EVS32 A world of E MOTION
2019 MAY 19 22
INTERNATIONAL ELECTRIC VEHICLE SYMPOSIUM & EXHIBITION
EVS 50th anniversary 1969-2019

Elaphe Propulsion Technologies

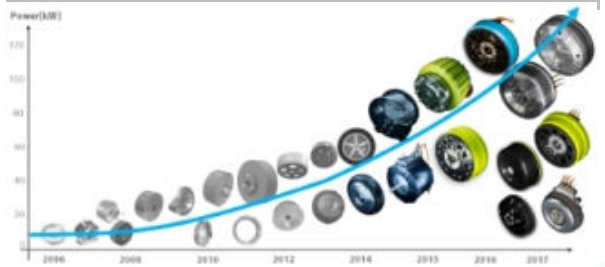
A holistic approach to noise reduction in an in-wheel electric motor drive

Martin Strojnik, PhD
Head of active part design

Elaphe Propulsion Technologies Ltd.

www.in-wheel.com
customer@elaphe-ev.com
elaphe Propulsion Technologies

Over 15 direct-drive motor designs delivered and integrated



Most powerful motor

Largest number of vehicles

Most powerful in-wheel car

Elaphe JV Production line

Company

- Formally established in 2006, research since 1980s
- Complete in-wheel drivetrain solution disrupting the mobility market
- Partnerships with key automotive suppliers in EU and China

Market position

- World leader in direct-drive
- Patented technology
- Headquarters in EU, JV in China

- Commercial, Develop & Deliver and Research projects in all key markets (US, EU, China, Asia)
- JV in China for local manufacturing with the largest Chinese Tier 1 brake supplier

R&D Team

- Large and focused R&D center (> 20% with PhD)
- Complete set of skills, knowledge and experience

