E-Motor NVH – from electric current to noise
Electrification is here to stay

By 2040, we expect 57% of all passenger vehicle sales, and over 30% of the global passenger vehicle fleet, will be electric.

Source: Electric Vehicle Outlook 2019, BloombergNEF

Global long-term passenger vehicle sales by drivetrain

Source: BloombergNEF
Electric Powertrain are not silent

Lower overall levels, but... high-frequency, tonal content makes e-motor noise annoying:

- Higher motor orders due to construction
- Very high frequency sounds
  - Off-zero orders
  - Related to PWM switching frequency
How to accurately predict e-motor noise and identify system sensitivities during the conceptual and detailed design phase of vehicle development?
“V”- design cycle for automotive electric drives

- Full Vehicle - System Design
- Subsystem EM design
- Motor 3D Detailed Engineering

SIL / HIL / MIL /...
Test verification:
N VH / Thermal
E-Powertrain Solution in the Subsystem Design Phase

“V”- design cycle for automotive electric drives

- Full Vehicle System Simulation
- Subsystem EM design
- Motor 3D Detailed Engineering

Control Loop Validation: SIL / HIL / MIL / ...
Test Verification: NVH / Thermal
Impact on product life cycle and cost
Model-Driven Design to evaluate upfront systems designs
Impact on product life cycle and cost
Model-Driven Design to evaluate upfront systems designs

- Ease of change
- Defects identification
- Cost to extract defects

Prototype driven design
FE driven design
Model driven design

Requirements | Architecture | Design, Implement & Test | Production | Delivery & Commissioning | Operation & Maintenance

FE model availability
Prototype availability

50%
100%
Impact on product life cycle and cost
Model-Driven Design to evaluate upfront systems designs

- Ease of change
- Defects identification
- Cost to extract defects

100%
50%

Requirements
Architecture
Design, Implement & Test
Production
Delivery & Commissioning
Operation & Maintenance

FE model availability
Prototype availability
FE driven design
Model driven design
Prototype driven design
Simcenter Amesim-based post-processing tool to
• estimate EM Forces from motor electrical model and control currents for given operating condition
• Predict radiated noise based on motor parameters and point source model
Providing NVH Teams an early tool to assess influence of different electric design variations on NVH

Addressing e-Motor NVH at concept stage
Frontloading of qualitative NVH risk assessment
Subsystem Design Phase
Simcenter Amesim System Model

The e-machine model is integrated in a **system-level modelling** environment.

Depending on application or maneuver, various **components** can be connected within a **multi-physical** cause/effect system of systems.

The e-motor produces **torque** based on EM maps and control signals, but also the flux linkage and flux density needed to **calculate internal EM forces**.
Subsystem Design Phase
Electro-Magnetic Concept Model

From actual EM model:
- Overall Geometry / Topology
- Machine materials

Magnetostatic Analysis:
- Flux linkage maps for $I_d$, $I_q$ and electrical angle

From Analytical model:
- EM model
- Geometric / topology parameters
- System Model

Future vision

\[
F(t, \alpha) = \Lambda(t, \alpha) \times MMF(t, \alpha)
\]

\[
\theta(t), i_{dq0}(t)
\]

\[
B(t, \alpha)
\]
The fluxes and forces from the EM model can be applied to simplified structural and acoustic models to calculate the vibration and acoustic responses.

**Structural model**
- Machine simplified geometry
- Machine materials
- Fluxes / Forces

**Acoustic model**
- Natural frequencies
- Modeshapes
- Vibration response

OUTPUT: acoustic pressure
Subsystem Design Phase
Design Modification Examples

Changing number of slots from 4 to 8

Changing stator geometry

48-4

48-8
Subsystem Design Phase
Design Modification Examples

Inverter Modelling and Controls:
Simulink controller integrated with inverter/motor
Simcenter Amesim model

Purpose: evaluate control strategies to balance switching noise & vehicle performance
Example: Random Carrier Frequency-PWM (RCFM)

