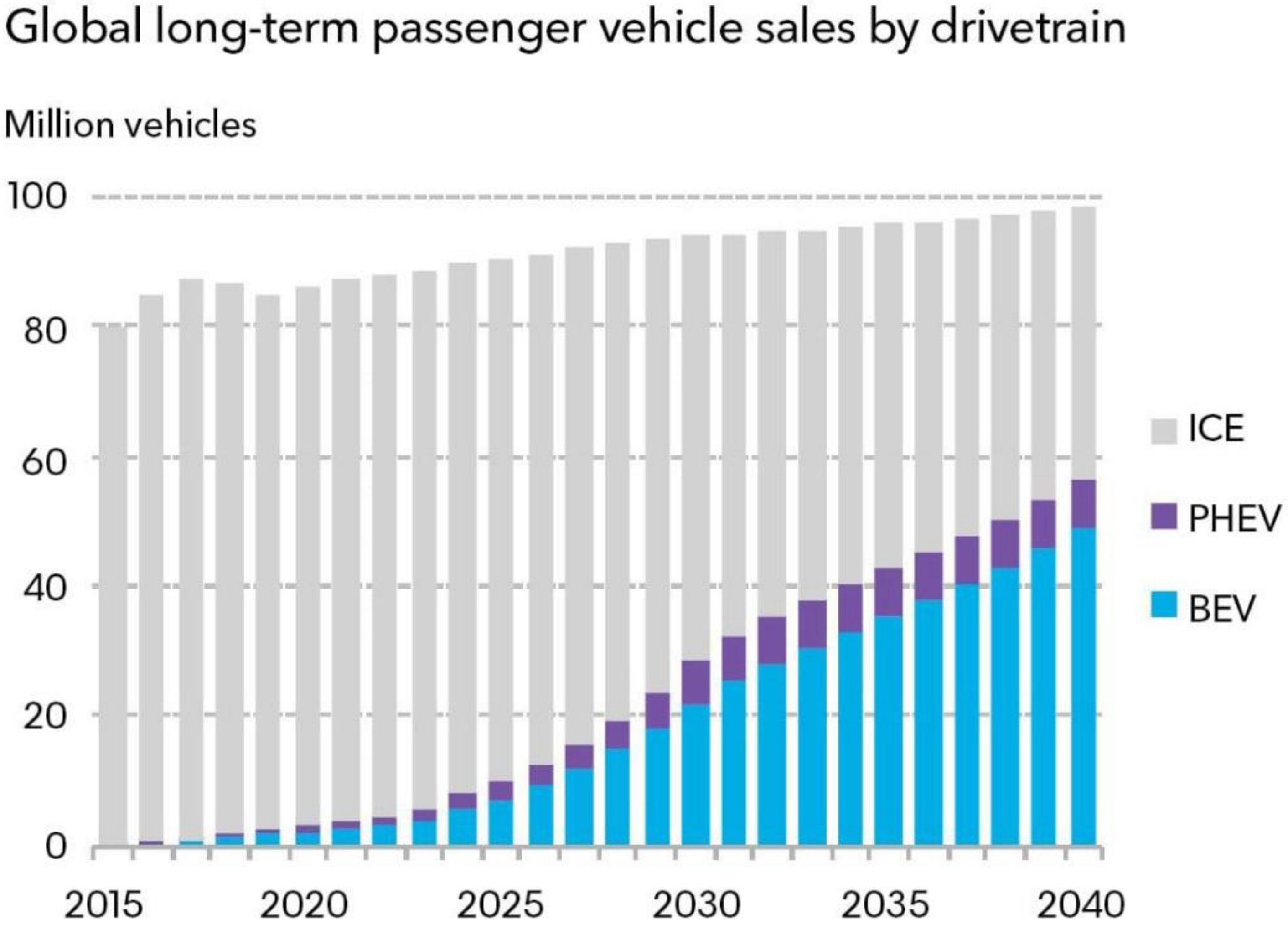
E-Motor NVH – from electric current to noise

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



Source: BloombergNEF

Electric Powertrain are not silent

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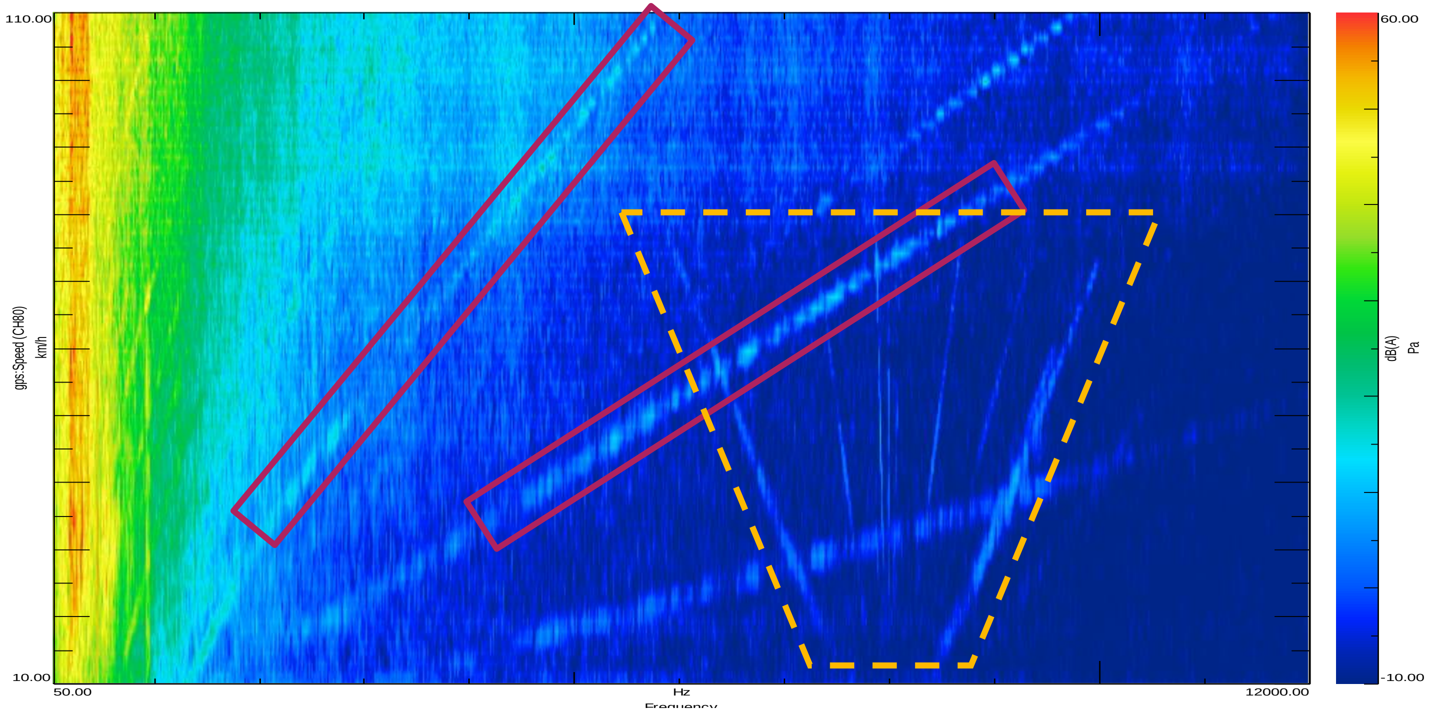
Lower overall levels, but… high-frequency, tonal content makes e-motor noise annoying:

- **Higher motor orders due to construction**
- **Very high frequency sounds**
  - Off-zero orders
  - Related to PWM switching frequency



Addressing these E-Motor NVH challenges – from electric current to noise

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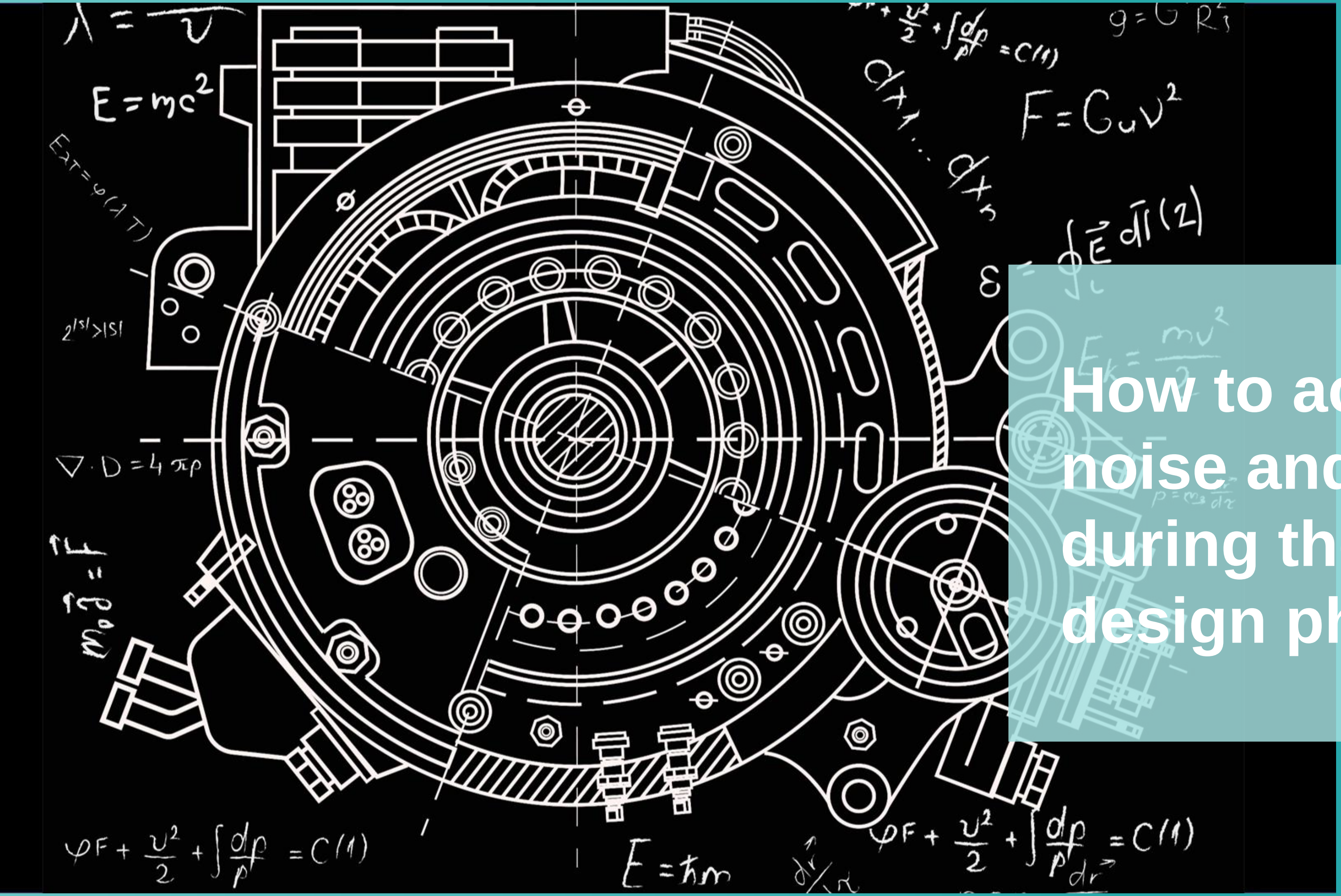

How to accurately predict e-motor noise and identify system sensitivities during the conceptual and detailed design phase of vehicle development?

“V”- design cycle for automotive electric drives

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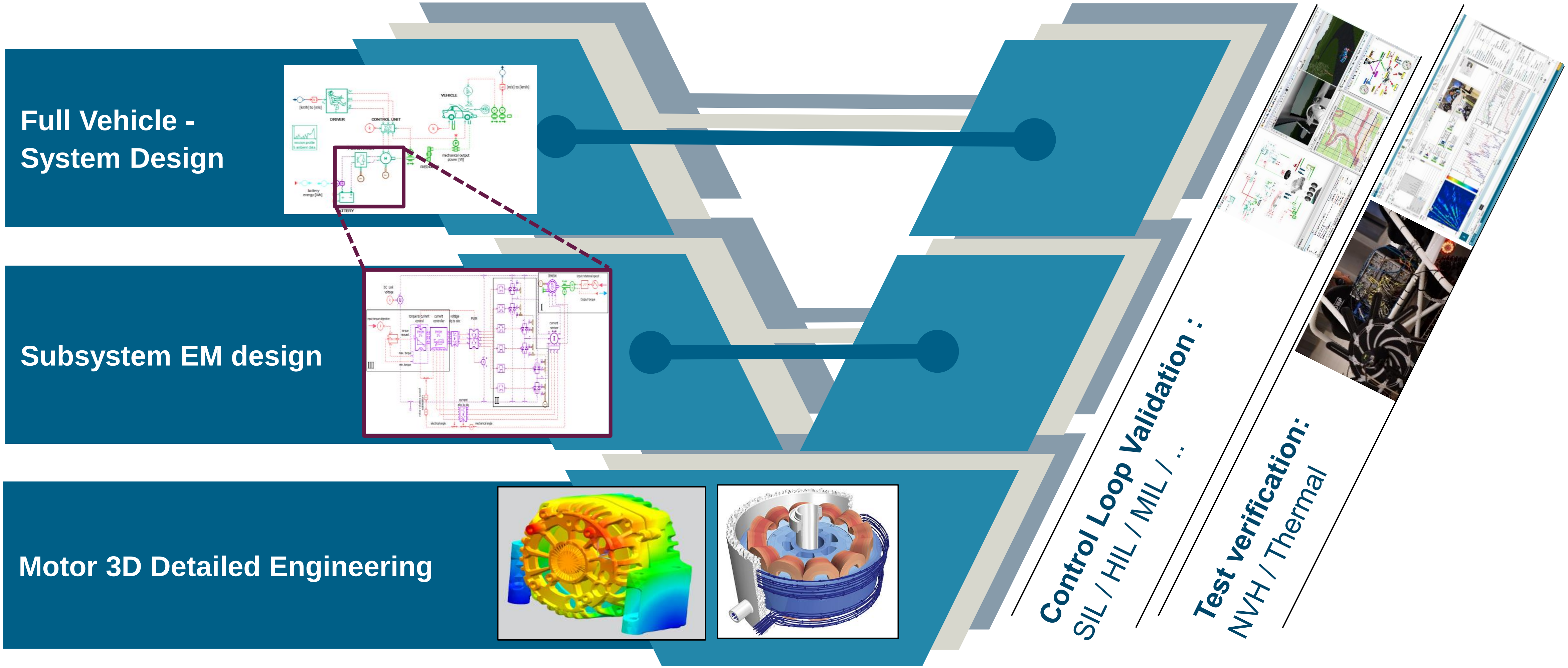
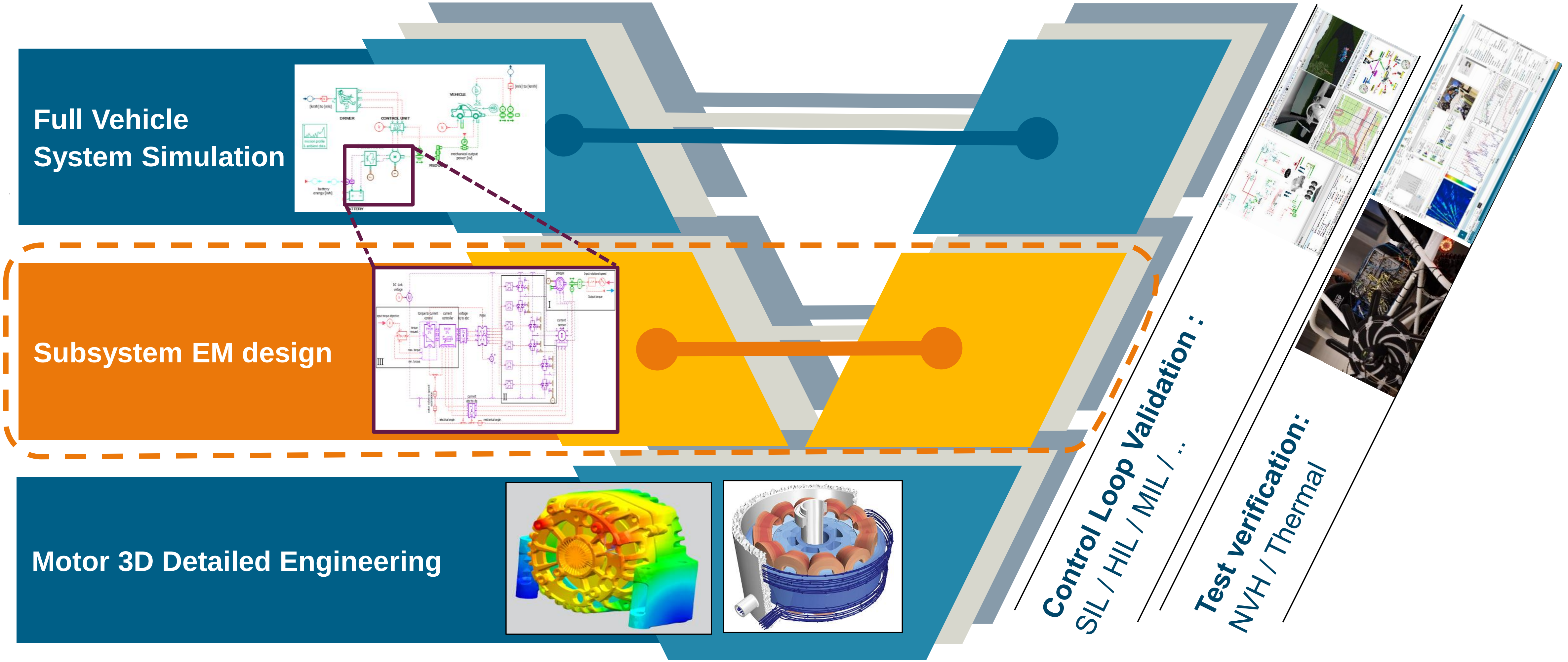