Some of Elaphe awards

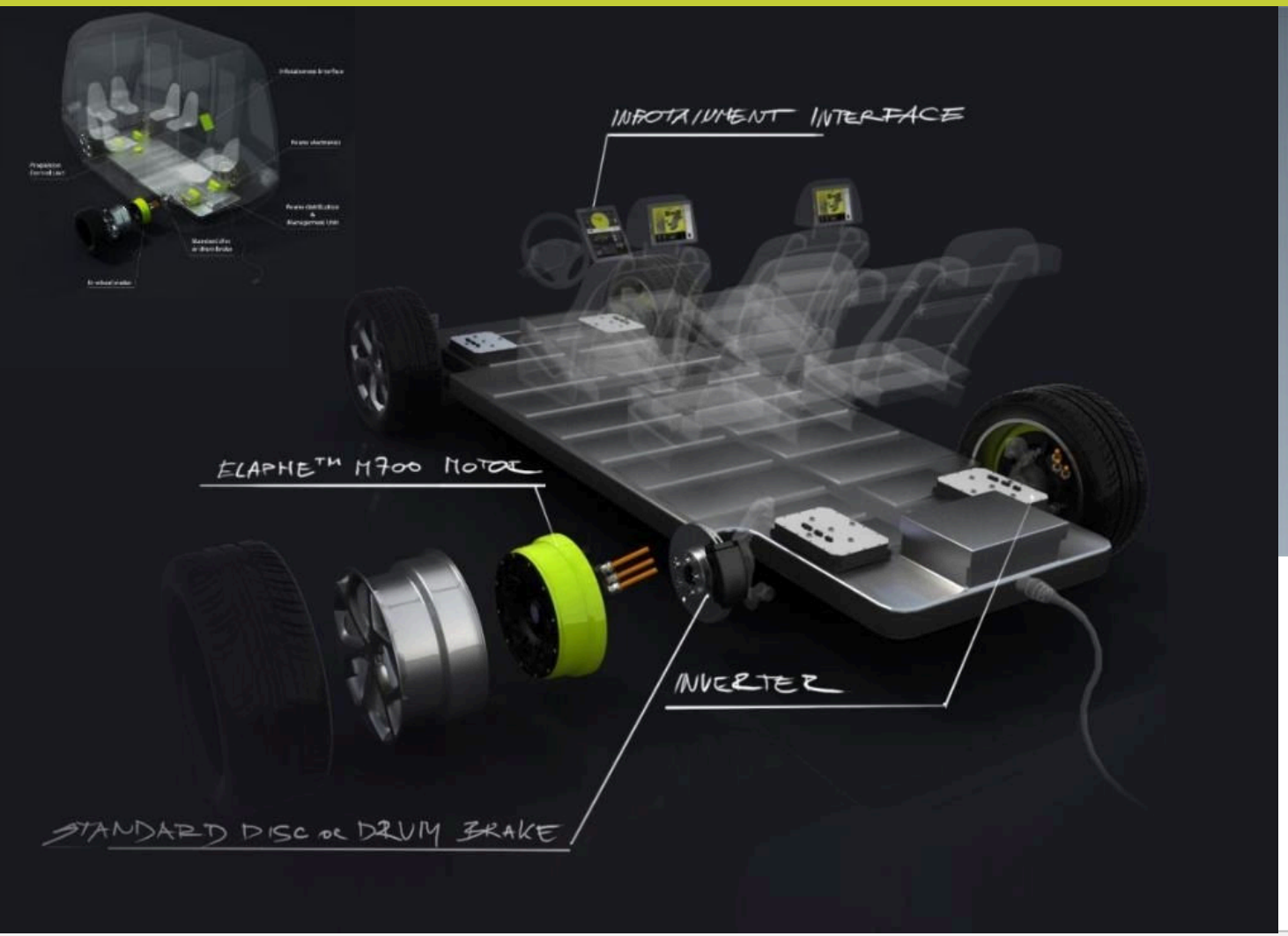
European partner network

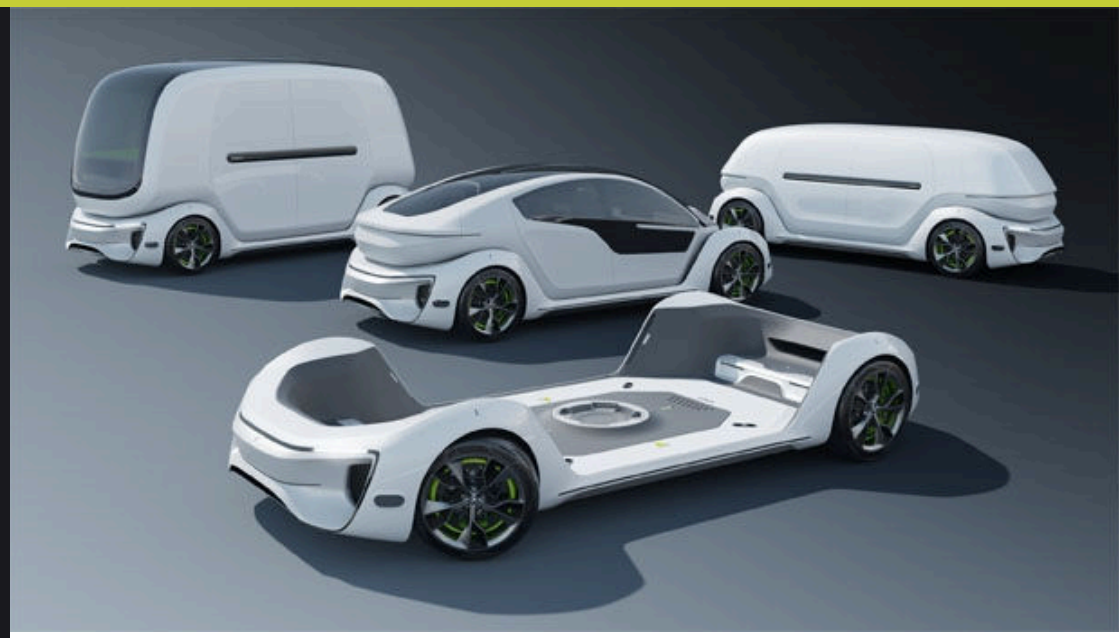
TURNING THINGS AROUND

elaphe Propulsion Technologies

In-wheel: The modular approach

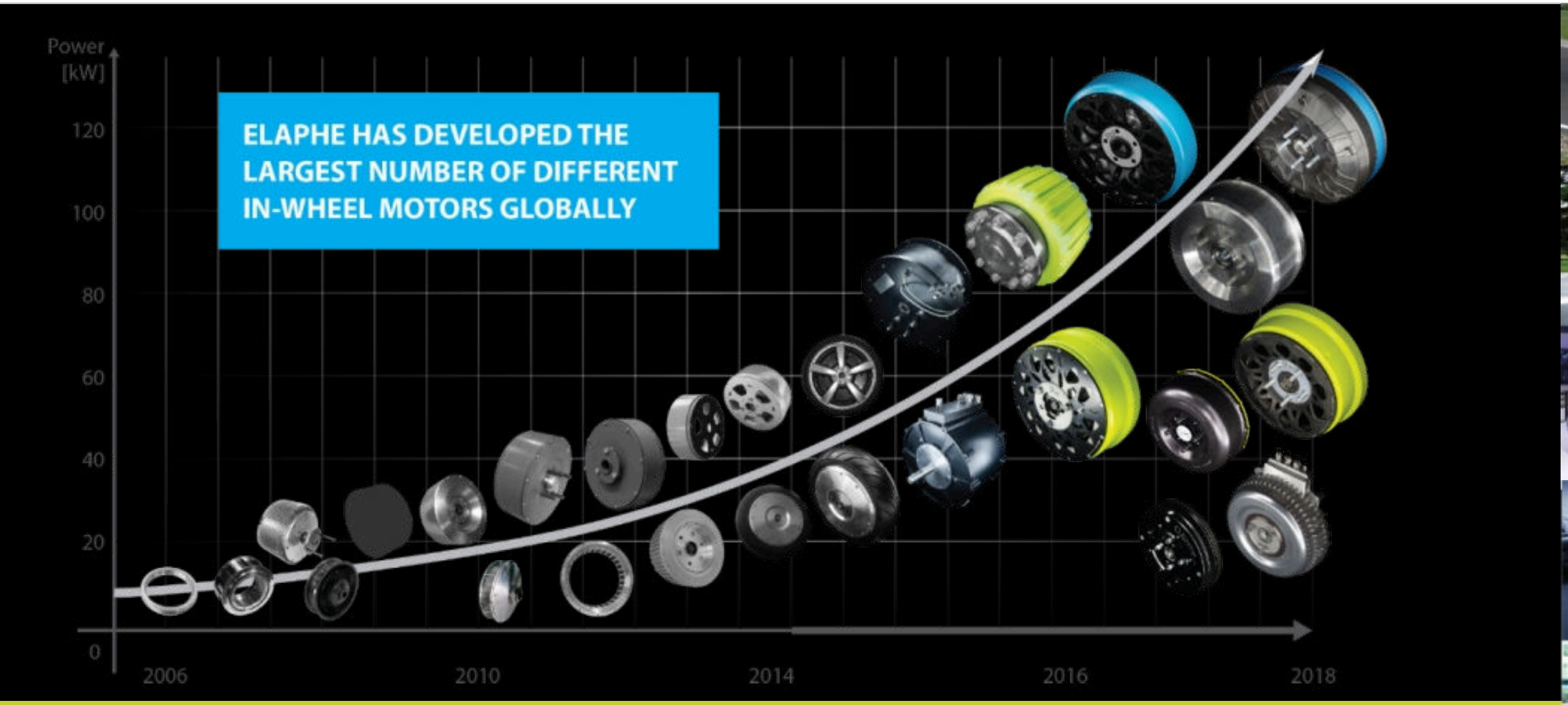
FUNCTION CENTERED VEHICLE DESIGN

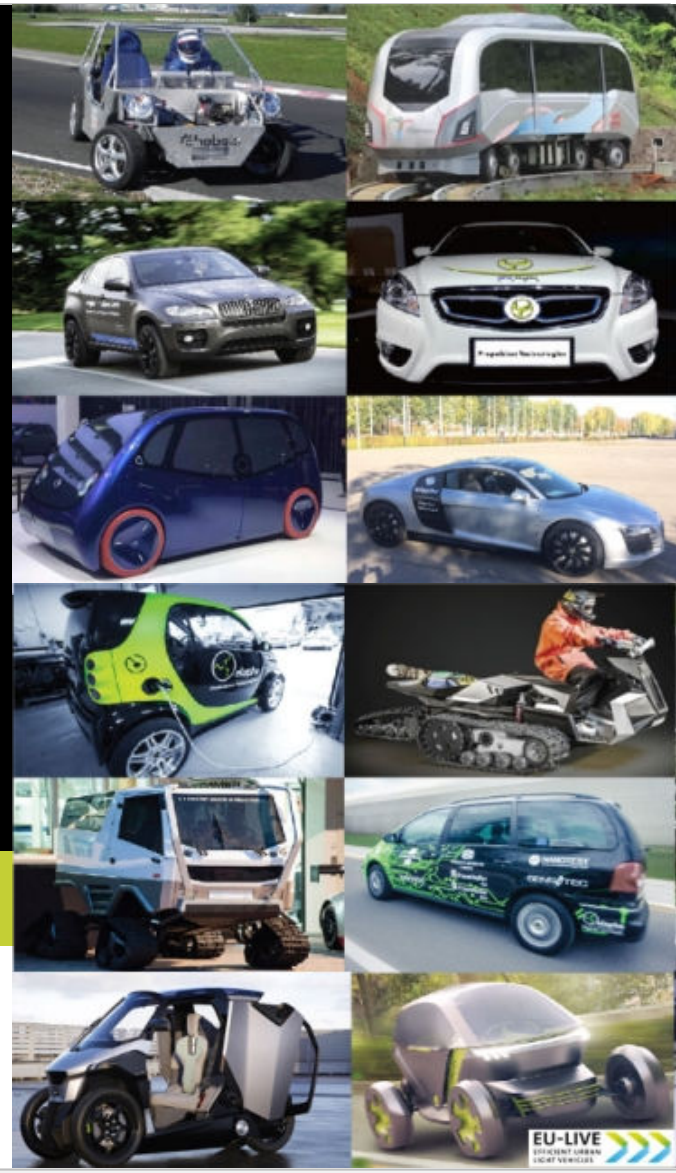




- Modularity of the platform
- Reducing the weight and number of components
- Lowering the total cost of development and ownership
- Increasing manoeuvreability

Scalable in-wheel motor design for multiple vehicle architectures





Versatile technology with many applications of the same products

- No gears necessary
- System with OEM parts
- Fully electric or hybrid
- Performance up to 1500 Nm
- Speeds up to 2000 rpm

Jump-Start to electrification

I. READY ADVANCED SOLUTIONS

II. WORKING WITH YOUR R&D

Adapting to your level of development need

Leading in-wheel solution	Complete HW & SW solution	System & Vehicle engineering	Beyond state-of-the-art	Building on Elaphe know-how	Completing your teams
PLUG & PLAY			**AGILE & DEDICATED**		

Completing the innovation: Advanced electronics

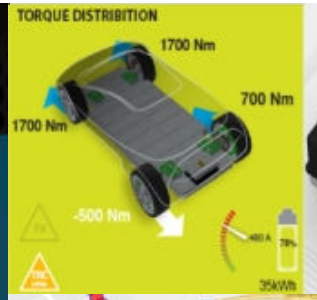
- High functional safety level (D)
- Automotive standards
- Modular & connected
- Rich, intelligent data

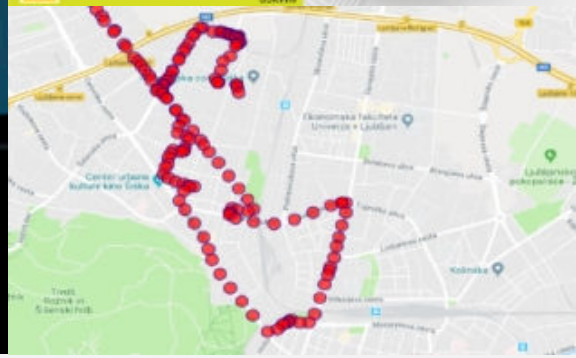
NEW POSSIBILITIES FOR SAFETY, BRAKING AND TRACTION CONTROL

THE POWERBRAIN

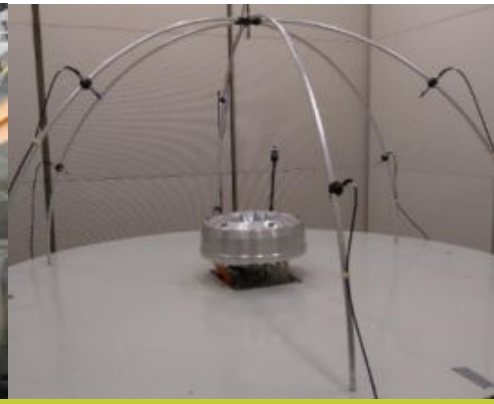
MULTIPLE-MOTOR PROPULSION CONTROL

Traction Control	Torque vectoring	Anti-lock regenerative braking system (ARBS)	Configurable motor control	Complete propulsion APIs
Connected & Safely integrated	Battery power control	Condition monitoring	Data logging & Drive analytics	Various driving modes





Key requirements for in-wheel motor design



- PACKAGING WITH STEERING, SUSPENSION, BRAKE AND WHEEL
- MECHANICAL AND ENVIRONMENTAL DURABILITY
- HIGH MASS AND VOLUME TORQUE DENSITY
- THERMAL MANAGEMENT
- **ACOUSTIC AND STRUCTURE BORNE NOISE**

In-wheel motor NVH aspects

What is the difference vs. conventional EVs?

