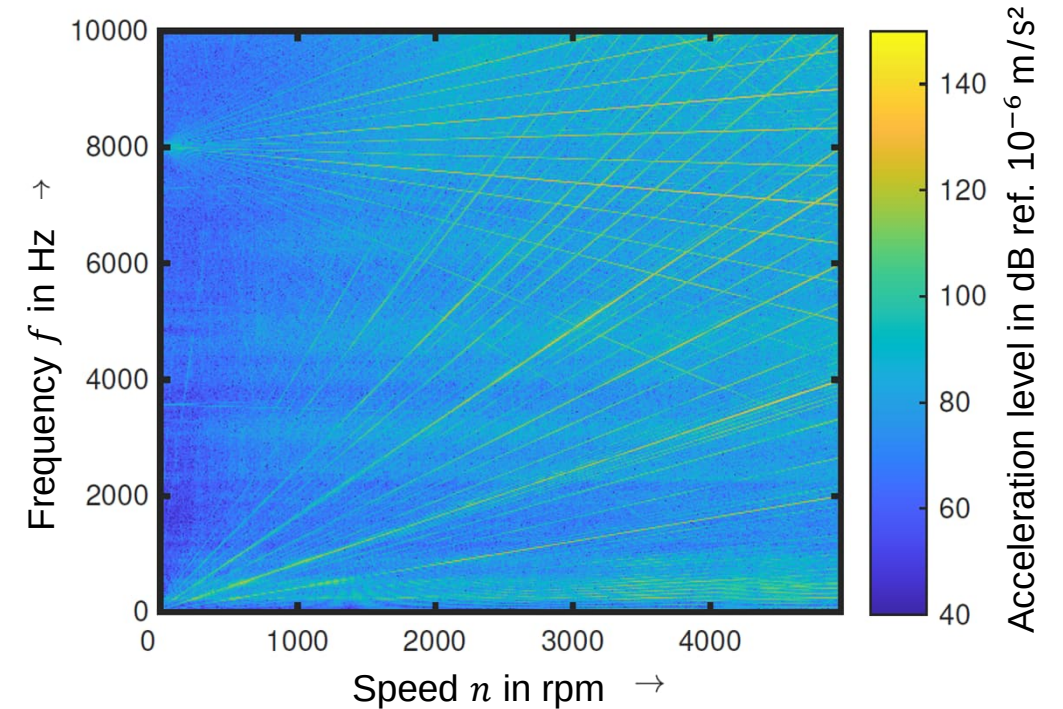


Assessing model accuracy in predicting system-level vibration

Calculated Surface Acceleration



Measured Surface Acceleration



This comparison demonstrates the model's capability to accurately reflect actual vibration patterns, validating its predictive utility.

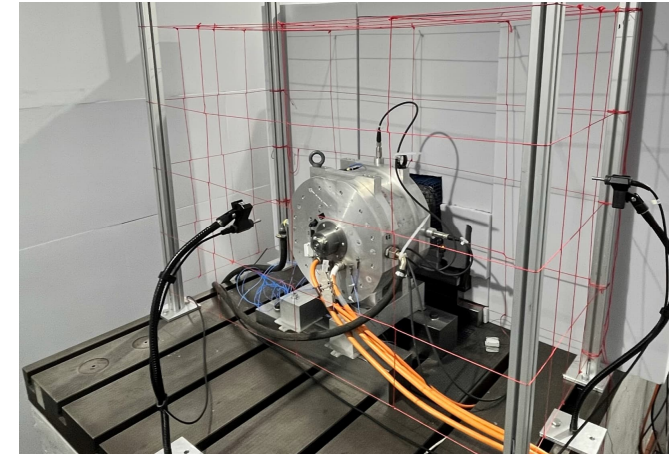
Assessing model accuracy in predicting system-level acoustics

Boundary Conditions

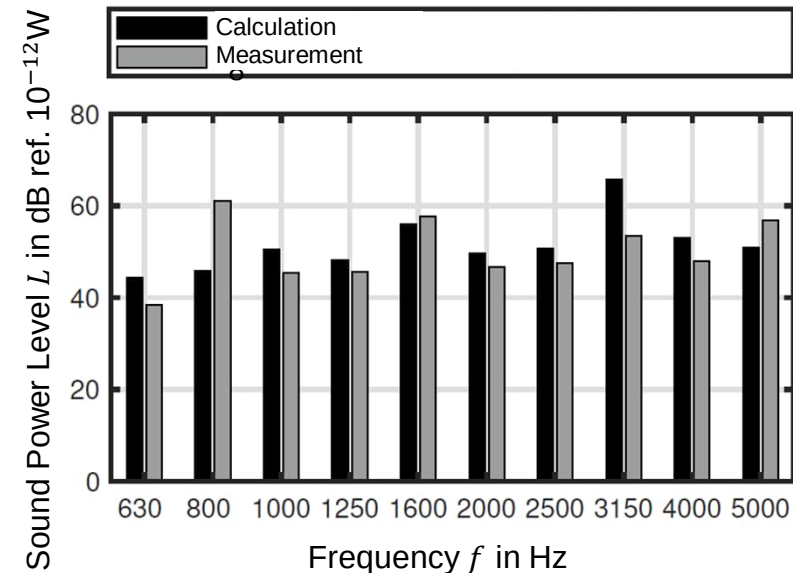
- Comparison of sound power at a constant operating point (constant Speed and Torque)
- Sound Power Measurement using an Intensity Probe

Results

- Average deviation between model and measurements: <5 dB, maximum: 15 dB
- Deviation in total sound level: < 1 dB
 - Calculated sound power level $L_{ERP} = 66.74 \text{ dB}$
 - Measured sound power level $L_P = 65.27 \text{ dB}$



FEV



Reduction of
development
cost and time:
Enabled by
comprehensive
damping models
and optimized
measurement
strategies

- Motivation: addressing acoustic challenges early
 - Late detection of acoustic problems leads to significant delays and increased costs.
 - Tonal noises result from the interaction between excitation forces and structural transfer behavior.
 - Mitigating acoustic risks early through virtual verification helps reduce both time and cost.
- Predictive modeling & simulation
 - Advance predictive damping methods to reduce physical testing efforts.
 - Assess model accuracy in predicting system-level vibration and damping behavior.
 - Integrate damping models into efficient transient co-simulations for E-machine acoustics.
- Integrated modeling approaches
 - Employ an integrated approach combining local and global damping models.
 - Use model-based optimization to enhance measurement strategies in experimental modal analysis.
- Validation & experimental techniques
 - Validation of developed methods on key E-machine components.
 - Enable efficient system-level validation using advanced 3D Laser-Doppler Vibrometry.

Get in touch with us!



Let's connect
on LinkedIn



Dr. Marius Franck
franck_m@fev.com

Team Manager

Simulation E-Drive and Transmission



FEV - Your Partner in E-Powertrain NVH

- Development of comprehensive CAE and validation approaches
- Noise and vibration analysis of electric powertrains
 - Modelling
 - Experimental validation
 - Trouble shooting
- Design of electrical powertrains with optimized NVH performance
- Design of testbenches and test strategies for NVH validation