E-Powertrain Solution in the Subsystem Design Phase

“V”- design cycle for automotive electric drives



Impact on product life cycle and cost

Model-Driven Design to evaluate upfront systems designs

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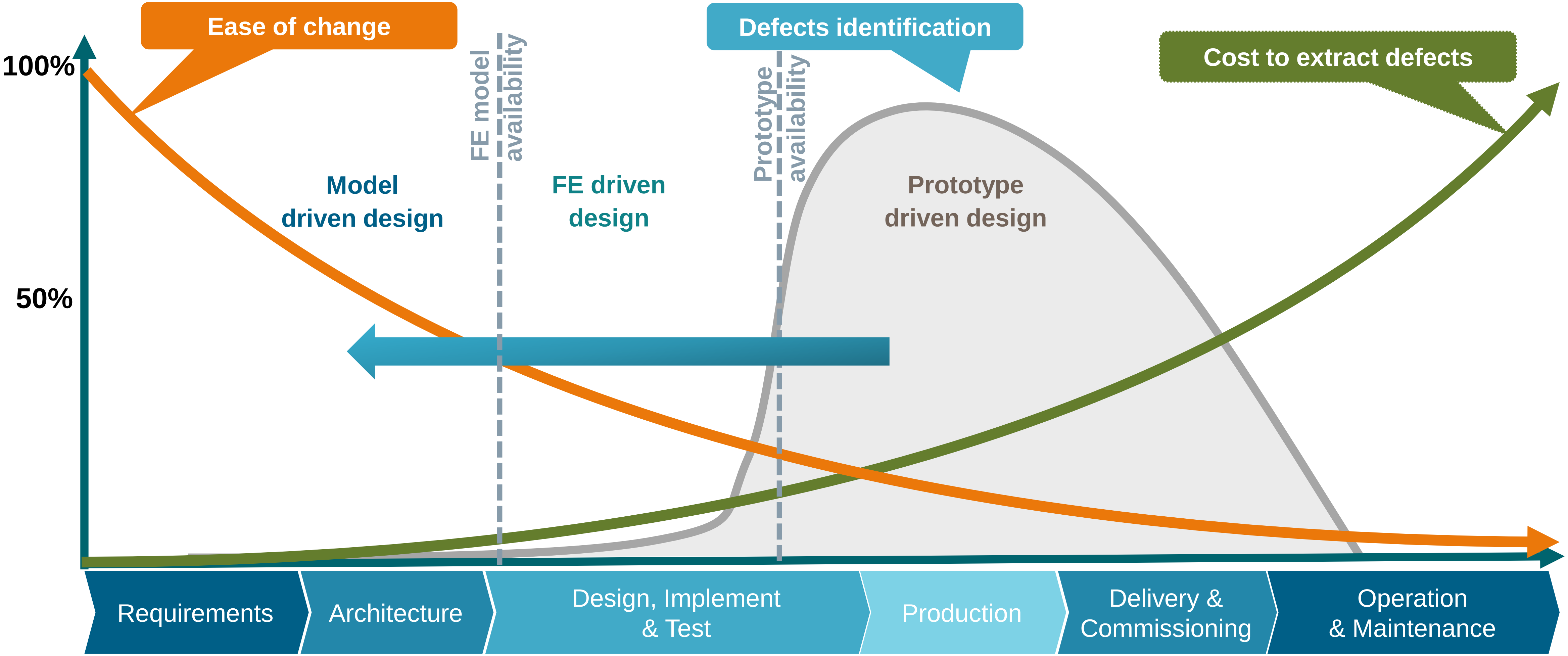

Impact on product life cycle and cost

Model-Driven Design to evaluate upfront systems designs

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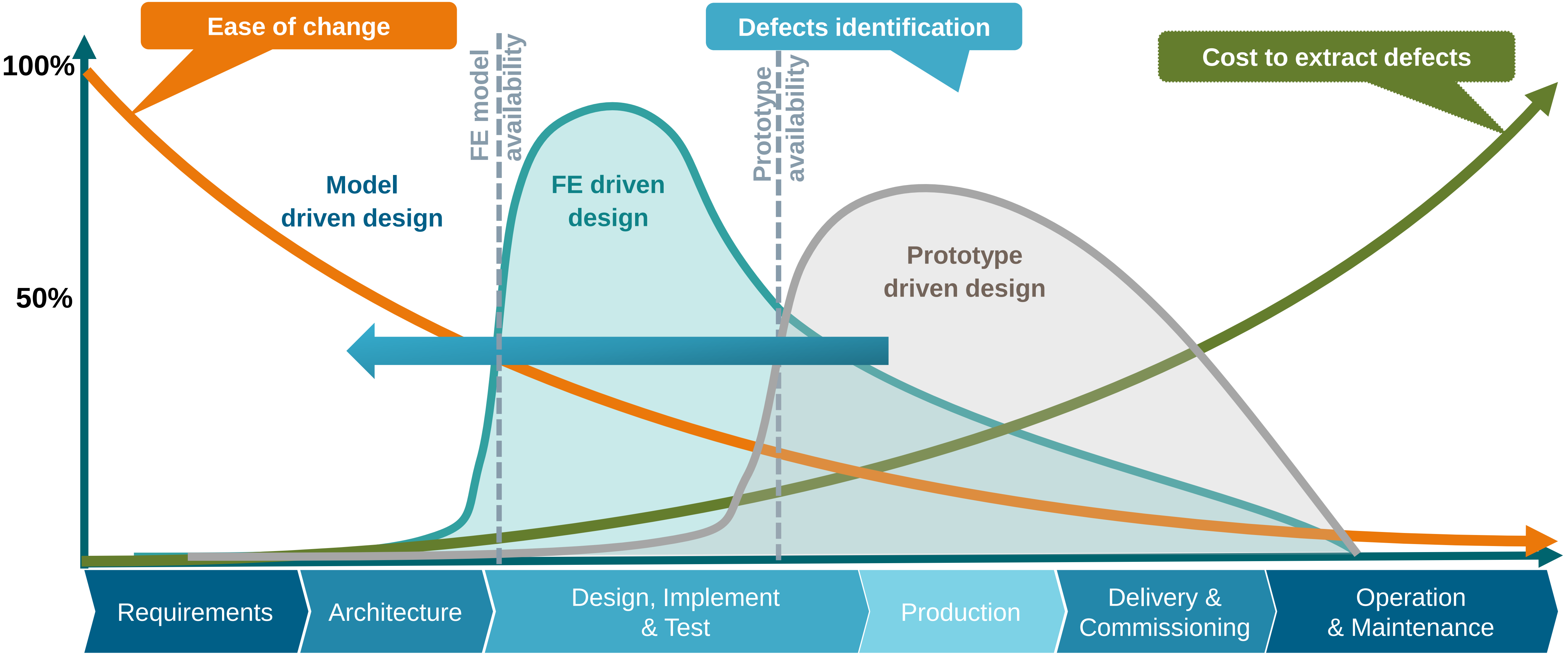

Impact on product life cycle and cost

Model-Driven Design to evaluate upfront systems designs

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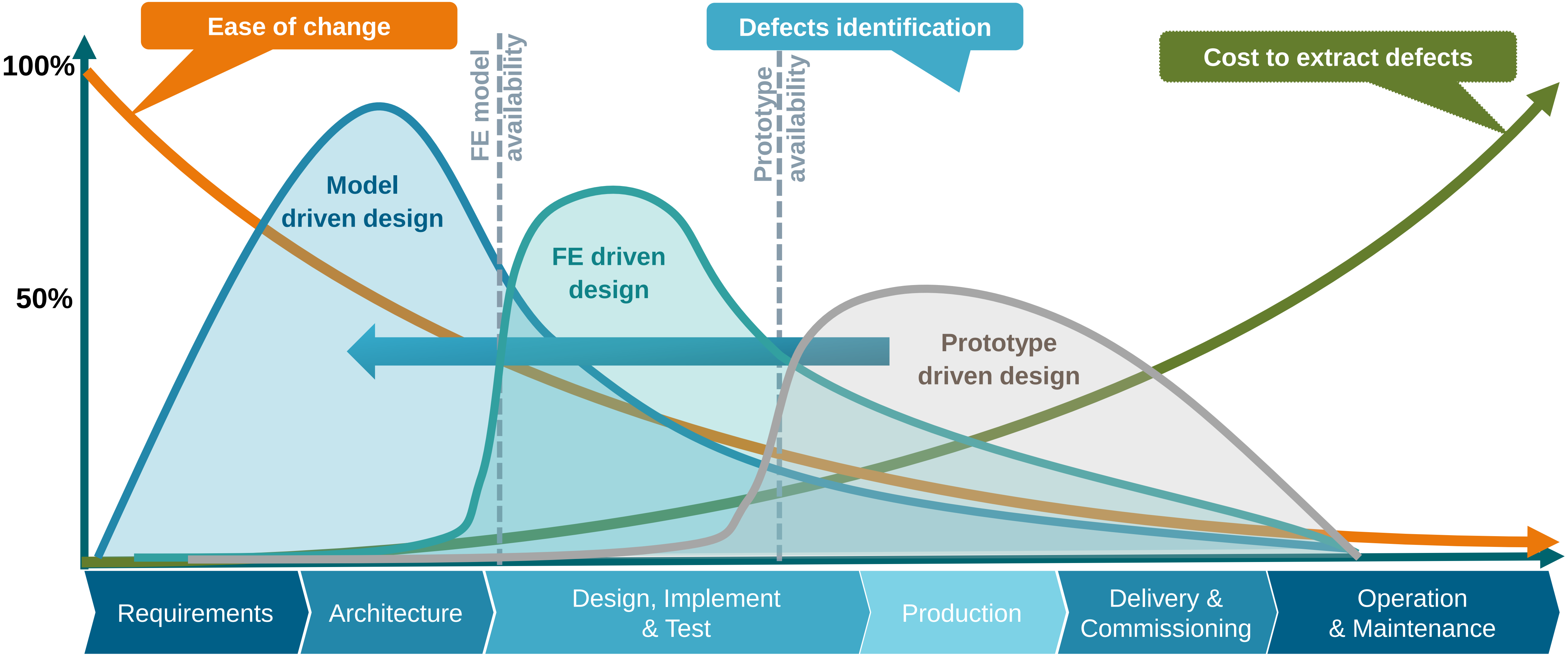
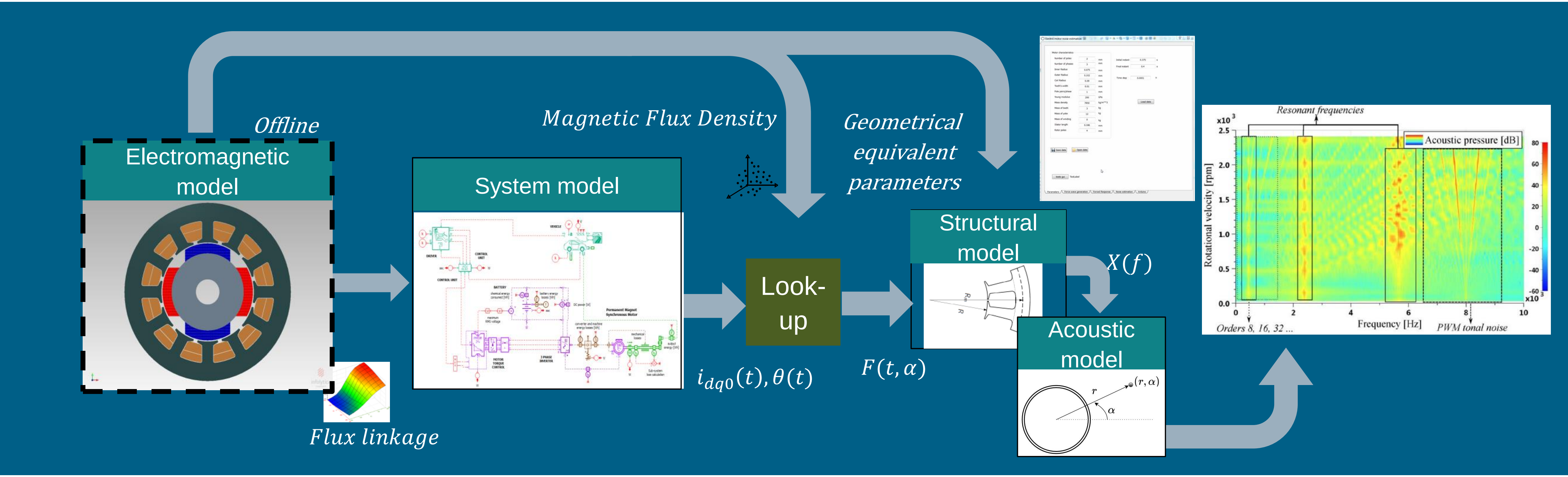