- In-Wheel motor noise cannot be shielded with same methods
- In-wheel motors are rigidly connected to the wheel knuckle – different vibration transfer path.
- Airborne noise is propagated directly to the environment.
- Structural design is limited by design space and weight restrictions
- Much higher pole count improves the EM excitation effects

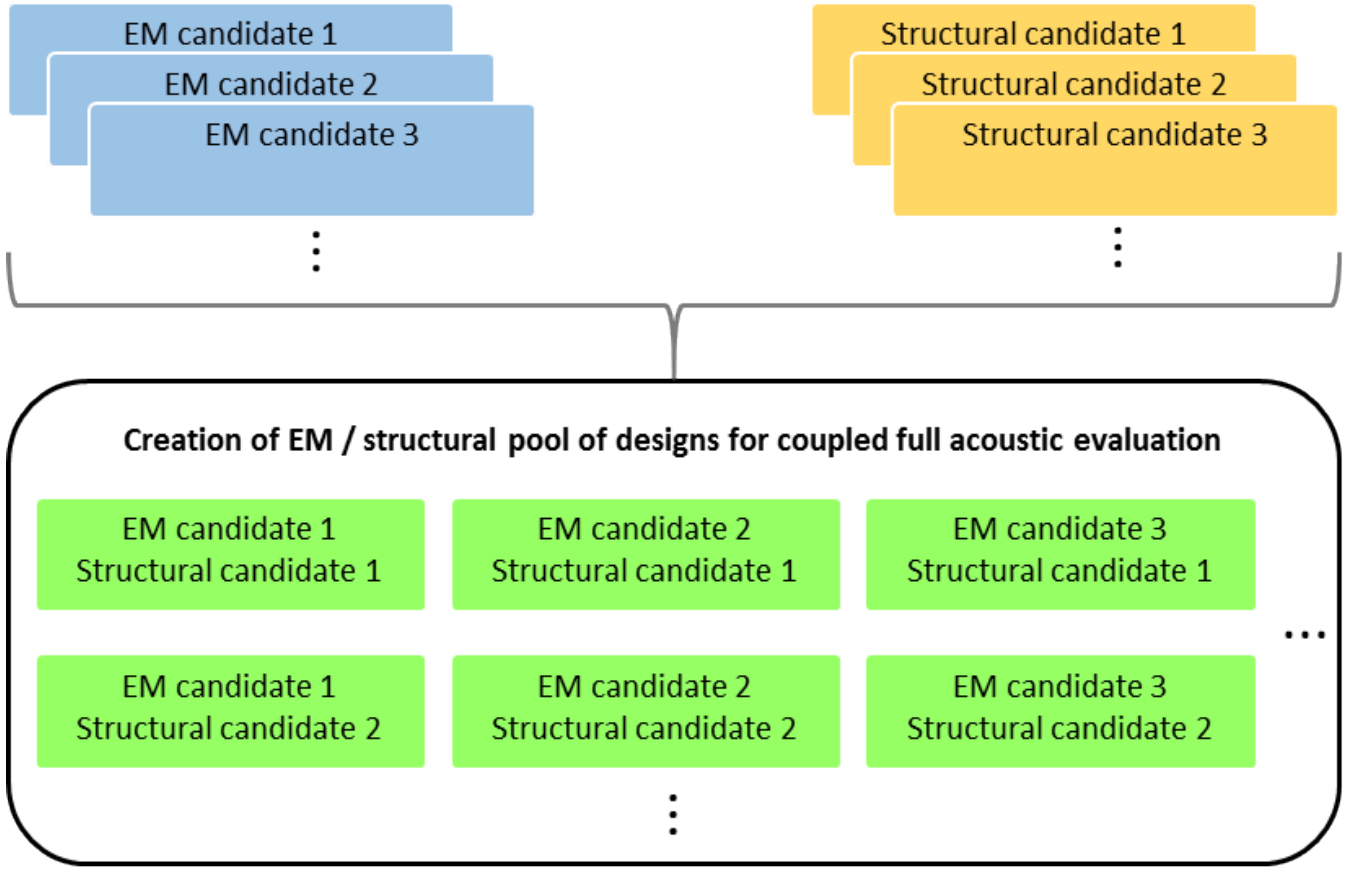
Holistic approach to NVH optimization

In-wheel motor NVH aspects

In-wheel motor structure optimization

- Focused on electromagnetic design and structural design
- Major effect on air-borne noise
- Partial effect on structure borne noise excitation

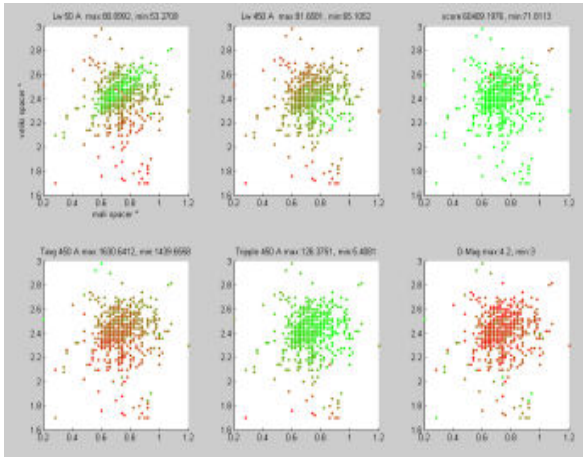
In-wheel motor structure optimization

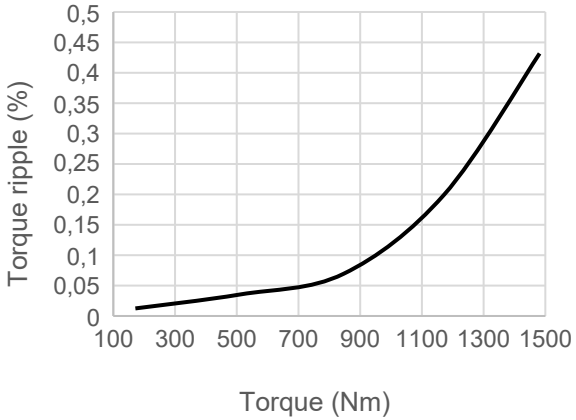


Two-step optimization

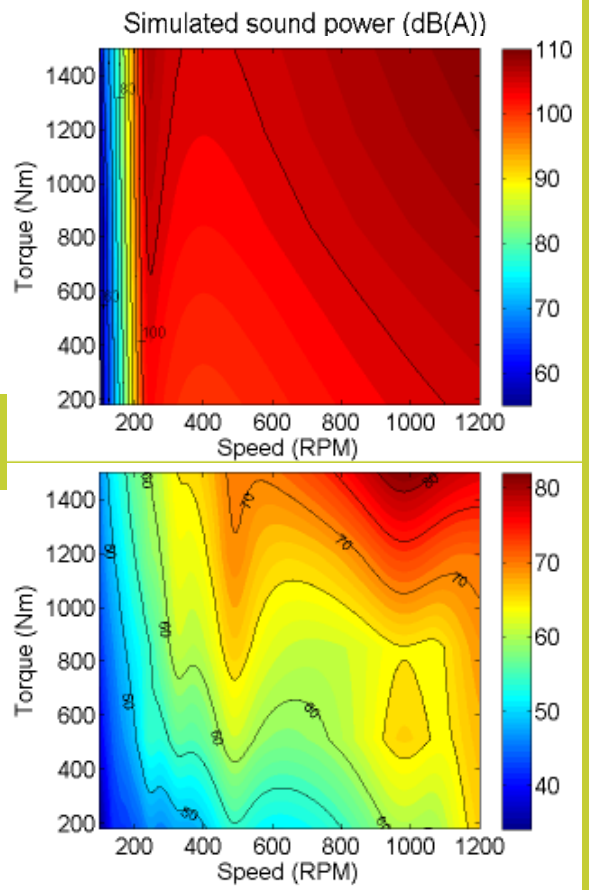
- Differential evolution for generation of candidates
- EM optimization target function:
  - Torque ripple
  - Sound emmission from analytical acoustic model
  - Performance (torque, speed, efficiency) used as BC
- Structural optimization target:
  - No structurally exited resonances in common driving scenarios
  - Decrease of ERP for excited resonant modes