![Diagram of Inverter Modelling and Controls]

![Graph showing PWM and RCPWM]

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Multi-Attribute, System-Level Design Process for Automotive Powertrain Electric Drives: An Integrated Approach

https://www.sae.org/publications/technical-papers/content/08-07-02-0007/
E-Powertrain Solution in the Subsystem Design Phase
Simcenter Amesim-based Noise App

Short demo:

The NoiseApp can be used inside Simcenter Amesim
E-Powertrain Solution in the Subsystem Design Phase
“V”- design cycle for automotive electric drives

Full Vehicle System Simulation

Subsystem EM design

Motor 3D Detailed Engineering

Control Loop Validation:
SIL / HIL / MIL /

Test Verification:
NVH / Thermal

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Siemens PLM Software
E-Powertrain Solutions in the Component Design Phase
From electromagnetics to radiated noise

- Current Waveforms
- Electro-magnetic FEM
- Gear micro-geometry / TE
- Gearbox Internals
- EM Loads
- Transmission Loads
- eMotor, gearbox and inverter
- Structural and vibro-acoustic FE Model
- Weak Point Analysis
- Design Improvement / Optimization
- Correlation and Updating

Casing Vibrations & Radiated Noise Prediction

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Providing NVH Teams an integrated process to accurately predict e-motor noise using state-of-the-art tools and expertise

Addressing e-Motor NVH in detailed design stage
End-to-end 3D simulation process
From electromagnetics to radiated noise
Focus on Electro-Magnetic field computation

Inverter Current Waveform with MBD representation of
- Control Logic
- Power Electronics
- Motor Electrical resistance

Electro-Magnetic Finite Elements Model with well established commercial FE codes
- Fast analytical calculation (MotorSolve)
- Accurate 2D/3D modeling (MagNet)

Inverter Current Waveforms

Transient magnetic forces
Infolytica MagNet

Calculated on EM mesh

Conversion Fourier components
Simcenter 3D
From electromagnetics to radiated noise
Focus on Transmission Loads

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
From electromagnetics to radiated noise
Focus on Transmission Loads

Simcenter 3D Transmission Builder
A vertical application within Simcenter 3D: up to 5x faster Model creation process

Gear train specification based on Industry standards
Simcenter 3D Transmission Builder
Automated creation of Multibody simulation model
Transmission builder Validation
Transmission error validation for lightweight gears

Validation cases ensure results as accurate as non-linear Finite Elements simulation

Research partners:

Microgeometry matches well (low loads)

Combined friction, microgeometry and deformation effects on TE

Low-frequency oscillation in both amplitude as global behavior due to body compliance (holes)

Comparison static TE Gear 17

- Measured Transmission error
- "State of the art" simulation
- Siemens STS Advanced

- 45 Nm
- 91 Nm
- 137 Nm
- 180 Nm
- 240 Nm
- 280 Nm

KU LEUVEN
UNIVERSITÀ DELLA CALABRIA
From electromagnetics to radiated noise
Focus on Structural modeling

1. Rotor/Stator modeling - Laminated Structures

Linear scalable CAE model with physical material properties:

- **Homogenization** of orthotropic material properties, for different area's;
- Tuning of material properties based on **test data**

![Diagram showing pre-test, FE model, test model, correlation, sensitivity and updating]

![Simulation core components]

![Test EMA images]
2. Windings Modeling – Discretization Strategies

Linear CAE model with limited modal density

- Test based analysis of coils mass and stiffness effects on e-Motor dynamics
- Dedicated coils modeling in CAE
- Tuning of material properties based on test data

Test EMA with and without windings

<table>
<thead>
<tr>
<th>NO COILS</th>
<th>WITH COILS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Mode</td>
<td>Test Response</td>
</tr>
<tr>
<td>1</td>
<td>131.7</td>
</tr>
<tr>
<td>2</td>
<td>140.2</td>
</tr>
<tr>
<td>3</td>
<td>150.5</td>
</tr>
<tr>
<td>4</td>
<td>160.2</td>
</tr>
<tr>
<td>5</td>
<td>171.0</td>
</tr>
</tbody>
</table>

Simulation complete assembly
From electromagnetics to radiated noise
Focus on Vibro-Acoustics simulation

Acoustic Meshing with dedicated tools
• Surface wrapping
• Convex Mesher
• Microphone Meshes
• ...