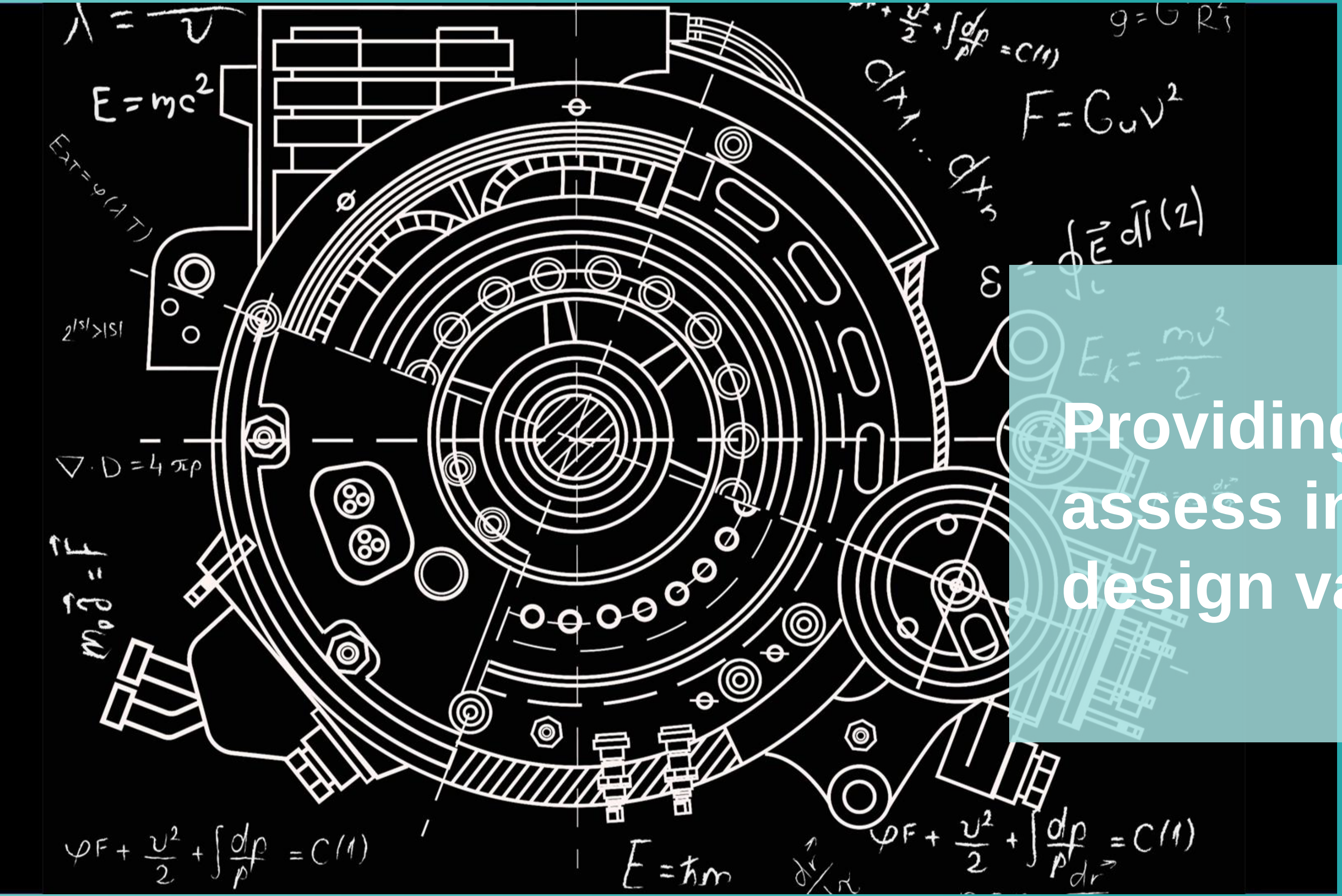
E-Powertrain Solution in the Subsystem Design Phase
Simcenter Amesim-based Noise App

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



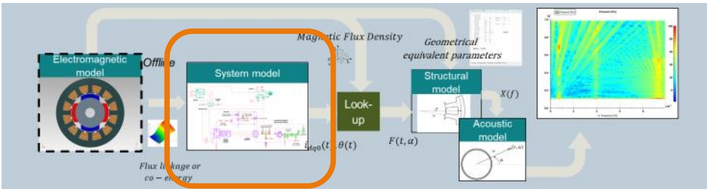
Addressing e-Motor NVH at concept stage

Frontloading of qualitative NVH risk assessment



Providing NVH Teams an early tool to assess influence of different electric design variations on NVH

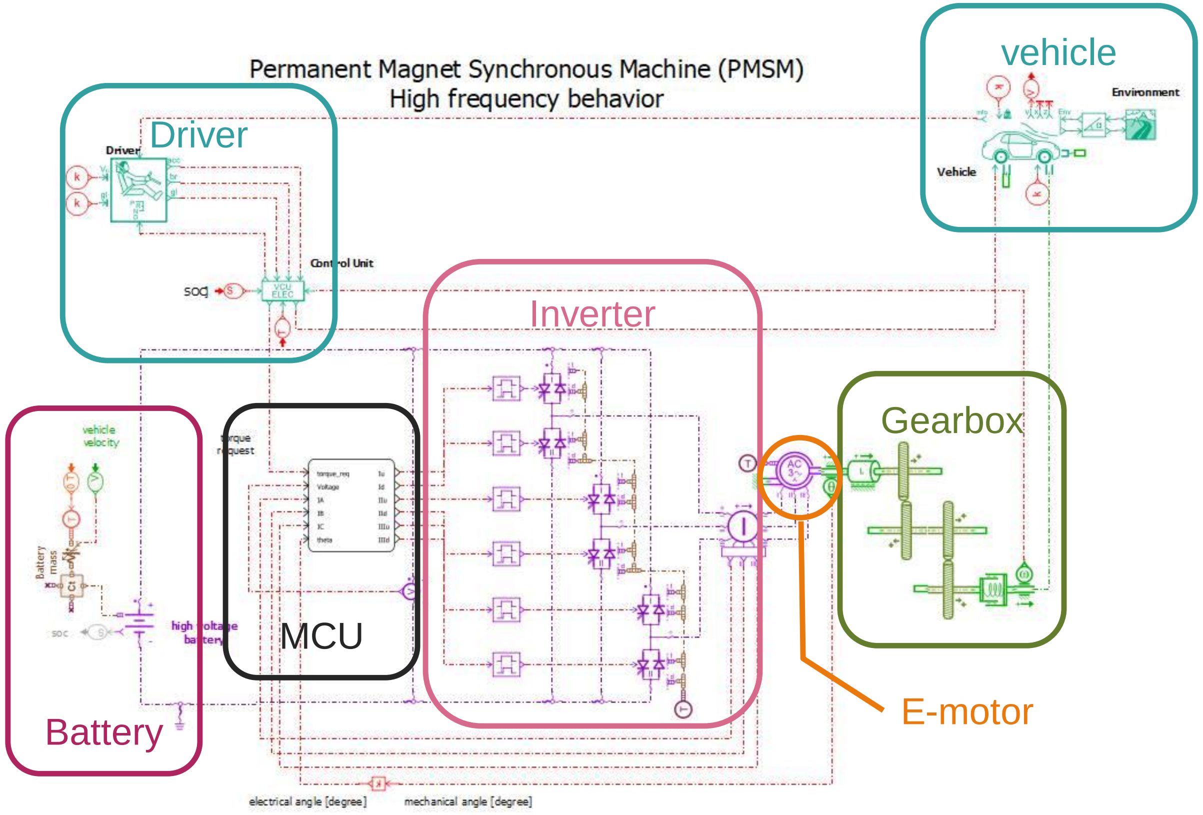
Subsystem Design Phase
Simcenter Amesim System Model



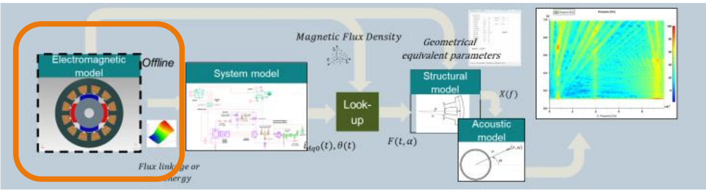
The e-machine model is integrated in a **system-level modelling** environment.

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



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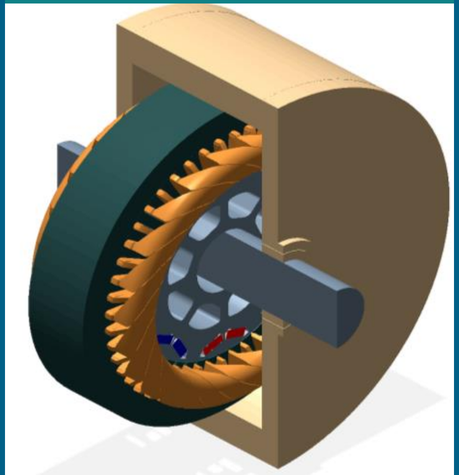
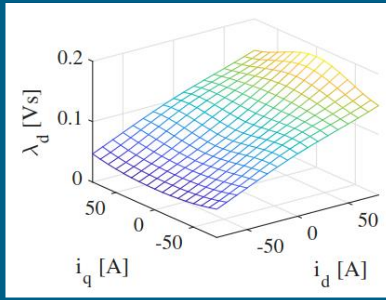
From actual EM model:

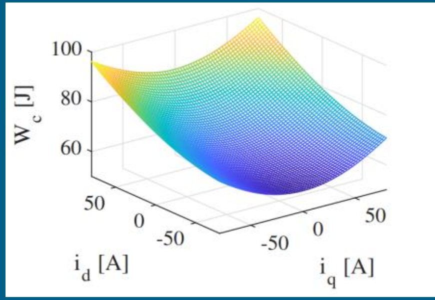
- Overall Geometry / Topology
- Machine materials

Magnetostatic Analysis:
- Flux linkage maps for Id, Iq and electrical angle

EM model



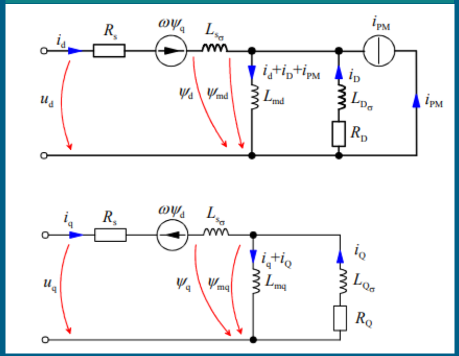




Future vision

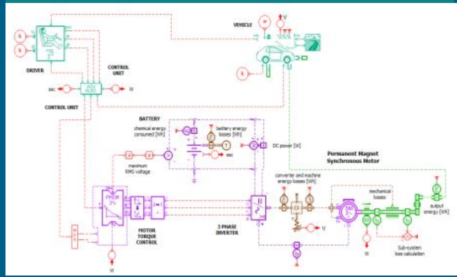
From Analytical model::

EM model



Geometric / topology parameters

System Model



$\theta(t), i_{dq0}(t)$

$F(t,\alpha)$

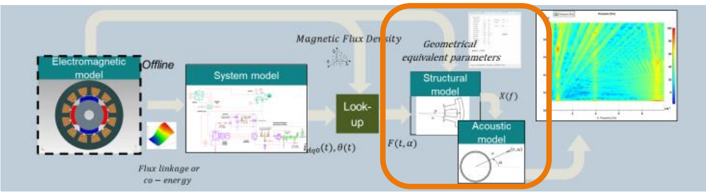
Build analytical force

$B(t,\alpha) = \Lambda(t,\alpha) \times MMF(t,\alpha)$

$F(t,\alpha)$

Subsystem Design Phase

Vibro-Acoustic Model



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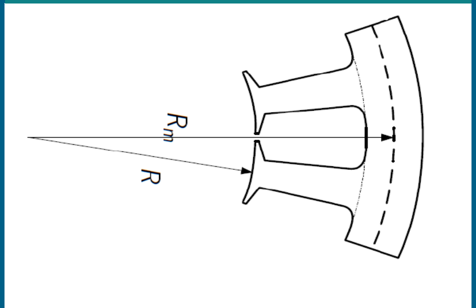
The fluxes and forces from the EM model can be applied to simplified structural and acoustic models to calculate the **vibration** and **acoustic** responses

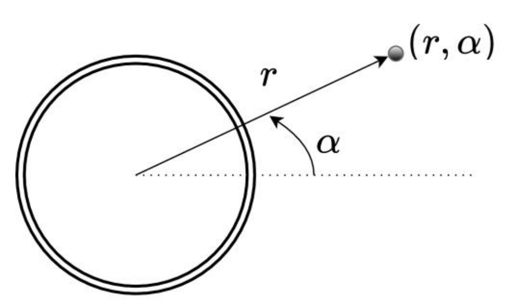
- Machine simplified geometry
- Machine materials
- Fluxes / Forces

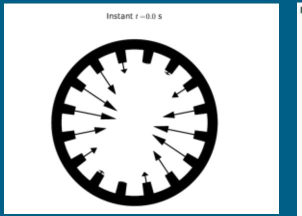
Structural model



- Natural frequencies
- Modeshapes
- Vibration response

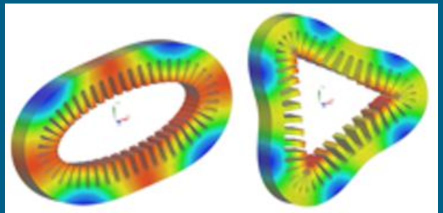
Acoustic model



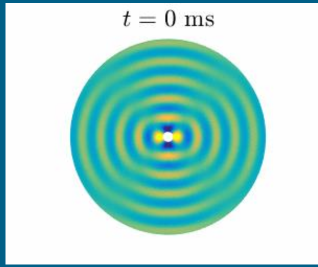


Motor characteristics

Number of poles	2	
Number of phases	3	
Inner Radius	0.075	m
Outer Radius	0.102	m
Coil Radius	0.09	m
Tooth's width	0.01	m
Pole pairs/phase	1	[]
Young modulus	200	GPa
Mass density	7850	kg/m**3
Mass of teeth	3	kg
Mass of yoke	12	kg
Mass of winding	0	kg
Stator length	0.186	m
Rotor poles	4	
Damping ratio	0.01	