In-wheel motor structure optimization





Bad vs. good noise design



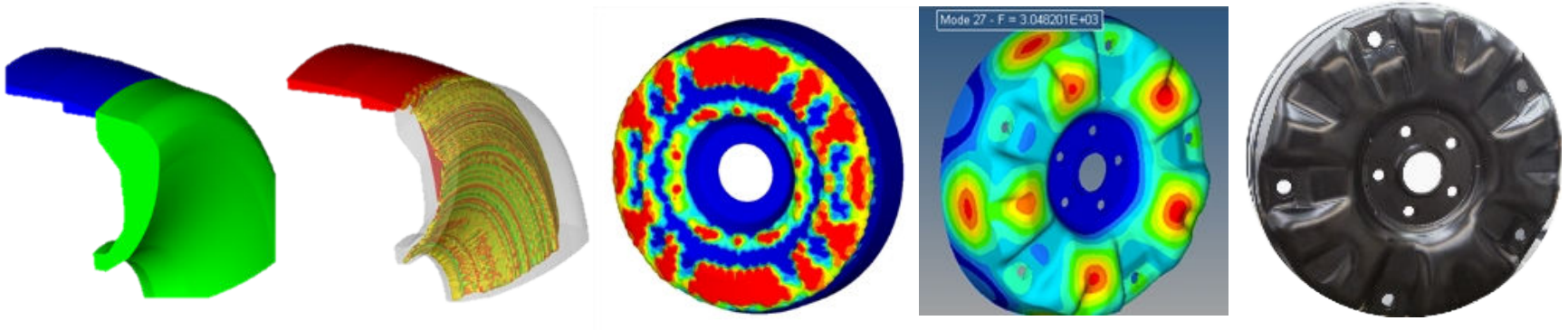
Active part design results

- Evaluation of each member in several working points (speed, torque)
- Analytical noise Analytical evaluation of emmited sound for the best performing candidates
- Export of excitations for analysis with rotor structures

Two-step optimization

- **Differential evolution for generation of candidates**
- **EM optimization target function:**
  - **Torque ripple**
  - **Sound emmission from analytical acoustic model**
  - **Performance (torque, speed, efficiency) used as BC**
- Structural optimization target:
  - No structurally exited resonances in common driving scenarios
  - Decrease of ERP for excited resonant modes

In-wheel motor structure optimization



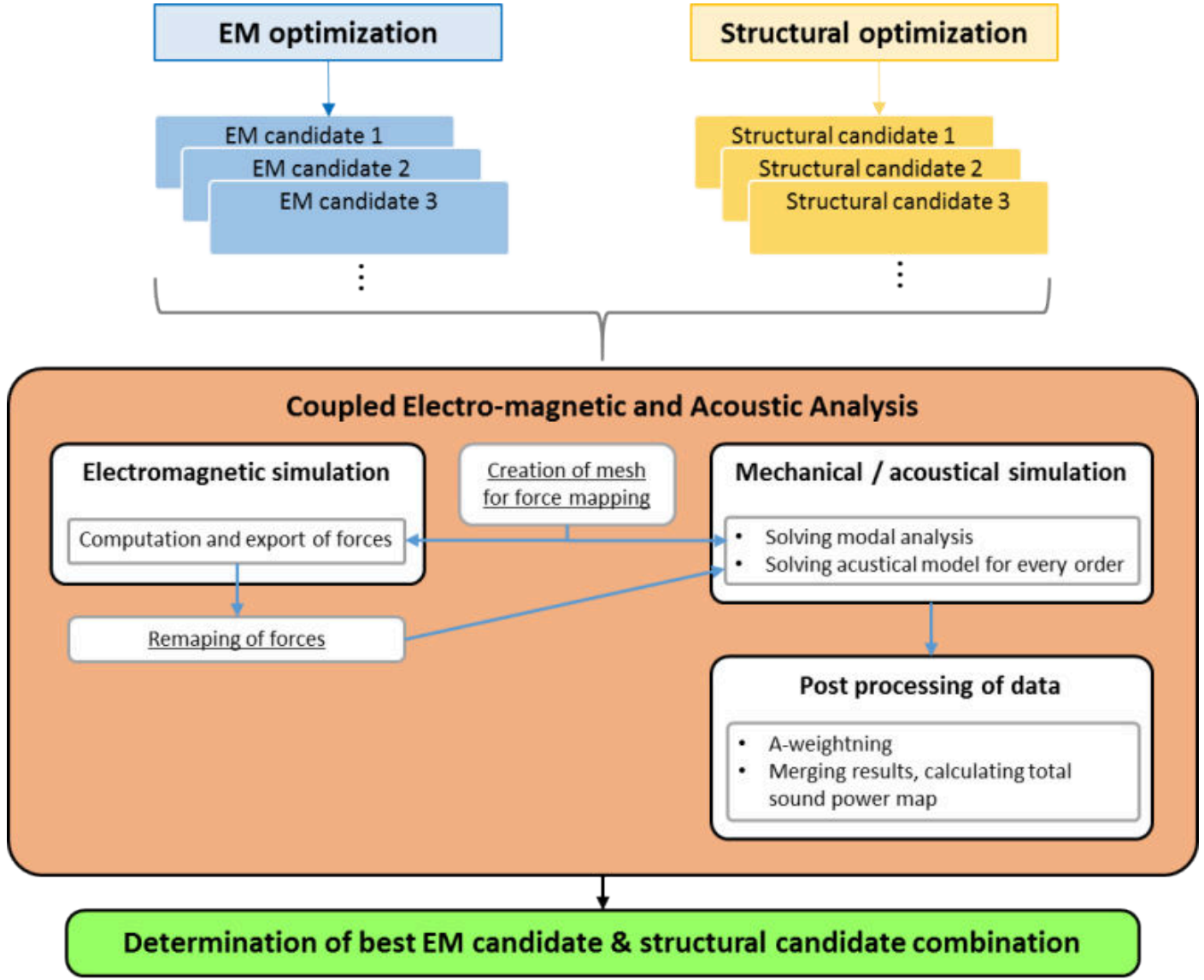
Mechanical design results

- Rotor thickness and shape optimization within boundary conditions (topology optimization)
- Appropriation of the manufacturing process
- Pairing with excitations by active part candidates

Two-step optimization

- **Differential evolution for generation of candidates**
- EM optimization target function:
  - Torque ripple
  - Sound emmission from analytical acoustic model
  - Performance (torque, speed, efficiency) used as BC
- **Structural optimization target:**
  - **No structurally exited resonances in common driving scenarios**
  - **Decrease of ERP for excited resonant modes**