Vibro-Acoustics simulation setup from Magnetic Loads
• Seamless workflow to re-use magnetic forces from electro-magnetic analyses
• Easy setup of combined simulation for Dynamics and Acoustics

Load recipes
From electromagnetics to radiated noise
Building a physical and reliable 3D model

Modal correlation – EMA testing

Operational correlation – Bench/Vehicle testing

Component testing and updating;
- Sub-assemblies testing and updating;
  - Full system testing and updating
  - Connections modeling and updating
    - Screw connections;
    - Welding connections;
    - Press-fit connections

- Experience – based knowledge of critical/sensitive parameters for operational response:
  - Assembly tolerances and design robustness;
  - Non linearities;
  - Stator and Rotor modeling (laminations vs. magnets and reinforcements);
<table>
<thead>
<tr>
<th>Technical paper at International Conference on Noise &amp; Vibration Engineering (ISMA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental Study on the Impact of the Number of Laminas on the Dynamics Behavior of an Electric Machine Stator</td>
</tr>
<tr>
<td><a href="https://link.springer.com/chapter/10.1007/978-3-319-30249-2_5">https://link.springer.com/chapter/10.1007/978-3-319-30249-2_5</a></td>
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<td>Experimental and Numerical Validation of Laminated Structure Dynamics from a Switched Reluctance Machine Stator</td>
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</tr>
<tr>
<td>Validation of homogenization technique used for accurate predictions of laminated structures’ mechanical behavior</td>
</tr>
</tbody>
</table>
Providing advanced methods for NVH optimization of controls as well as design robustness.
Vibration Synthesis
Full system optimization by use of model reduction technology

System Simulation

- **Offline**
  - Magnetic analysis
  - Un陯ary forces
  - FE model

- **Online**
  - Force Decomposition + FFT
  - Vibration Synthesis
  - E-motor vibration/white in variable speed/load condition

Mathematical equations:

\[ F(t_i, i_1, i_2, N) \]

\[ Y(t_1, i_1, i_2, N) \]
Vibration Synthesis
Full system optimization by use of model reduction technology

**Advantage:** Faster design of control strategies with full accuracy of the detailed EM and structural models

- Potentially same accuracy as traditional 3D process
- Can reach >10 times faster calculations
- Insight in relevance of the different spatial orders

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Assembly tolerances and design robustness
Effect of rotor alignment on NVH performances

Unbalanced Magnetic Pull (UMP)

- Rotor misalignment results in unbalanced forces due to non-uniform airgap distribution
- 3D coupled electromagnetic calculation requires huge computational efforts

→ Efficient process developed using a MBS model of the rotor combined with table-based EM loads

Effect of clearances & non-linearities

- MBS model can be used to study:
  - Assembly tolerances, pre-load settings
  - Bearing clearances
  - Angular misalignments by using sliced approach
- Typical studies:
  - Rattle phenomena;
  - Evaluation of higher harmonics due to EM forces disturbances → Degradation of NVH performances
Summary

NVH assessment at concept stage

- Brings NVH team to discussion table during electrical subsystem design phase
- Multi-attribute balancing through system modelling approach
- Qualitative NVH risk assessment and quick evaluation of different design options

3D simulation in detailed design stage

- Integrated toolchain enabling design improvement prediction on all aspects of e-motor NVH: controls, EM, transmission, structural
- High model quality and good correlation through updating and parameter optimization process
- Reduced-order model to enable fast controls iterations
- Links to design robustness and manufacturing tolerances
eMotor NVH – from electric current to noise