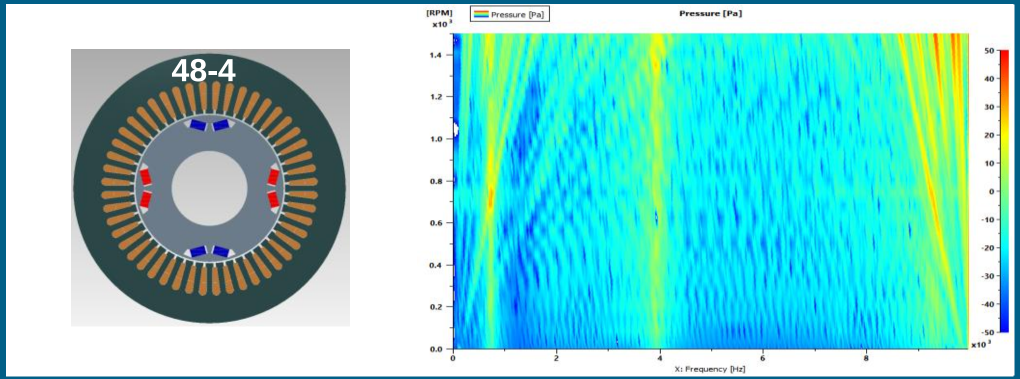


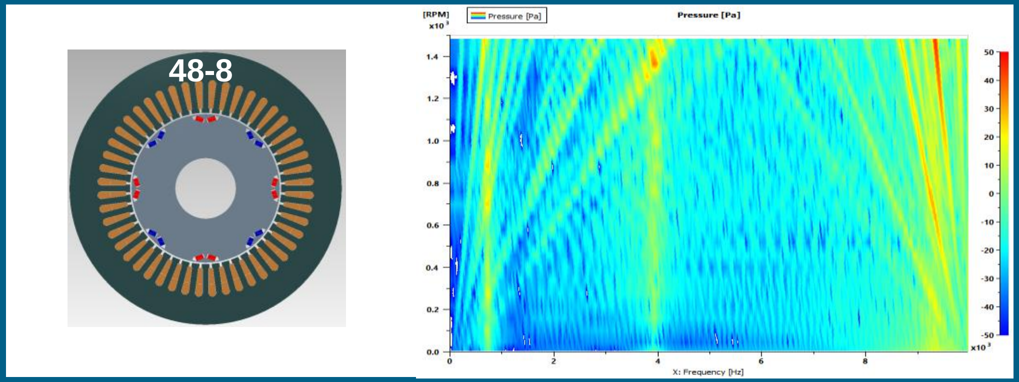
OUTPUT:
acoustic pressure



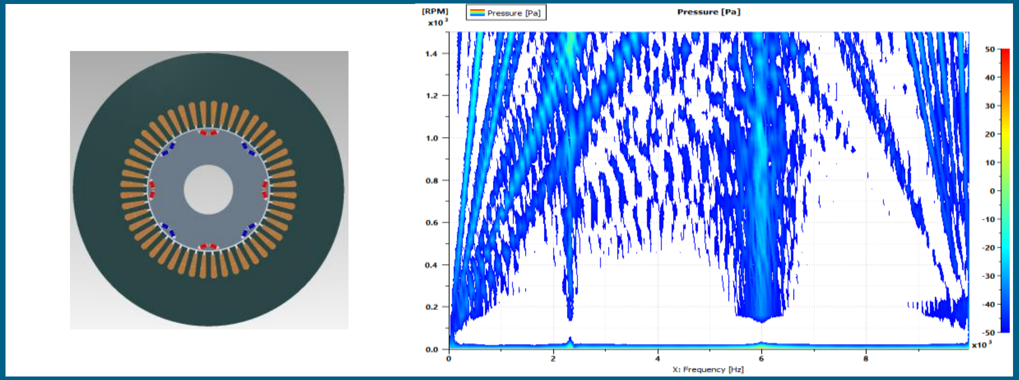
Subsystem Design Phase
Design Modification Examples

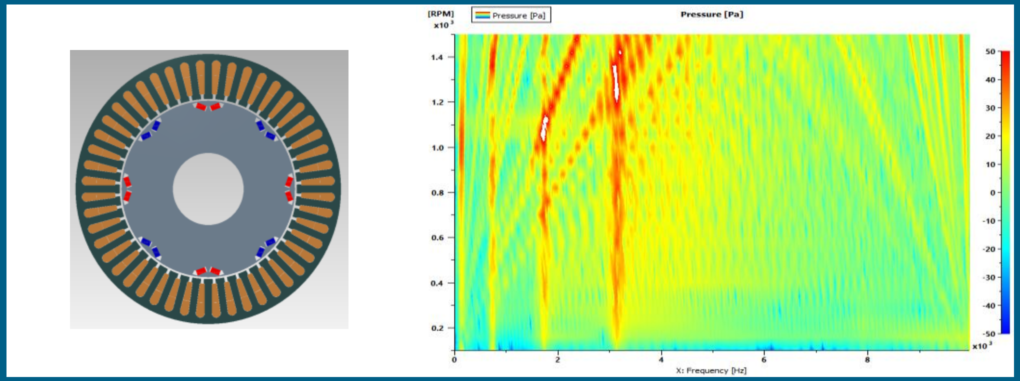
Changing number of slots from 4 to 8





Changing stator geometry



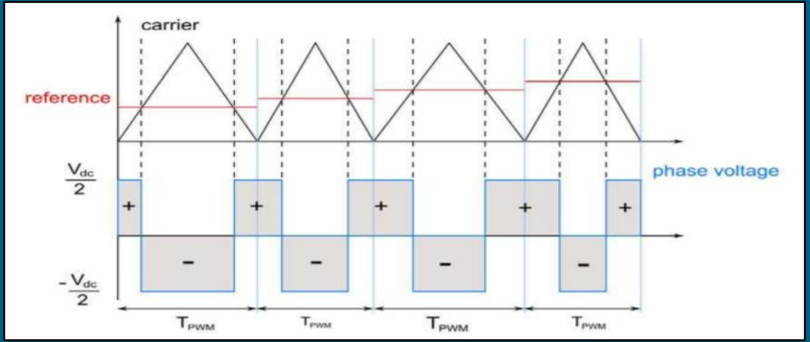


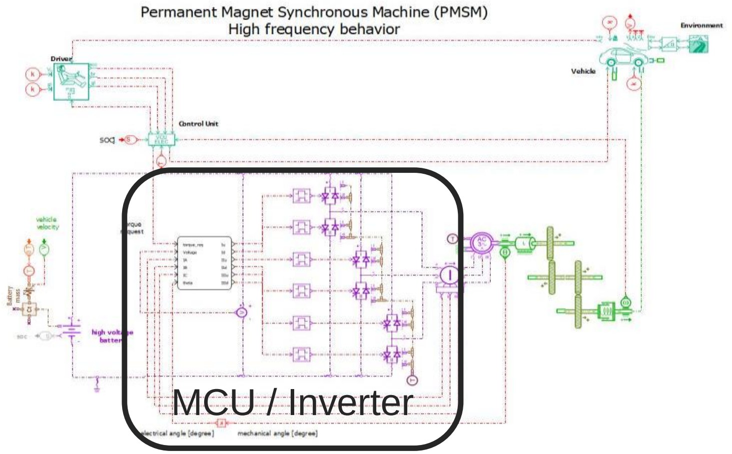
Subsystem Design Phase
Design Modification Examples

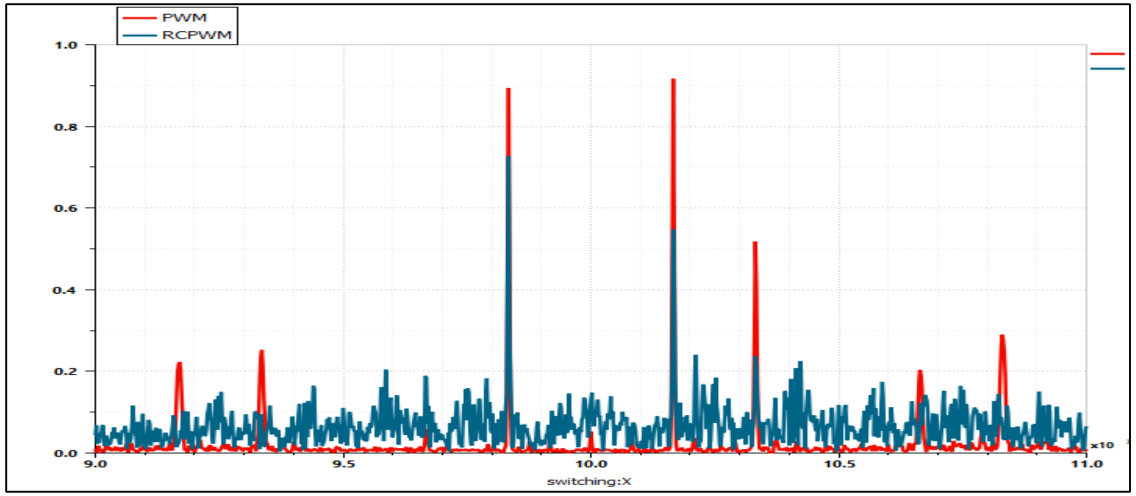
Inverter Modelling and Controls:
Simulink controller integrated with inverter/motor Simcenter Amesim model

Purpose: evaluate control strategies to balance switching noise & vehicle performance

Example: Random Carrier Frequency-PWM (RCFM)







System-level design process for electric drives

Public reference of research project

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Technical paper at SAE 2018 and publication in SAE International Journal of Alternative Powertrains

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/

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2018-06-05

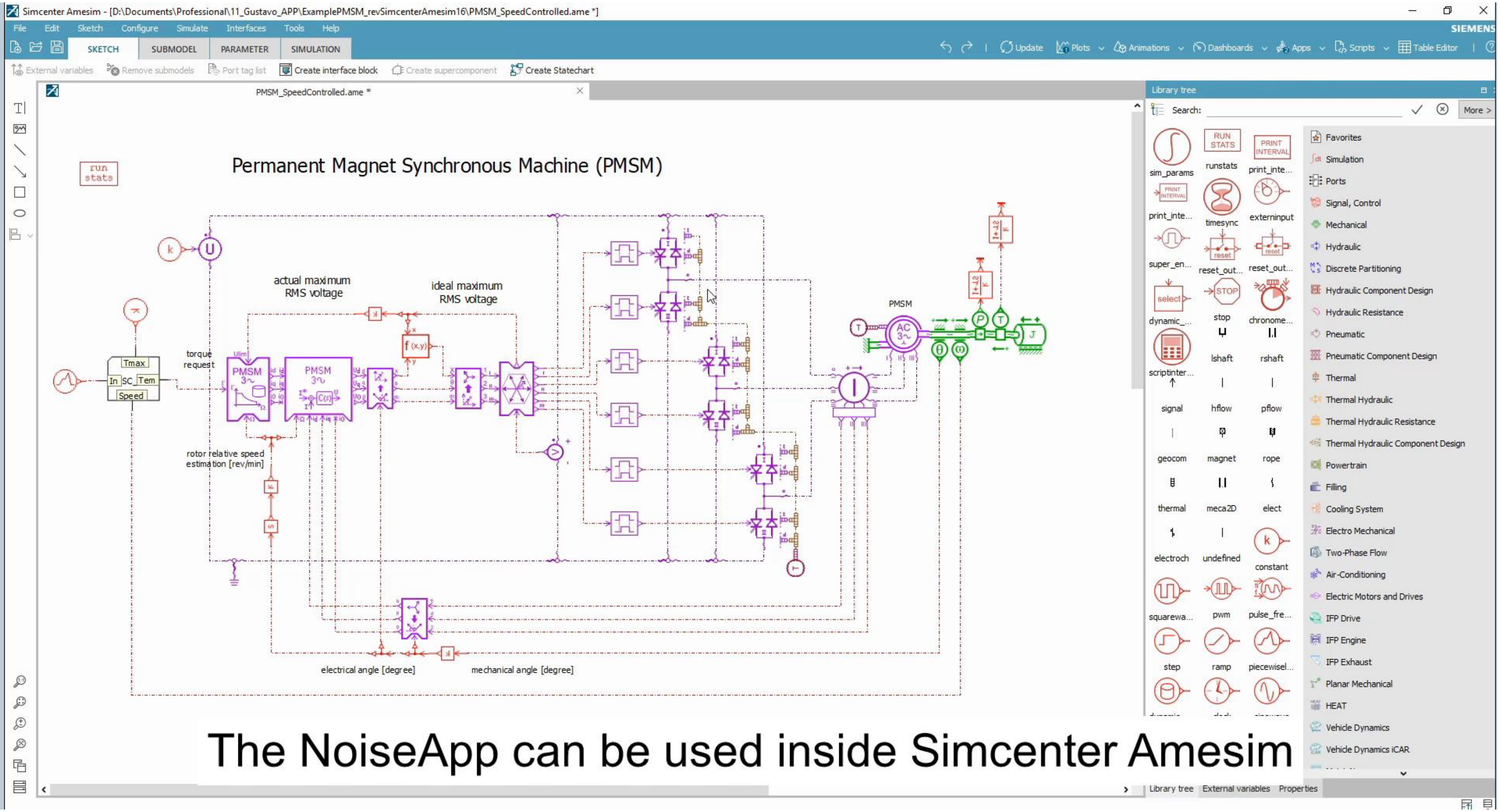
Multi-Attribute, System-Level Design Process for Automotive Powertrain Electric Drives: An Integrated Approach 08-07-02-0007

This also appears in SAE International Journal of Alternative Powertrains-V127-8EJ

This article presents an electric drive powertrain design and virtual integration methodology in the context of electric vehicle systems. In the first stage, using the Model-Based System Engineering paradigm, the electric vehicle performance requirements are translated into electric drive target specifications using a system-level vehicle model. Subsequently, a functional electric drive subsystem-level model is developed based on magnetic co-energy and iron losses data obtained from a reference electric machine design. The functional electric drive model is scaled in order to meet the requested specifications, and it is coupled with different 1D (i.e. lumped-parameter) multi-physics sub-models that are later integrated into the electric vehicle system-level model. At the electric drive level the torque ripple and Noise, Vibration and Harshness characteristics are analyzed. At the vehicle level the energy consumption, thermal behavior, and mechanical performances are determined with reduced computational time. The proposed approach allows for early assessment of multiple attributes and enables designers to make decisions supported by accurate system-level simulations.