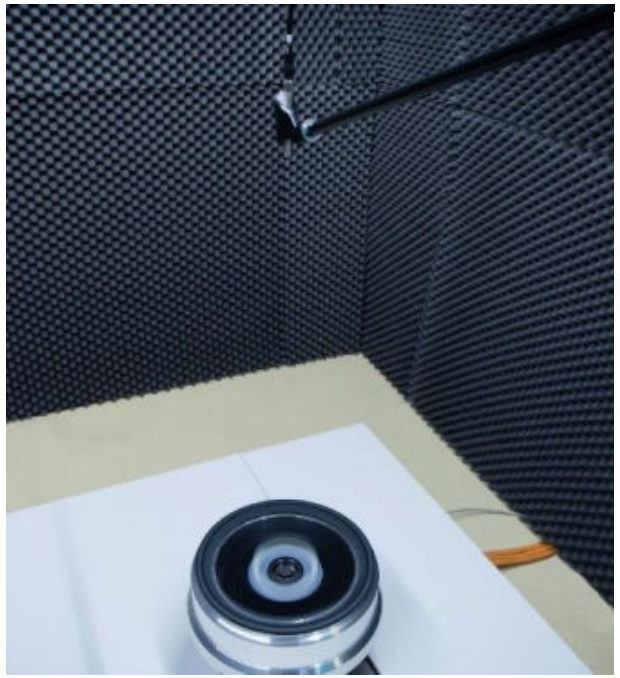
In-wheel motor structure optimization

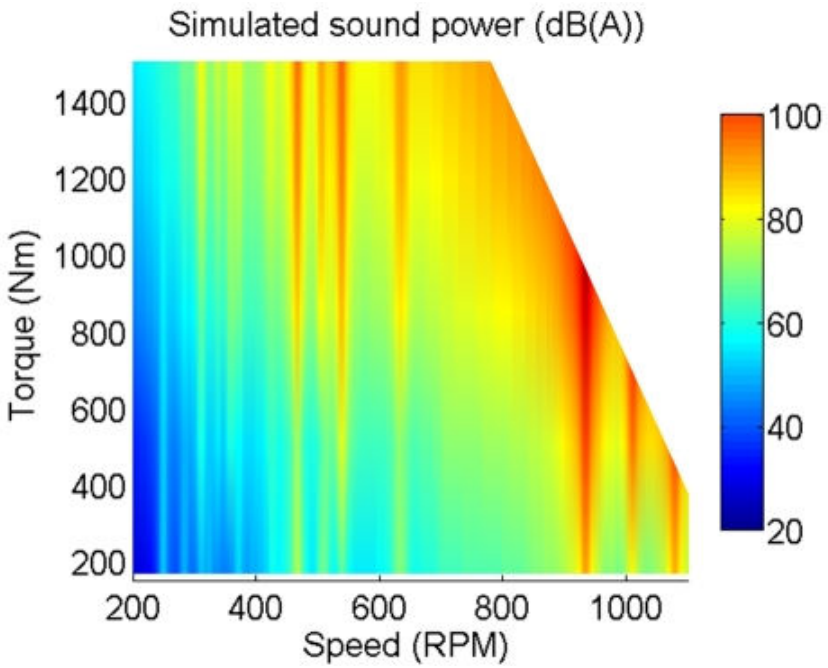


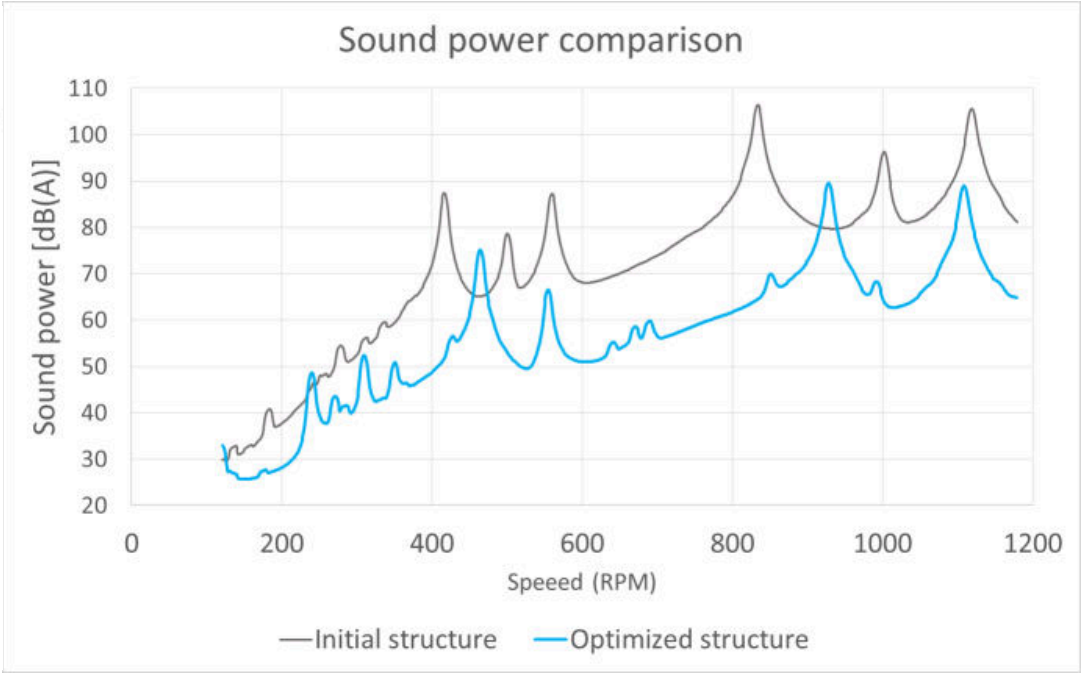
Two-step optimization

- Differential evolution for generation of candidates
- EM optimization target function:
  - Torque ripple
  - Sound emmission from analytical acoustic model
  - Performance (torque, speed, efficiency) used as BC
- Structural optimization target:
  - No structurally exited resonances in common driving scenarios
  - Decrease of ERP for excited resonant modes

In wheel motor structure optimization







Airborne noise output

Large improvement over intial prototypes

- Sound optimization focused on urban environment driving and low and medium torque successful
- Improvement over the version A considerable – 10-20 dB(A) in most working points
- SPL at pass-by is expected to be around 20 dB lower than motor sound power

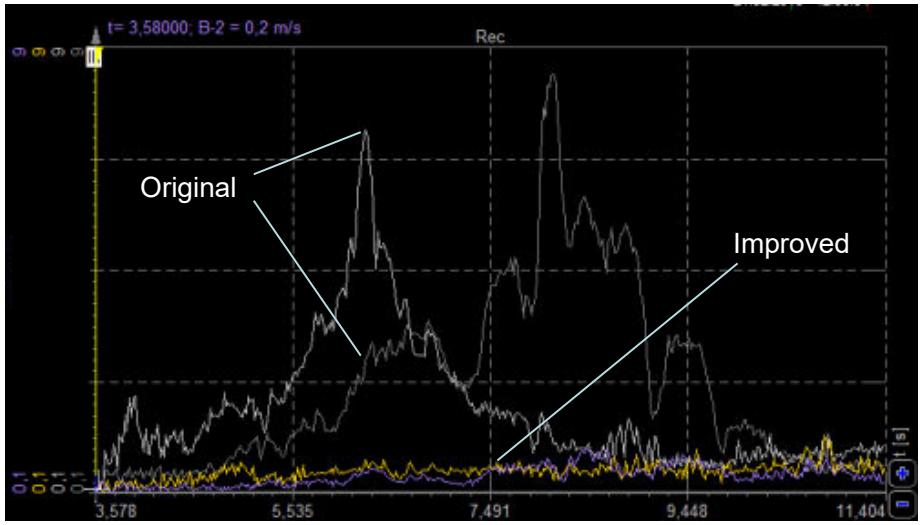
In-wheel motor NVH aspects

Control optimization

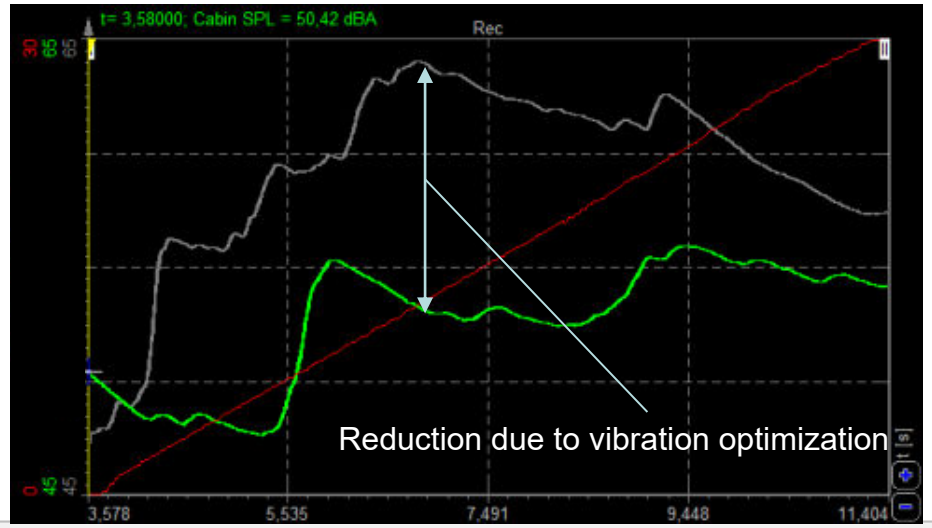
- Focus on torque ripple reduction
- Major effect on structure-borne noise excitation
- Small effect on air-borne noise

