Multi-domain simulation for the assessment of the NVH-behavior of electric vehicles with special attention to the influence of rotor eccentricity

Pascal Driche, Mark Mueller-Giebeler, Markus Jäger
Joerg Berroth, Georg Jacobs, Kay Hamayer, Michael Vorländer
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1. Motivation and objective

   Multi-domain approach

   - **Today:** Hot spot analysis
   - **Our vision:** Balancing model fidelity with psychoacoustics
   - **On the way:** Influence of rotor eccentricity
     - Efficient 3D electric machine force calculation
     - Efficient calculation of acoustic radiation

2. Summary and outlook
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles

Motivation and objective

- Increasing electrification in all vehicle classes, e.g.
  - e Go
  - VW E-Golf
  - Tesla Model 3

- New challenges regarding NVH behavior
  - Tonal electric motor noise at higher frequencies
  - No broadband ICE masking

- Handling through the use of methods of virtual product development

- Further development of tools for the assessment, optimization of drivetrain variants necessary
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles

Motivation and objective

Airborne sound

Structure-borne sound

Excitation of gears and electric machine
Motivation and objective

Multi-domain approach

1. Today: Hot spot analysis
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3. On the way: Influence of rotor eccentricity
   Efficient 3D electric machine force calculation
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Summary and outlook
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Multi-domain-approach

- Assessment of electrical drivetrains in the vehicle interior
- Development of a multi-domain, hybrid system model
- Development tool for hot spot analysis and optimization

Driver's wish

Multi-domain hybrid system model

Simulation

Electrics Structural dynamics Acoustics

Measurement

Components Drivetrain Driving situation
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Structural dynamics subsystem model

Elastic housings

Elastic Multi-body-simulation model

Laminar stator with windings

Elastomeric mounts

Gear mesh excitation

Bearings

Fluid-Structure-Interaction

MSE uforce

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Pascal Driehs, Mark Mueller-Glebelter, Markus Jager, Joerg Berndt, Georg Jacobs, Kay Hamayer, Michael Vorlander
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Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Structural dynamics subsystem model – Validation
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Structural dynamics subsystem model – Understanding and optimization
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Structural dynamics subsystem model – Understanding and optimization

Without elastic rotor decoupling

With elastic rotor decoupling

Comprehension & optimization on system level

Observed eigenfrequency

System

Level

Mode shape

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Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles

Ongoing work

- Control
- Sensors
- PWM
- Joint damping (housing)
  - Elastomeric mounts
  - Flexible gearwheels
  - Rotor model
- Sound radiation
  - Determining transfer paths
  - Psychoacoustic assessment
  - Listening test methods
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles

Ongoing work

Numerous model components and fidelity levels

Computation time

Now
Current development

Rotor model
Listening test methods

Result quality

Psychoacoustics

IEM
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ITA

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Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Impact of rotor eccentricity and interaction of system components

<table>
<thead>
<tr>
<th>Electric machine</th>
<th>Interaction of system components</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator</td>
<td>Stator</td>
<td>ideal</td>
</tr>
<tr>
<td>Rotor</td>
<td>Rotor</td>
<td>eccentric</td>
</tr>
<tr>
<td>Bearings</td>
<td>Bearings</td>
<td>eccentric</td>
</tr>
</tbody>
</table>

- Inertia
- Stiffness
- Electromagnetic loads
- Contact
- Backlash
- (Nonlinear) stiffness
- Inertia and weight force
- Stiffness
- Imbalance and rotational speed
- F
- F
- F
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Psychoacoustic effect of rotor eccentricity
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Psychoacoustic effect of rotor eccentricity

Psychoacoustic effect differs significantly
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Run-up with rotor eccentricity
### Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles

**Run-up with rotor eccentricity – Low speed area**

<table>
<thead>
<tr>
<th>Main principle</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- **Time = 02.00025 s**
- **Diagram**
- **Rotor position [m]**
- **Rotational speed [rpm]**

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**Sources:**
- RWTH Aachen University | Institute for Machine Elements and Systems Engineering (MSE)
- Institute for Electric Machines (IEM) | Institute for Technical Acoustics (ITA)
- Pascal Dorchel, Mark Mueller-Geleis, Markus Jager, Joerg Berroth, Georg Jacobs, Kay Hamayer, Michael Vorlander
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Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Run-up with rotor eccentricity – High speed area
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Psychoacoustic effect of rotor eccentricity

Electric machine modell shows physically meaningful results

Validation with measurements on testrig
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Multi-domain-approach – Interface Electrics / Structural dynamics
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles

Electrics

Physical phenomenon

Fundamental 3D MBS model concept

MBS model with „multi-slice“-method

3D-modeling is cumbersome and resource intensive

- 2D FEM
- Use of symmetries for reduction of:
  - Computational effort
  - Size of lookup table

- Current
- Phase
- Rotation angle
- Eccentricity displ.
- Eccentricity angle

Abstraction

Precalculation

Lookup table

Transformation

Efficient 3D-modeling with 2D-precalculation
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Multi-domain-approach – Interface Structural dynamics / Acoustics
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Interface structural dynamics and acoustics – Motivation

Analytic Drivetrain
High frequency and spatial resolution
High sampling rate

Boundary-Element-Method (BEM)
Electric machine
Drivetrain

Volume of transferred data
~250 GB
~35 GB
~10 GB
~0.16 GB

Number of nodes for the acoustic mesh
~0.21 GB

Amount of data for run-up with 10 sec, with sampling rate of 20kHz

Surface velocities v(t)
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Interface structural dynamics and acoustics – Concept

\[ \dot{x}_K(t) = \dot{x}_{Flex}(t) + \dot{x}_{Rigid}(t) \]

\[ \dot{x}_K(t) = \dot{q}(t) \cdot R + \dot{x}(t) + \dot{\alpha}(t) \times R \]
Drivetrain simulation for the assessment of the NVH-behavior of electric vehicles
Interface structural dynamics and acoustics – Improvements in prediction quality
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Summary and outlook

- Assessment of NVH-behavior of electrical drivetrains
- Development of a multi-domain, hybrid system model
- Development tool for hot spot analysis and optimization
- Efficient 3D electric machine force calculation with 2D-precalculation
- Efficient calculation of transient acoustic radiation
- Non-ideal behavior of electric machine has pronounced effect on psychoacoustics

- Balancing result quality and computation time with the analysis of different model fidelity levels using psychoacoustic metrics
Thank you for your attention.

Kontakt
Dipl.-Ing. Pascal Drichel
Team leader Noise Vibration Harshness
pascal_drichel@imse.rwth-aachen.de
Phone: 0241/80-95639

Prof. Dr.-Ing. Georg Jacobs
greg.jacobs@imse.rwth-aachen.de
Phone: 0241/80-95635

Institute for machine elements and systems engineering
Schinkelstraße 10
52062 Aachen (Germany)

Dr.-Ing. Joerg Berroth
Chief Engineer Drive Technology
joerg.berroth@imse.rwth-aachen.de
Phone: 0241/80-95609