E-Powertrain Solution in the Subsystem Design Phase
Simcenter Amesim-based Noise App

Short demo:



E-Powertrain Solution in the Subsystem Design Phase

“V”- design cycle for automotive electric drives

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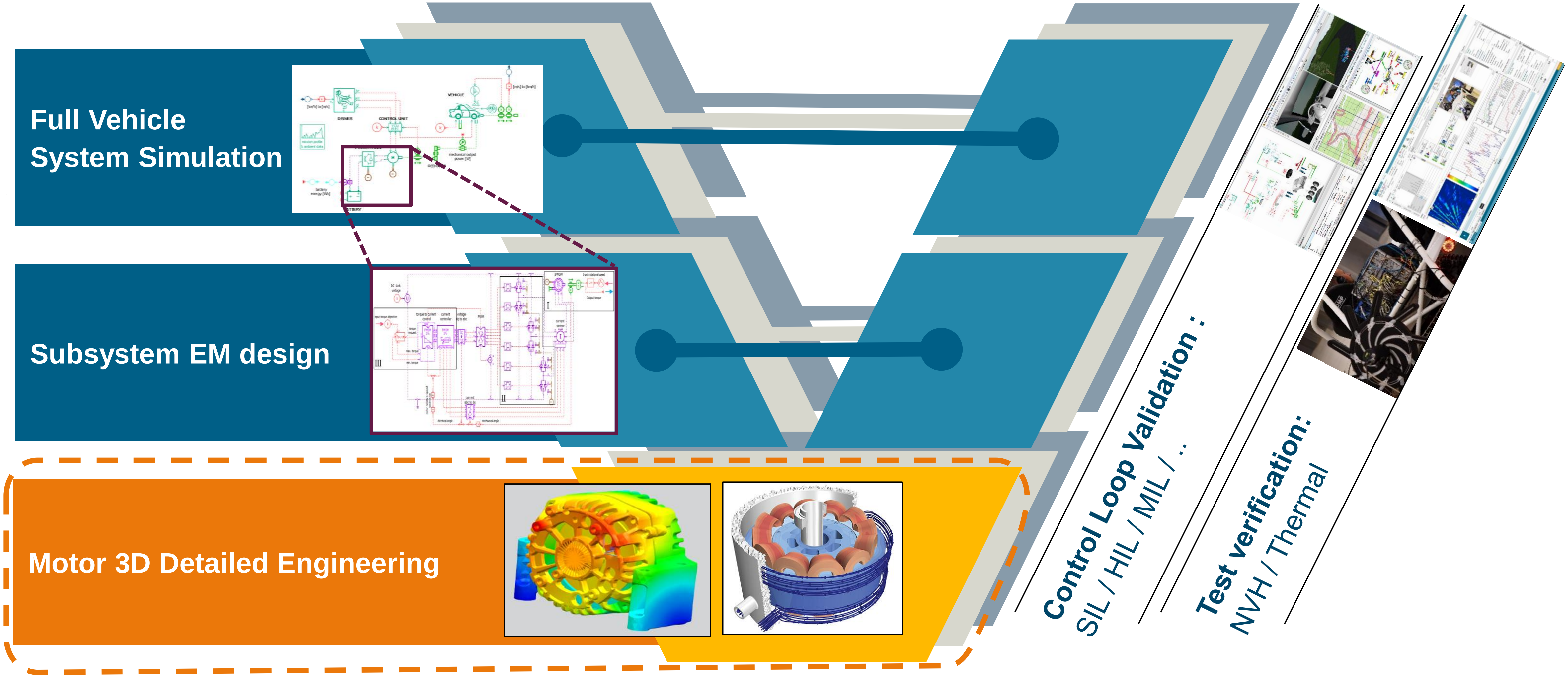

E-Powertrain Solutions in the Component Design Phase

From electromagnetics to radiated noise

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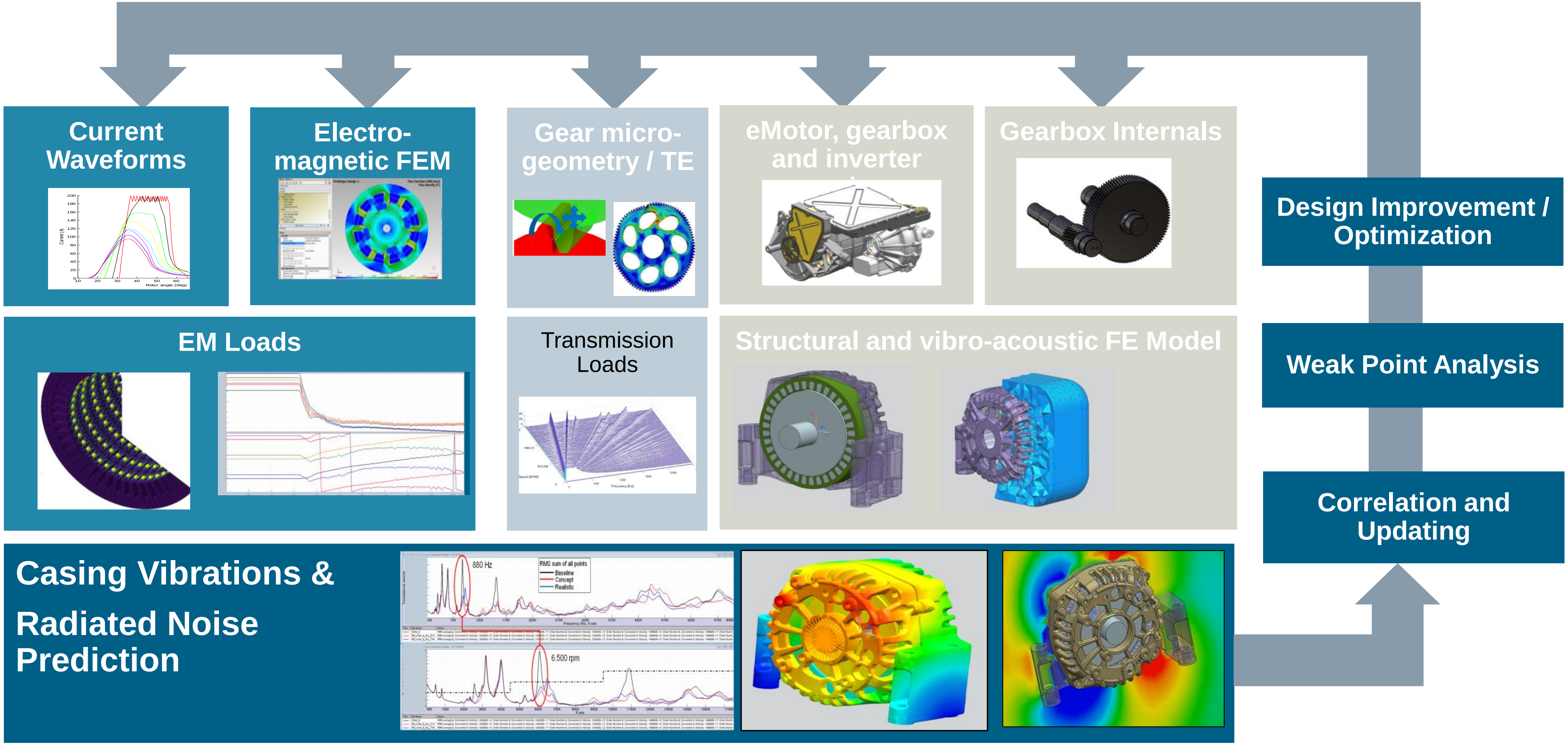

Addressing e-Motor NVH in detailed design stage

End-to-end 3D simulation process

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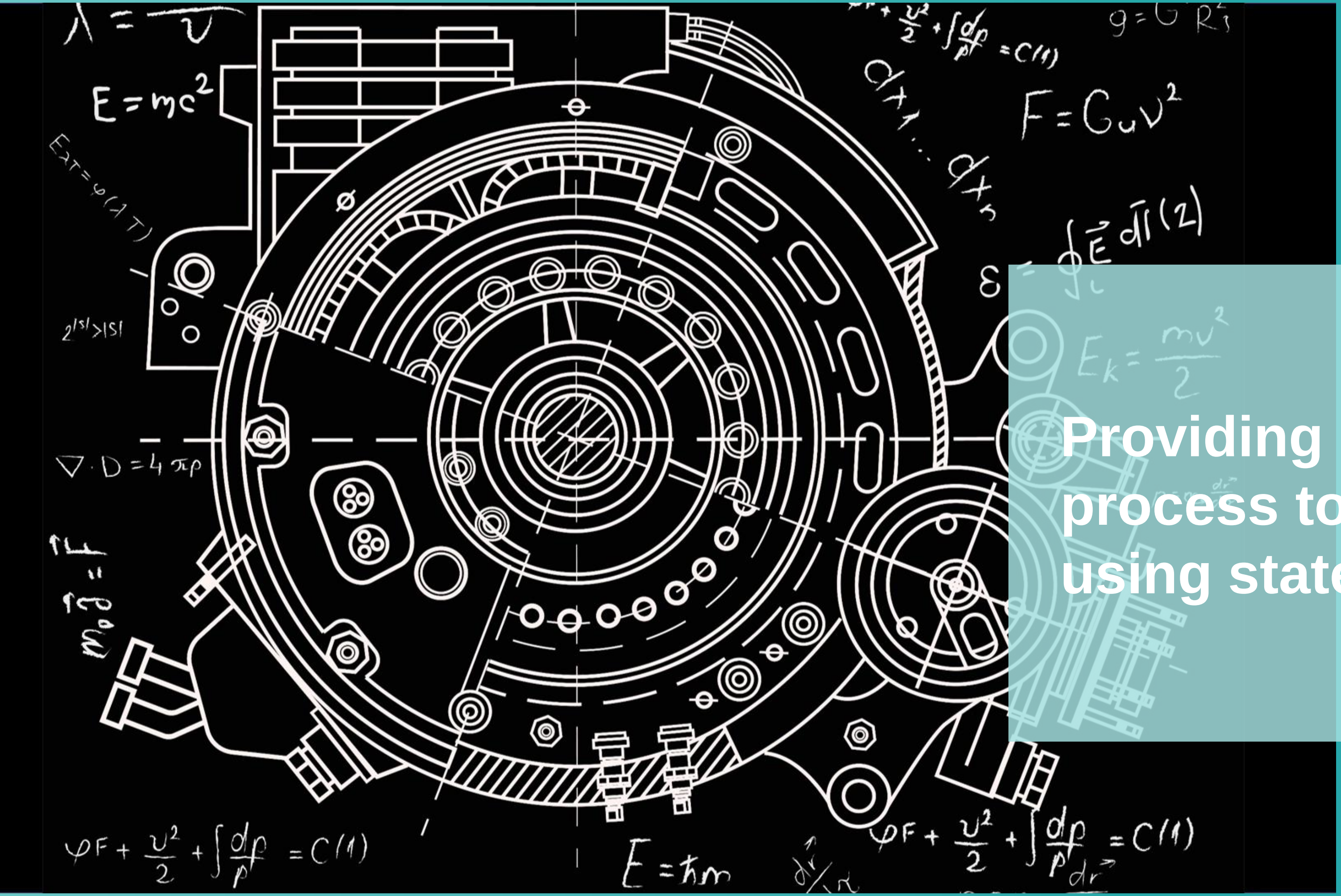
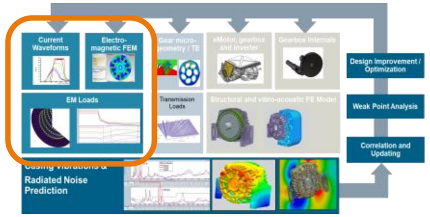


Providing NVH Teams an integrated process to accurately predict e-motor noise using state-of-the art tools and expertise

From electromagnetics to radiated noise

Focus on Electro-Magnetic field computation



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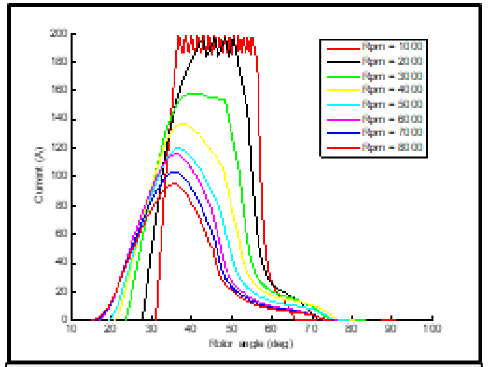
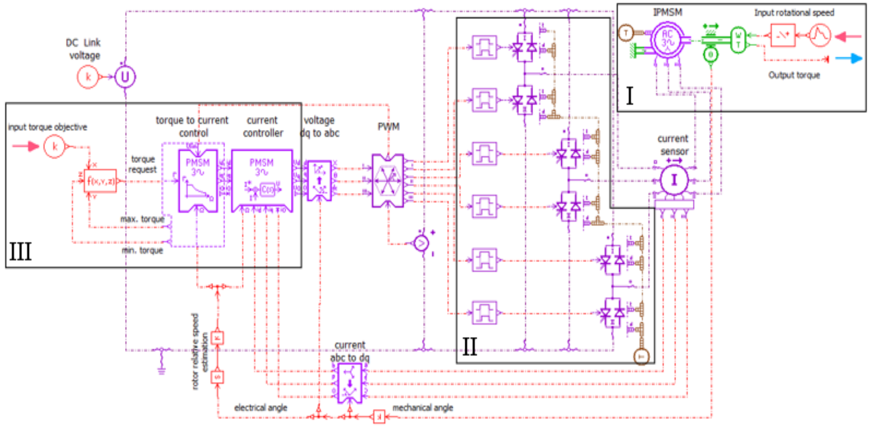
Inverter Current Waveform with MBD representation of

- Control Logic
- Power Electronics
- Motor Electrical resistance

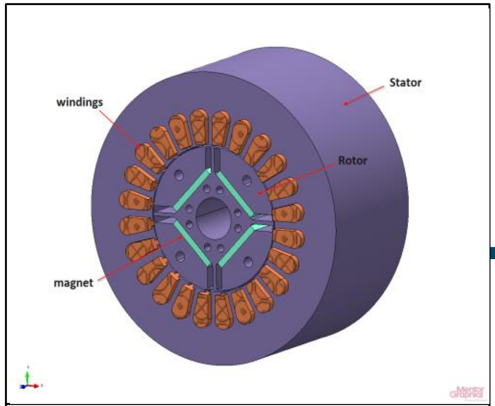


Inverter Current waveforms

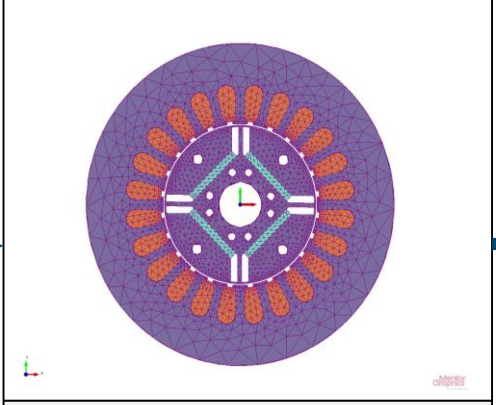


Electro-Magnetic Finite Elements Model with well established commercial FE codes

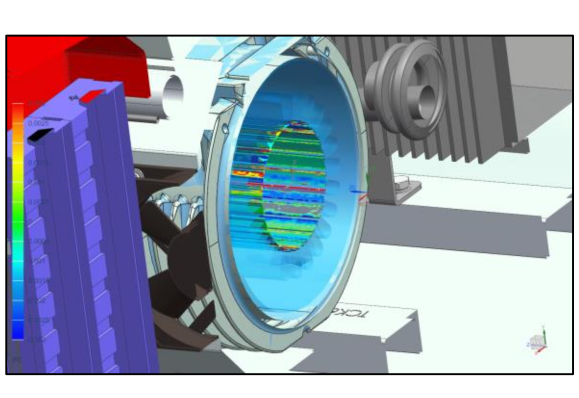
- Fast analytical calculation (MotorSolve)
- Accurate 2D/3D modeling (MagNet)



Transient magnetic forces
Infolytica MagNet

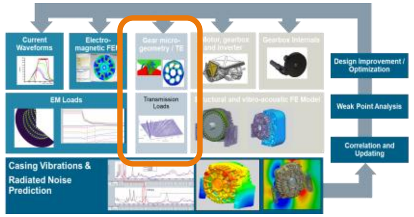


Calculated on EM mesh



Conversion Fourier components
Simcenter 3D

From electromagnetics to radiated noise
Focus on Transmission Loads

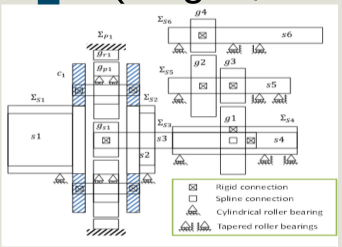


Typical process for NVH analysis

Transmission layout (stages, dimensions)

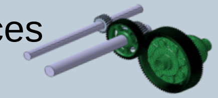
Transmission Error or Stiffness, parameters