Control optimization

Vibration on suspension



Acoustic noise in cabin



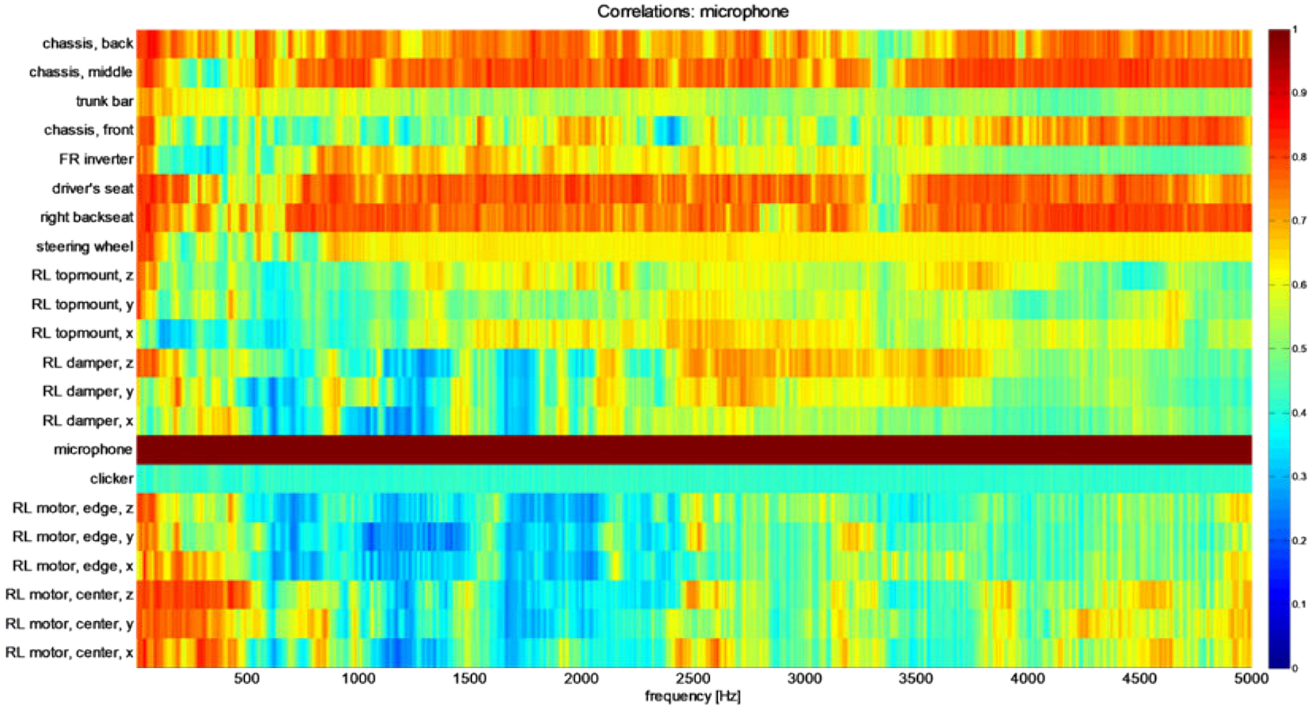
Cause of vibrations

- Interaction between rotor magnets and stator current harmonics magnetic fields
- Origins
  - motor geometry
  - Production tolerances
  - **Motor control**
- **Ripple induced by motor control**
  - **PWM control artefacts**
  - **Position sensor non-linearity**
  - **Inverter current control inaccuracy**
- Cogging is negligible

Control optimization

Approach

- **Identification of structure-borne noise source through measurement on vehicle (vibration, sound)**
- **Identification of appropriate tuning sensor positions and targets**
- Compensation of PWM control inaccuracy
- Compensation of inverter position and current sensing inaccuracy
- Active injection of higher harmonics:
  - Simultaneous tuning of 12 parameters corresponding to 6 harmonics (phase, gain)
  - One day tuning through automated processing and iteration



Control optimization

Approach

- Identification of structure-borne noise source through measurement on vehicle (vibration, sound)
- Identification of appropriate tuning sensor positions and targets
- **Compensation of PWM control artefacts**
- Compensation of inverter position and current sensing inaccuracy
- Active injection of higher harmonics:
  - Simultaneous tuning of 12 parameters corresponding to 6 harmonics (phase, gain)
    - One day tuning through automated processing and iteration

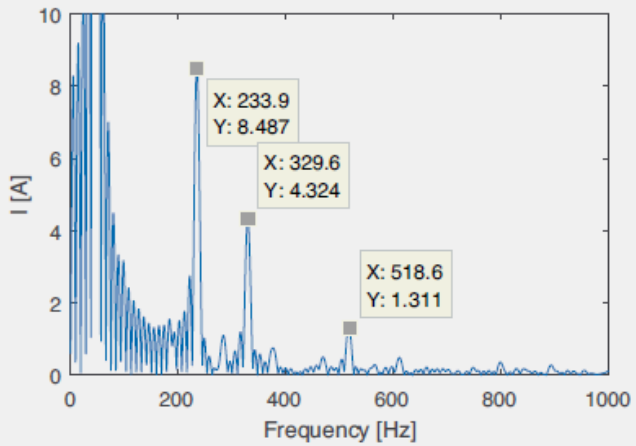


Figure 9: FFT of current without dead-time compensation.

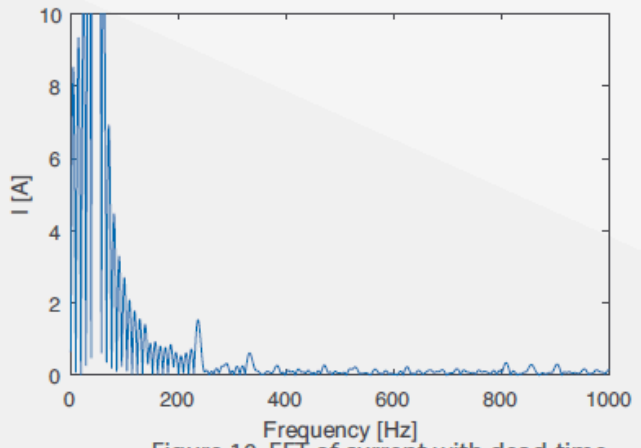
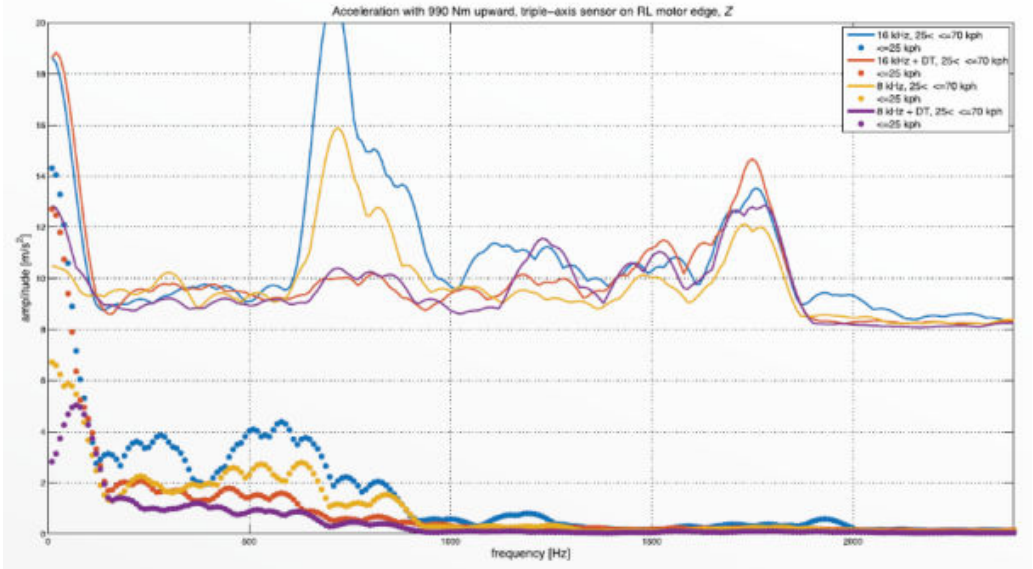