Pre-processing of loads or surface vibrations

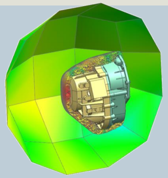


Gear-centric tool
- Analysis of gear pairs

Multi-body simulation
- Simulation of forces and dynamics

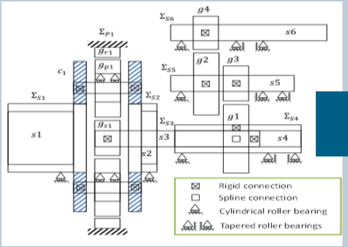


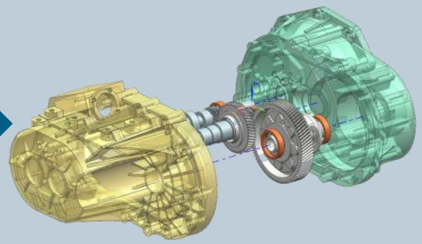
Acoustics, NVH
- Gear whine
- Gear rattle



Positioning, dimensions…

More efficient process in Simcenter 3D

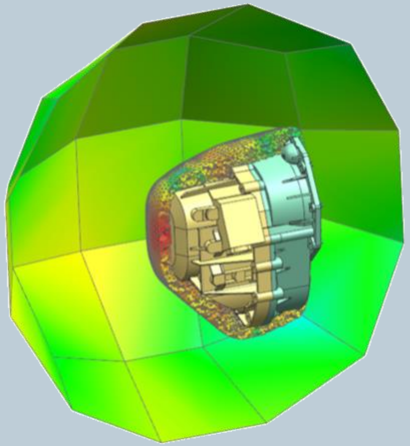




End-to-end integrated process for transmission simulation from CAD to Loads to Noise

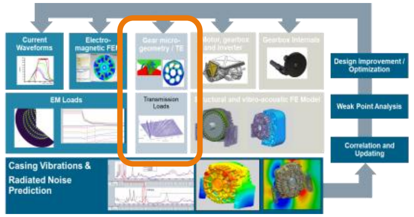
Transmission Builder → Motion → Motion-to-Acoustics → Acoustic Analysis

- **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



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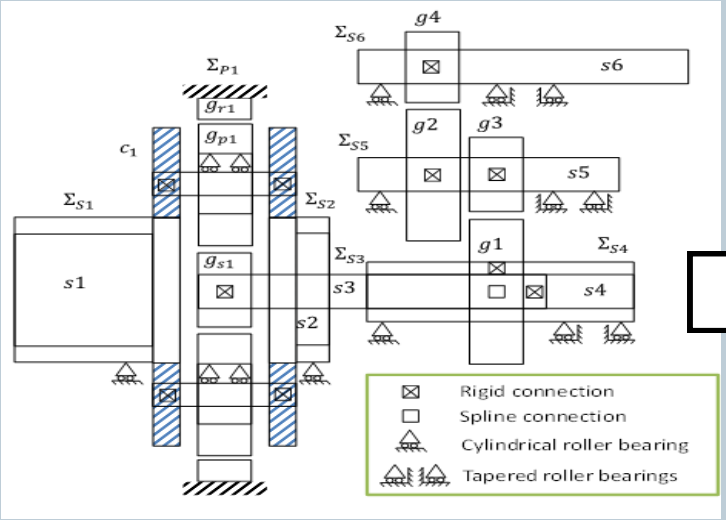
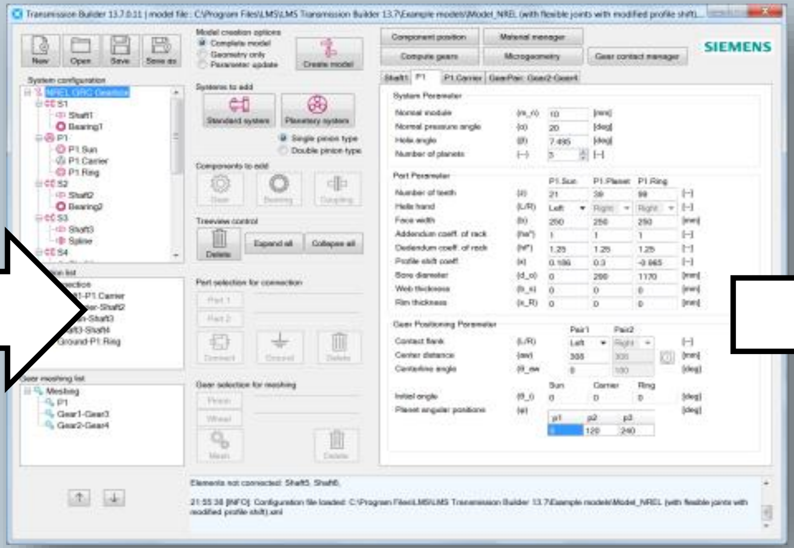
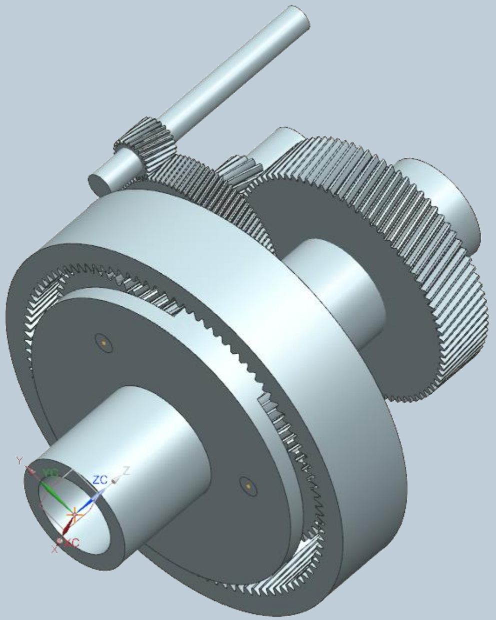
Simcenter 3D Transmission Builder

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







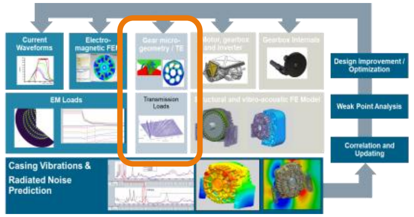
Gear train specification based on Industry standards

Simcenter 3D Transmission Builder

Automated creation of Multibody simulation model

Transmission builder Validation

Transmission error validation for lightweight gears



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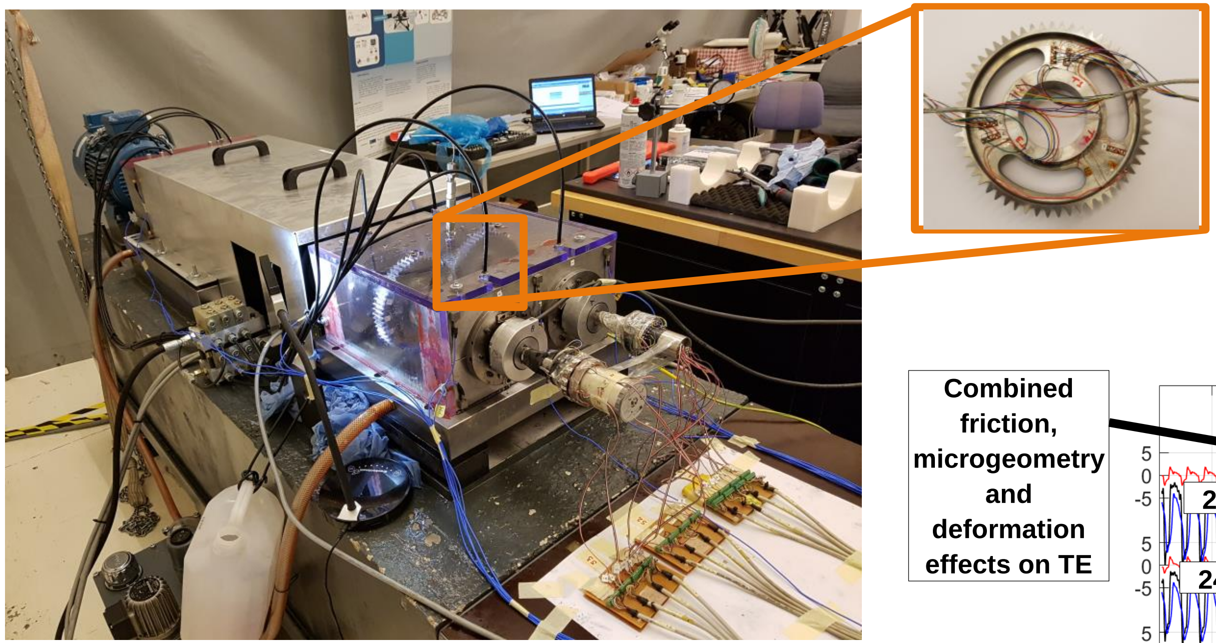
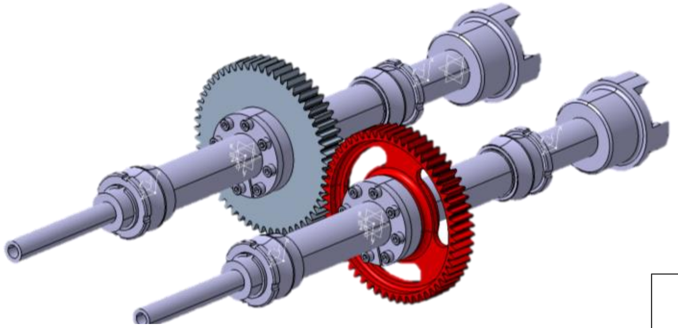
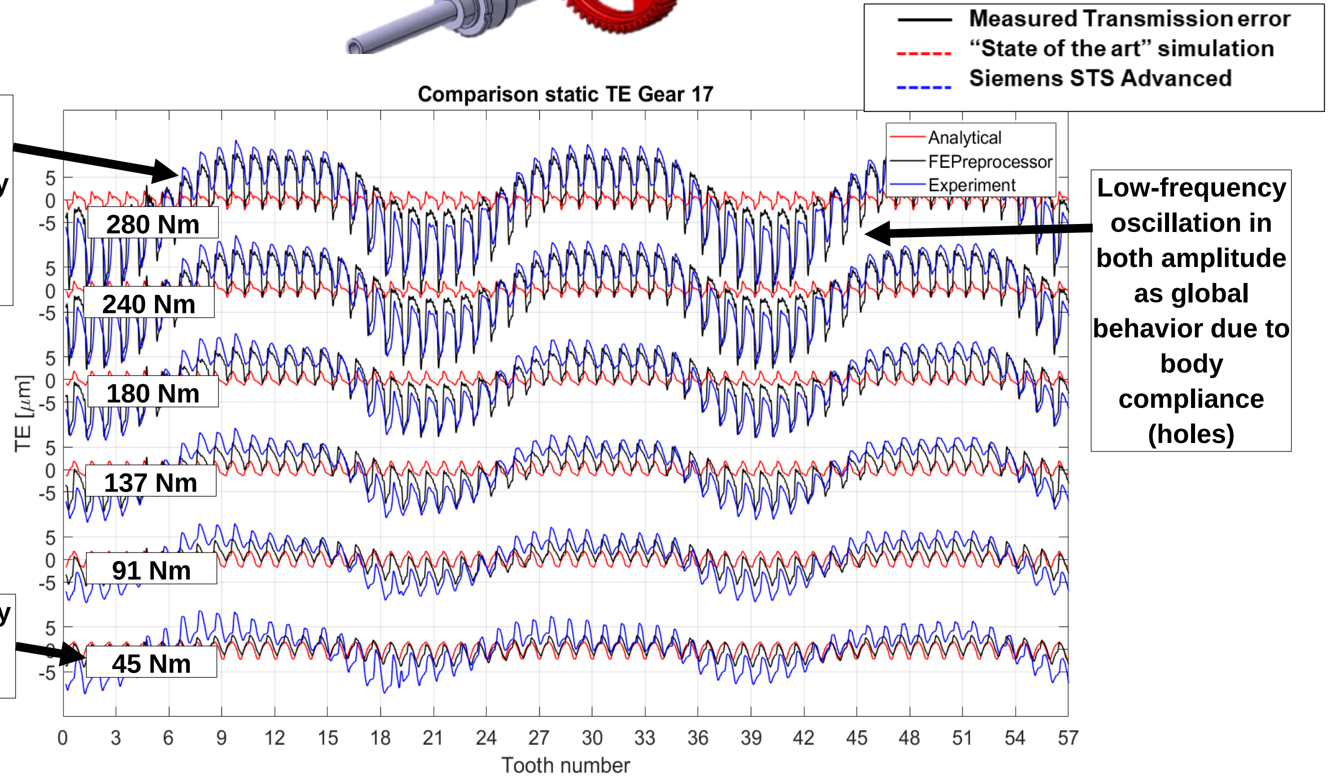




Combined friction, microgeometry and deformation effects on TE



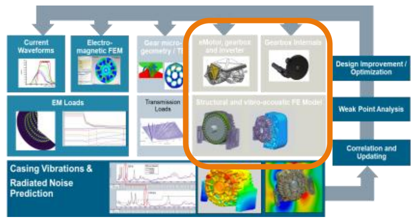
Low-frequency oscillation in both amplitude as global behavior due to body compliance (holes)

Microgeometry matches well (low loads)

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

Research partners: KU LEUVEN UNIVERSITÀ DELLA CALABRIA

From electromagnetics to radiated noise
Focus on Structural modeling



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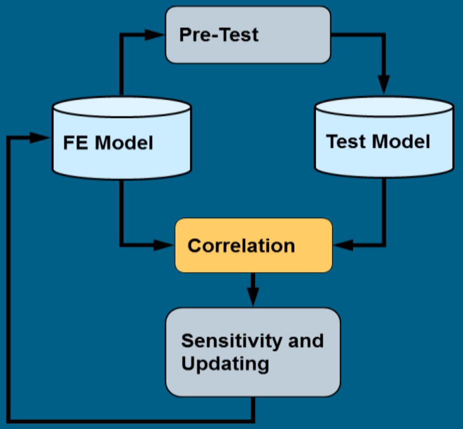
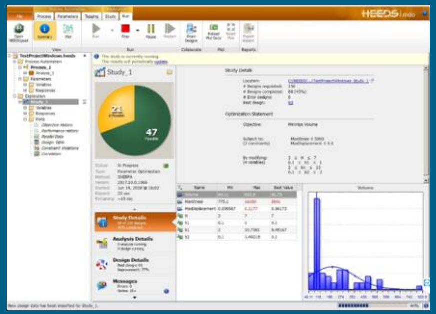
1. Rotor/Stator modeling - Laminated Structures

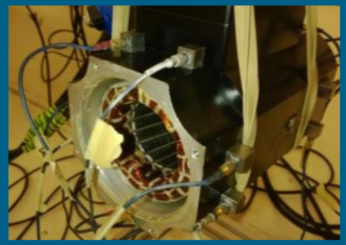
Linear scalable CAE model with physical material properties:

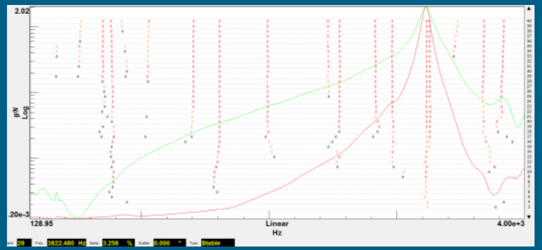
- **Homogenization** of orthotropic material properties, for different area’s;
- Tuning of material properties based on **test data**