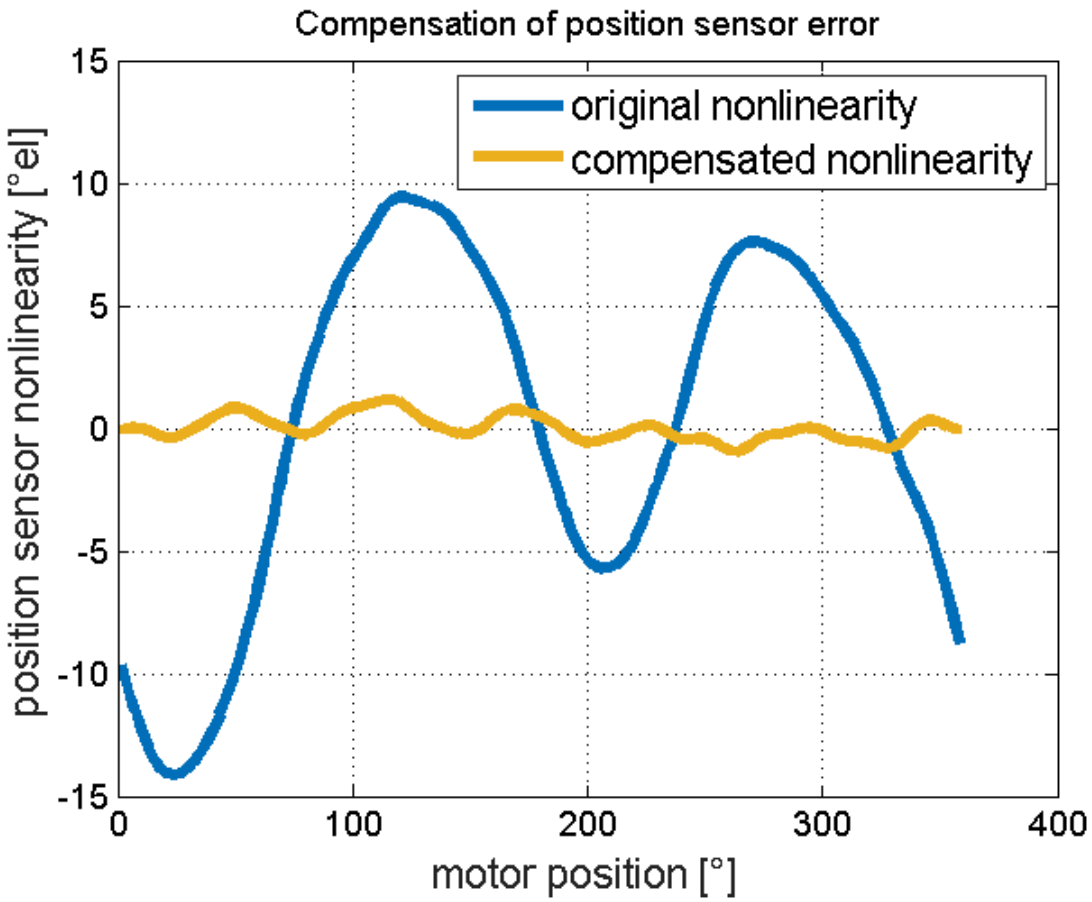
Figure 10: FFT of current with dead-time compensation.



Control optimization

Approach

- Identification of structure-borne noise source through measurement on vehicle (vibration, sound)
- Identification of appropriate tuning sensor positions and targets
- Compensation of PWM control inaccuracy
- **Compensation of inverter position and current sensing inaccuracy**
- Active injection of higher harmonics:
  - Simultaneous tuning of 12 parameters corresponding to 6 harmonics (phase, gain)
  - One day tuning through automated processing and iteration



Compensation of an extreme case of position sensor nonlinearity

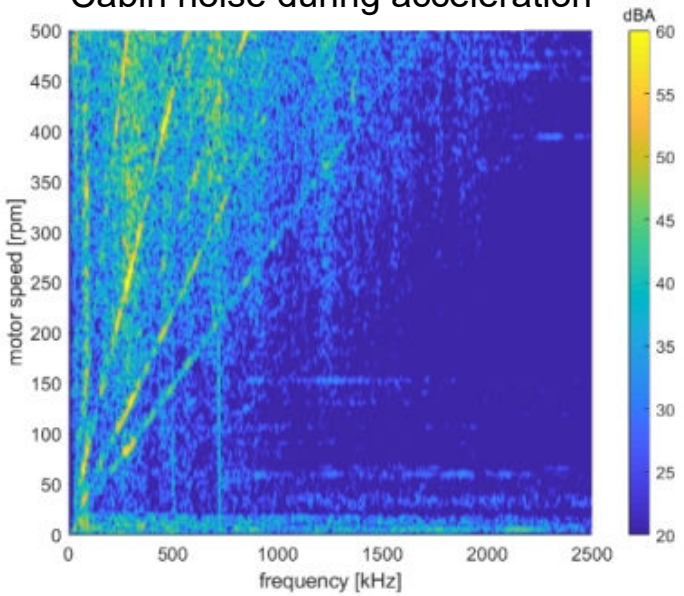
Control optimization

Approach

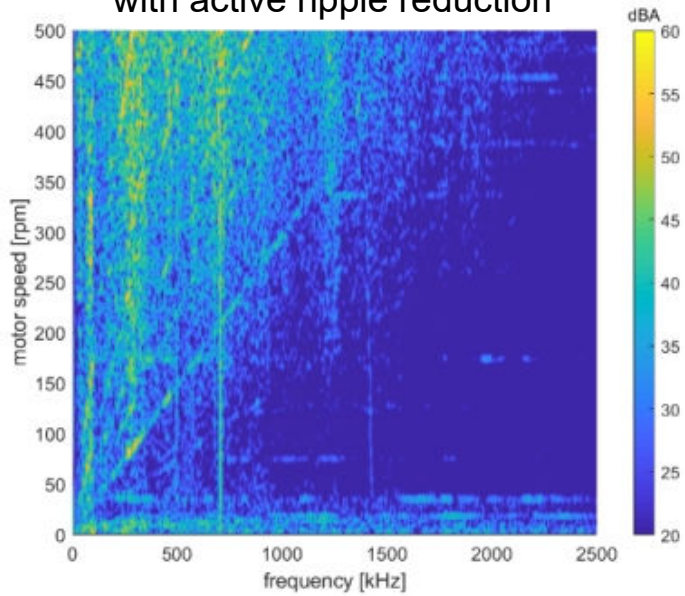
- Identification of structure-borne noise source through measurement on vehicle (vibration, sound)
- Identification of appropriate tuning sensor positions and targets
- Compensation of PWM control inaccuracy
- Compensation of inverter position and current sensing inaccuracy
- **Active injection of higher harmonics:**
  - **Simultaneous tuning of 12 parameters corresponding to 6 harmonics (phase, gain)**
  - **One day tuning through automated processing and iteration**