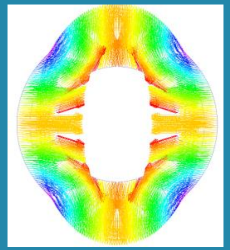


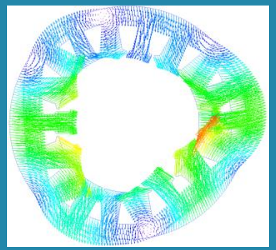
Test EMA

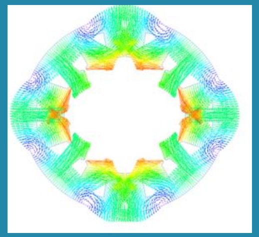


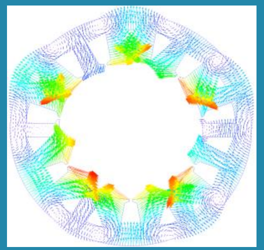


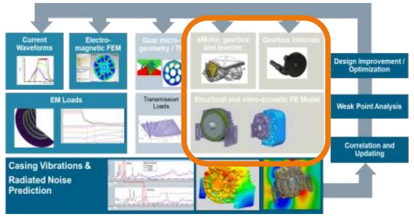
Simulation core components











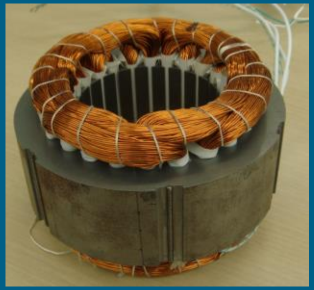
From electromagnetics to radiated noise
Focus on Structural modeling

2. Windings Modeling – Discretization Strategies

Linear CAE model with limited modal density

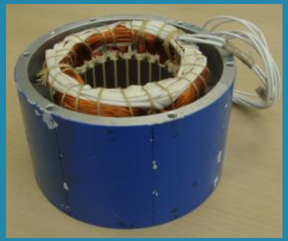
- Test based analysis of coils **mass and stiffness effects** on e-Motor dynamics
- **Dedicated coils modeling** in CAE
- Tuning of material properties based on **test data**

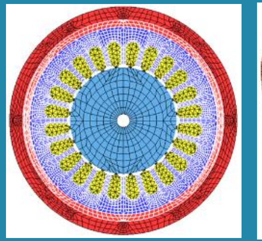
Test EMA with and without windings

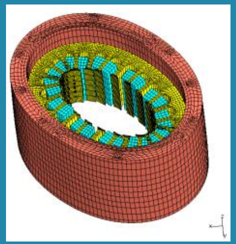


NO COILS		WITH COILS			
Test Mode Number	Test Frequency	Test Mode Number	Test Frequency	Delta (Hz)	Mode Type
1	151.7	2	335.8	-184.1	First in-plane bending
2	165.2	1	331.9	-166.7	First in-plane bending
5	475.2	3	405.5	69.7	Mode Type 2 (Ovalization)
7	476.9	4	408.8	68.1	Mode Type 2 (Ovalization)
11	4188.2	8	3175.6	1012.6	Mode Type 0.1 (out of plane Breathing)
12	4706.1	11	3976.9	729.2	Mode Type 0 (Breathing)

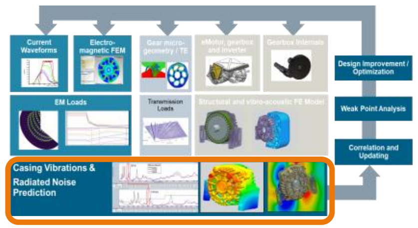
Simulation complete assembly







From electromagnetics to radiated noise
Focus on Vibro-Acoustics simulation



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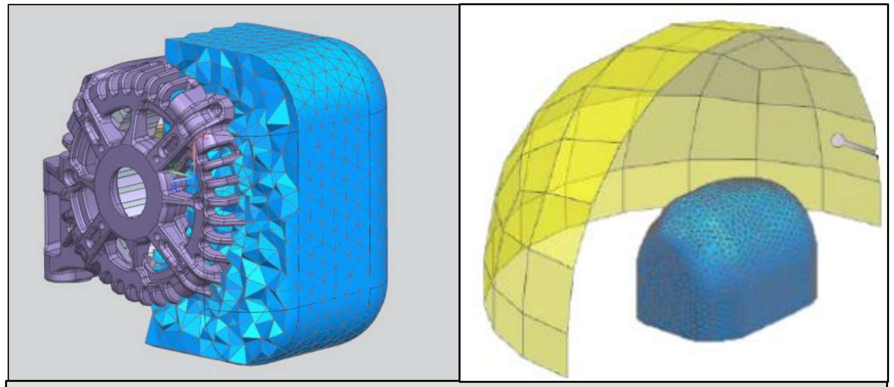
Acoustic Meshing with dedicated tools

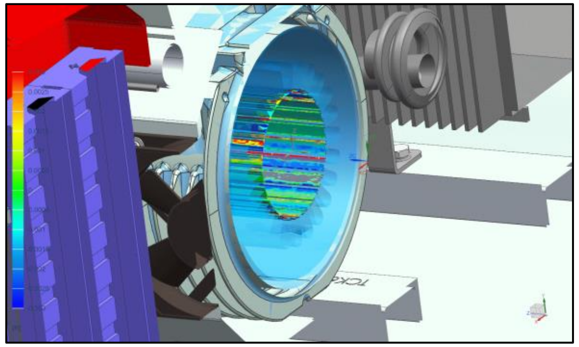
- Surface wrapping
- Convex Mesher
- Microphone Meshes
- …



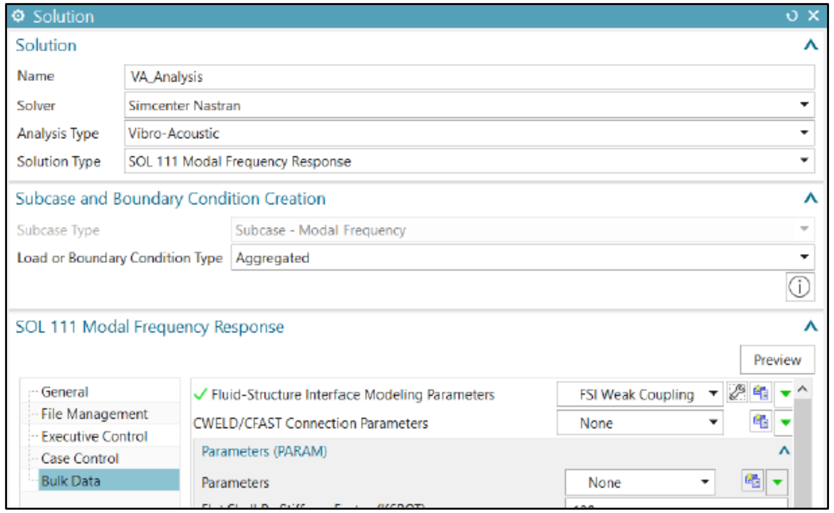
Acoustics meshing

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

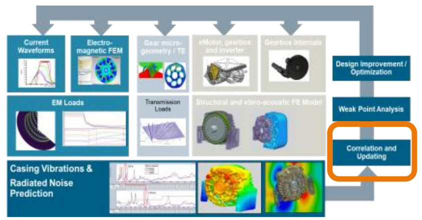


Load recipes

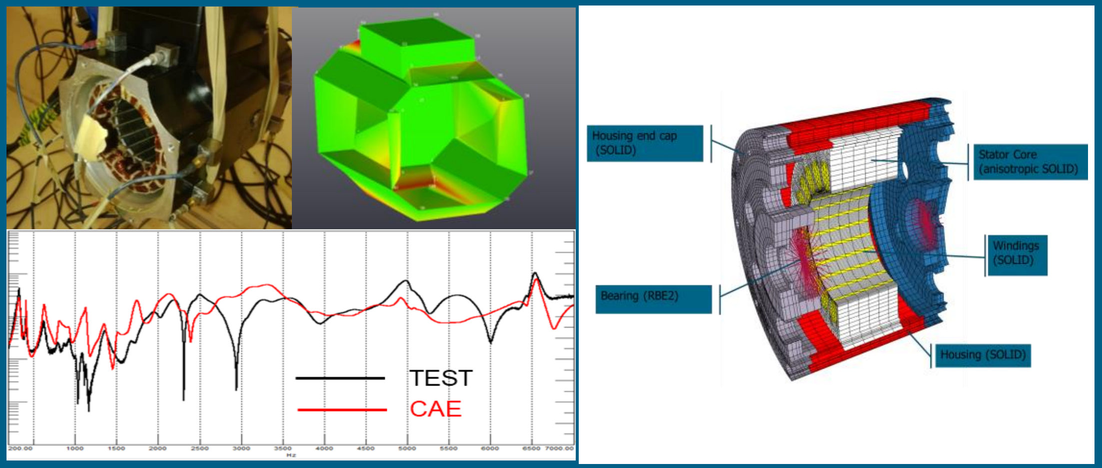


From electromagnetics to radiated noise

Building a physical and reliable 3D model



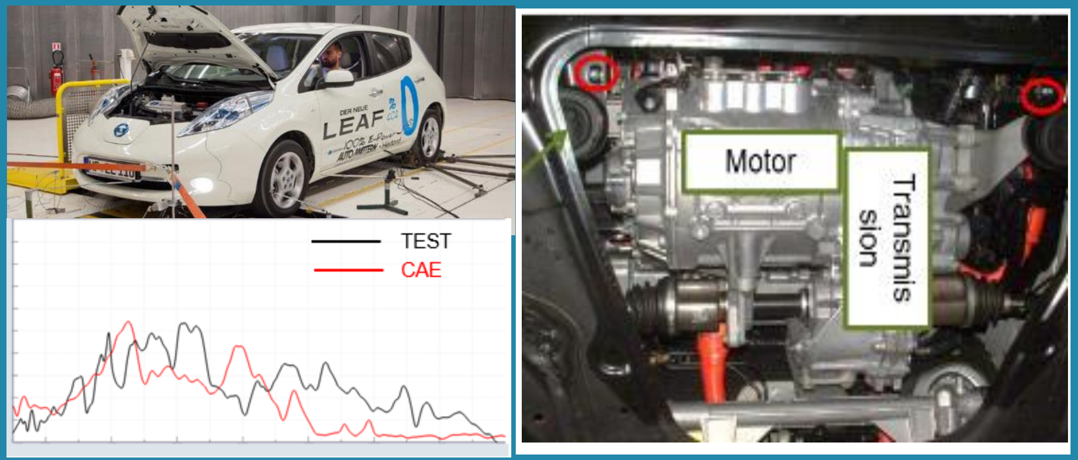
Modal correlation – EMA testing



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

Operational correlation– Bench/Vehicle testing



- 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);

Rotor / stator modeling
Public references of research project

Technical paper at International Conference on Noise & Vibration Engineering (ISMA)

Experimental Study on the Impact of the Number of Laminas on the Dynamics Behavior of an Electric Machine Stator

https://link.springer.com/chapter/10.1007/978-3-319-30249-2_5

Technical paper at International Conference on Structural Engineering Dynamics (ICEDyn)

Experimental and Numerical Validation of Laminated Structure Dynamics from a Switched Reluctance Machine Stator

https://lirias.kuleuven.be/1748547?limo=0

Technical paper at International Conference on Noise & Vibration Engineering (ISMA)

Validation of homogenization technique used for accurate predictions of laminated structures' mechanical behavior

http://past.isma-isaac.be/downloads/isma2016/papers/isma2016_0379.pdf

Addressing e-Motor NVH in detailed design stage

Advanced Simulation topics

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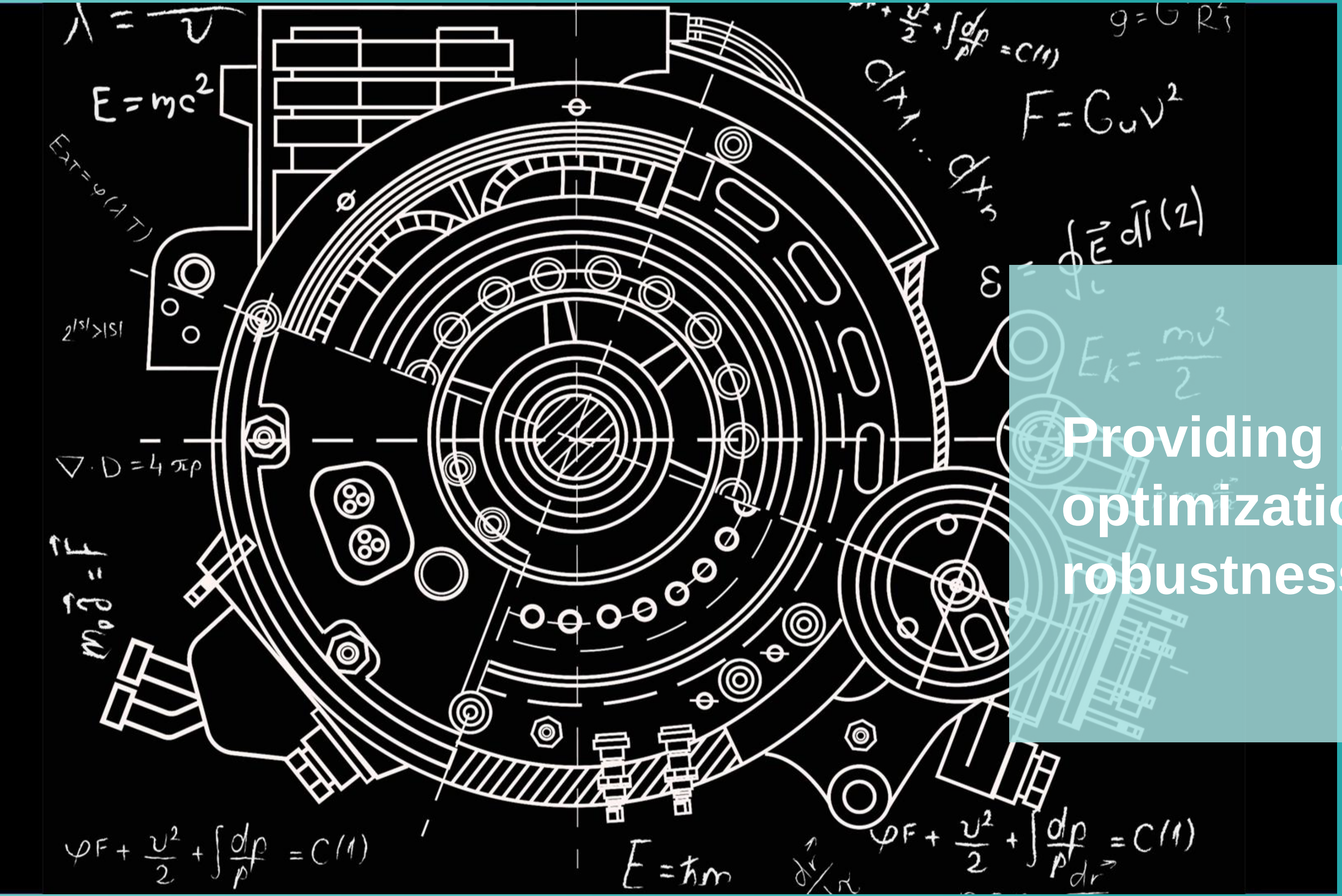
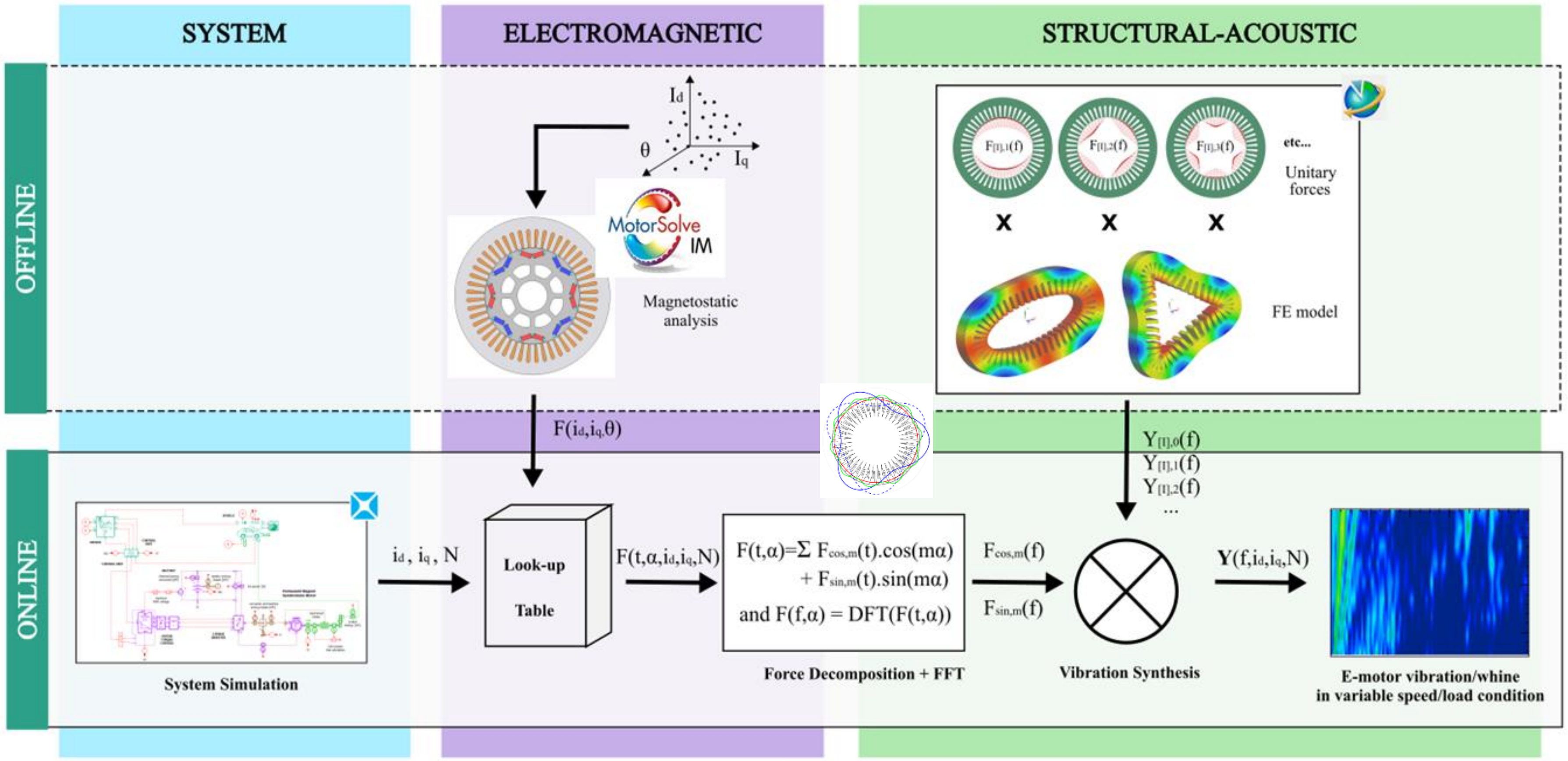
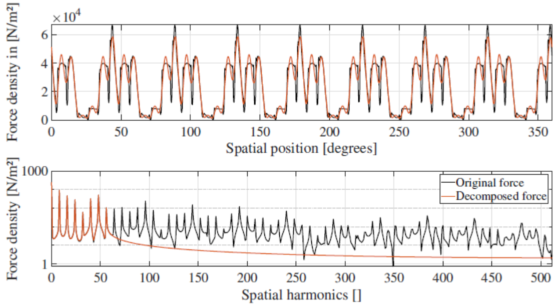


Providing advanced methods for NVH optimization of controls as well as design robustness

Vibration Synthesis

Full system optimization by use of model reduction technology





Vibration Synthesis

Full system optimization by use of model reduction technology

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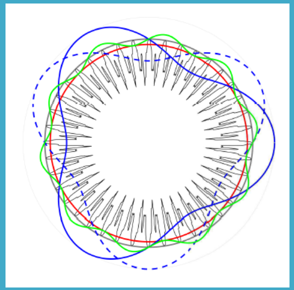
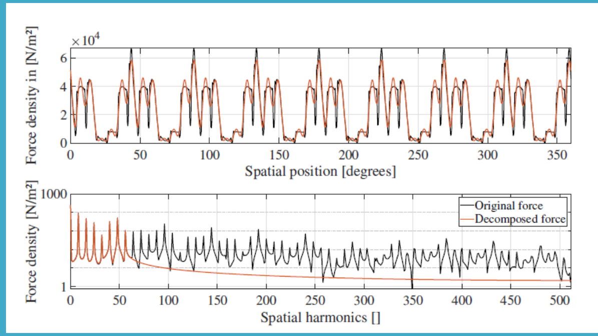
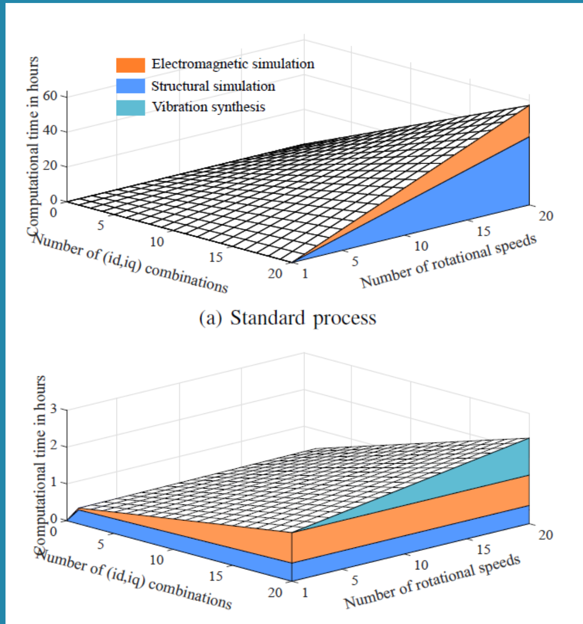
Advantage: Faster design of control strategies with full accuracy of the detailed EM and structural models

Potentially same accuracy as traditional 3D process





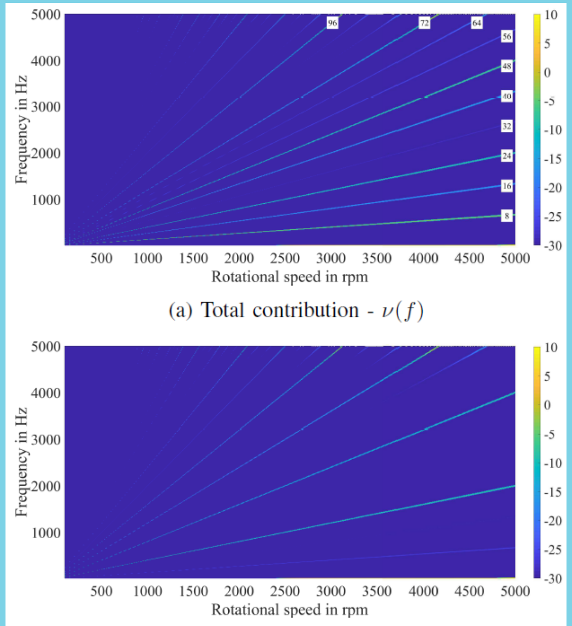
Can reach >10 times faster calculations



(a) Standard process

(b) Vibration synthesis

Insight in relevance of the different spatial orders



(a) Total contribution - $\nu(f)$

(b) Contribution from shape 0 - $\nu_0(f)$

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

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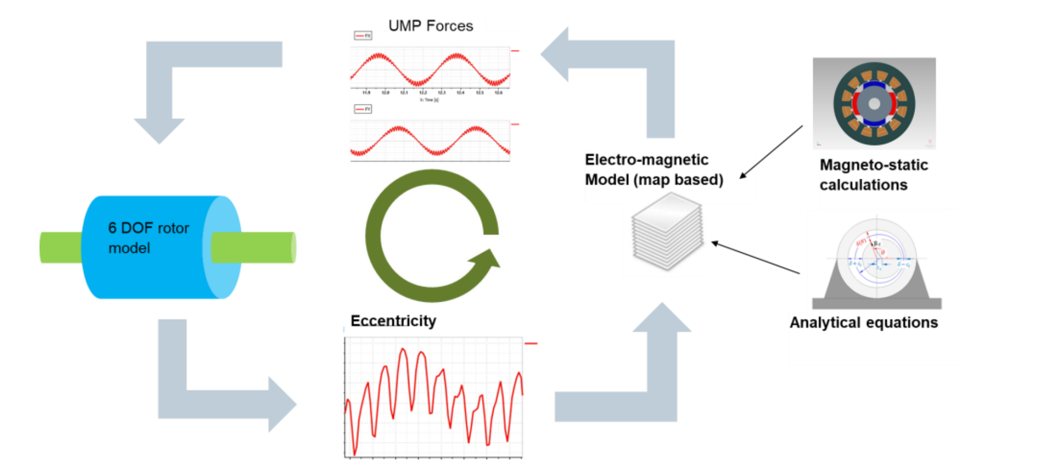
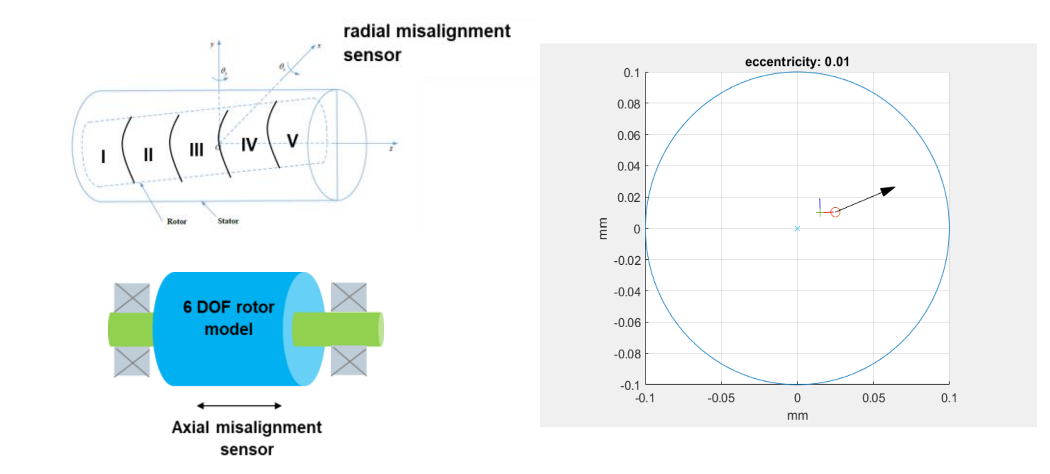
Unbalanced Magnetic Pull (UMP)



- Rotor misalignment results to 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

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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

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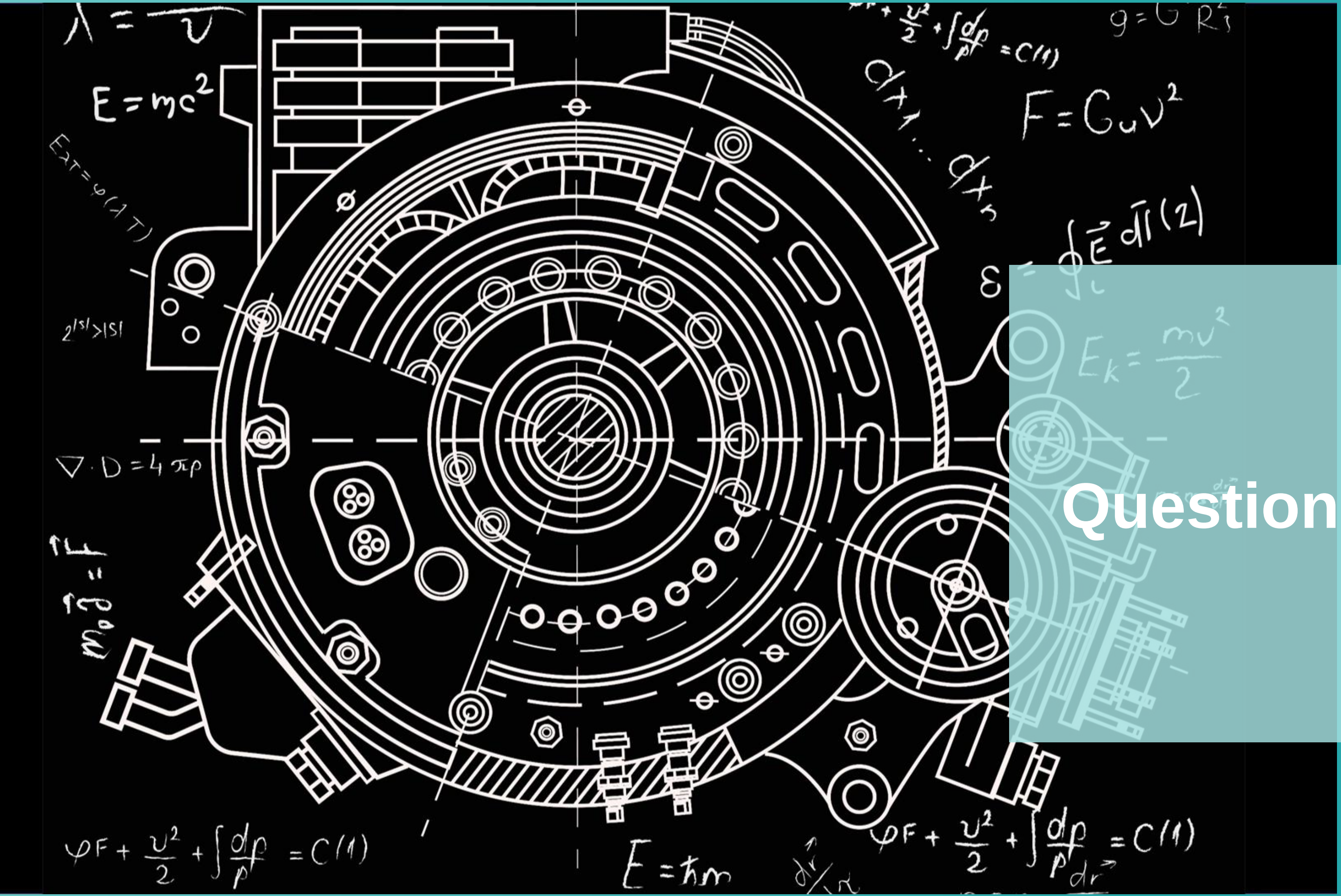

Questions?