Acceleration at full torque – 6000 Nm

Cabin noise during acceleration



Cabin noise during acceleration with active ripple reduction



In-wheel motor NVH aspects

System level approach

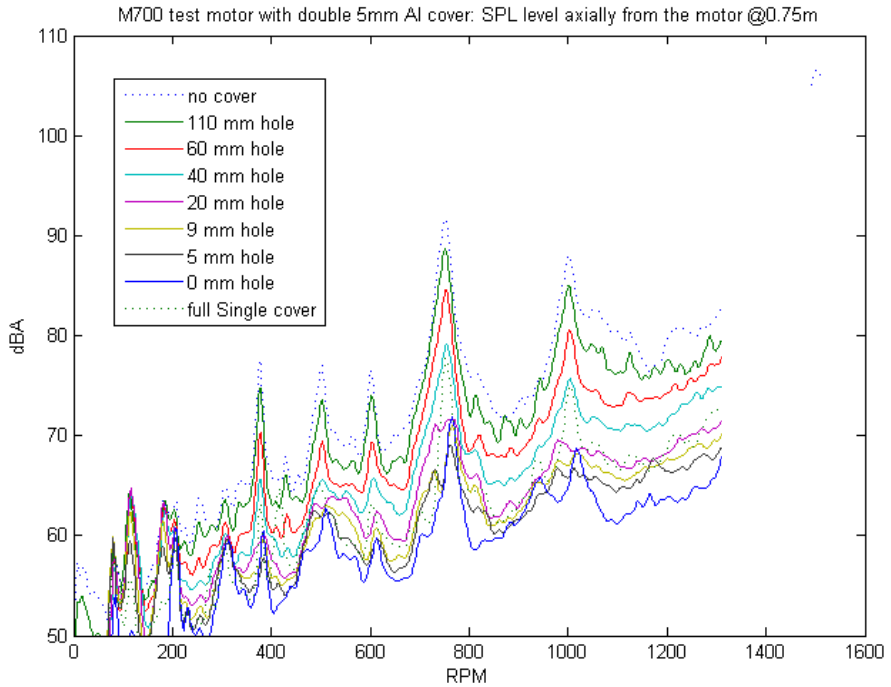
- Air-borne noise shielding with rim
- Structure-borne noise damping optimization by suspension and mounting
- Active noise cancelling in cabin

System level approach

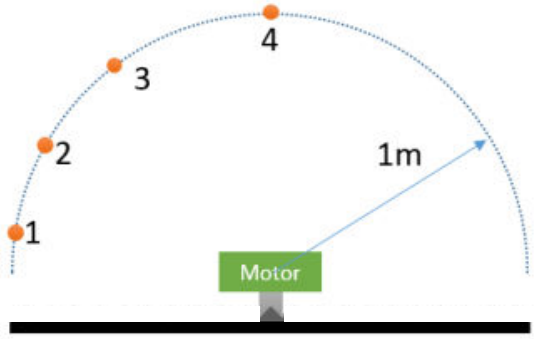
External acoustic sound optimization through rim and bumper design

Concept tested and confirmed:

- Reduction of noise by up to 20-25 dB with closed rim
- Reduction of more than 10 dB with 20% opened rim
- Rotor cooling concept possible and shown in existing rims



Sound pressure levels at mic 4 position at different rim cover openings during speed sweep.

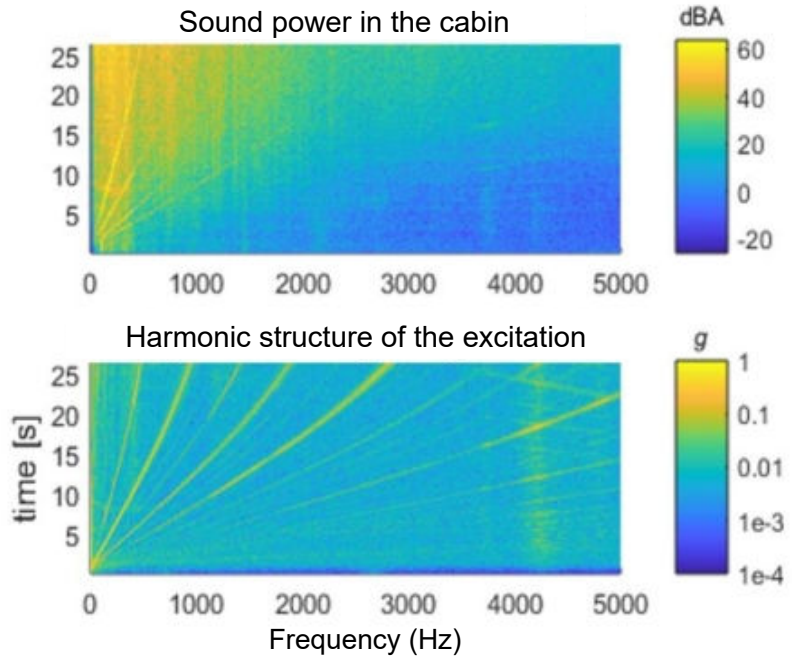


Some EV rim designs already go in the direction of reducing the size of the rim holes

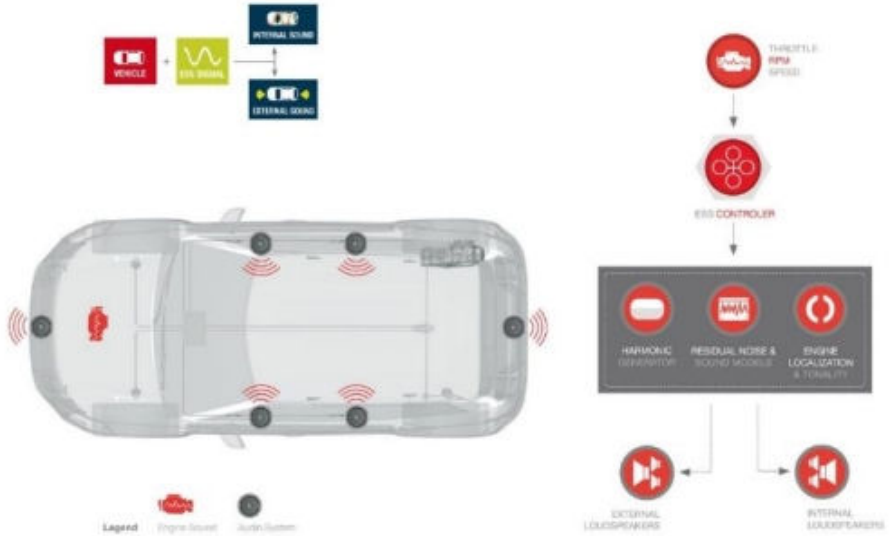
Further work for maximum comfort

Completely eliminate passenger cabin noise for sensitive applications

- Optimization of interfaces between suspension and vehicle body
  - Challenge: high frequency damping and low frequency stiffness
  - Even non-optimized suspension can contribute substantially to damping



HALOsonic system by Harman



- Active cancelling of cabin noise
  - Periodic signals
  - Predictable volumes and frequencies
  - Possible challenges not yet known

Summary

Holistic approach solves the challenges of in-wheel motor NVH

- Design optimization for air- and structure-borne noise optimization
- Control solutions for further optimization of cabin noise
- Advanced system level solutions available for most sensitive applications

EVS32
A world of E MOTION
2019 MAY 19 22

INTERNATIONAL ELECTRIC VEHICLE SYMPOSIUM & EXHIBITION

EVS 50th anniversary 1969-2019

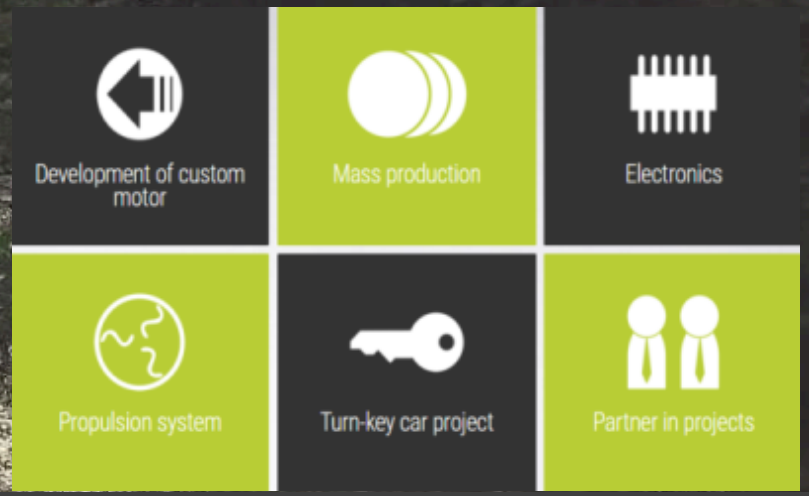
ELAPHE SOLUTIONS

- Off-the-shelf in-wheel motors
- Development of custom in-wheel motors

Development of a complete powertrain and control systems

Support in bottom-up new vehicle development

Turn-key electric vehicle propulsion systems



www.in-wheel.com

elaphe
Propulsion Technologies

customer@elaphe-ev.com

TURNING THINGS AROUND

elaphe
Propulsion Technologies