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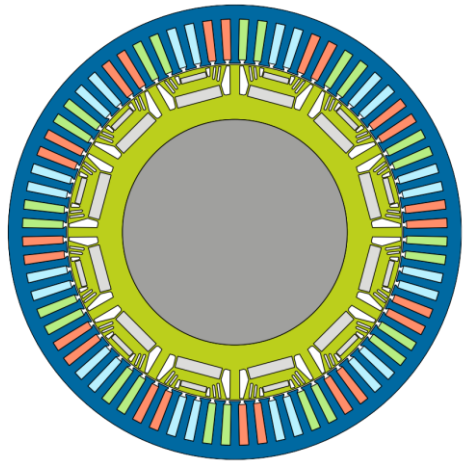
Manatee® e-NVH CAE collaborative environment
Solutions for electrical systems engineering challenges

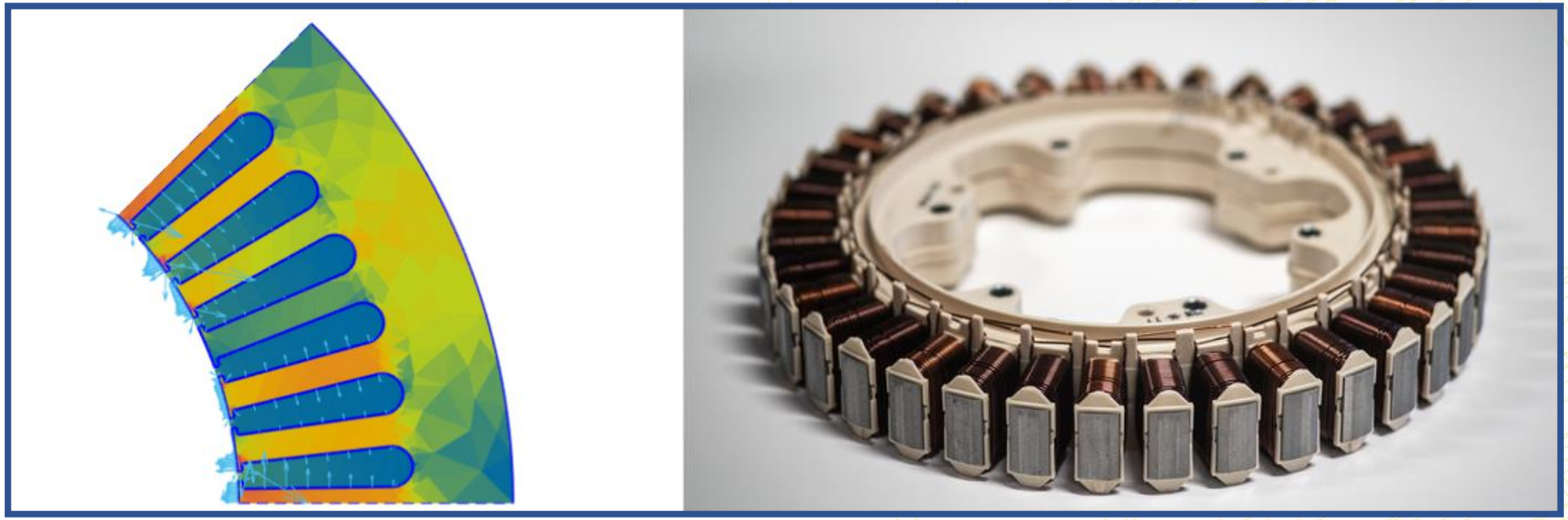
From e-machine geometry & control parameters…



… to system-level electromagnetic noise and vibrations

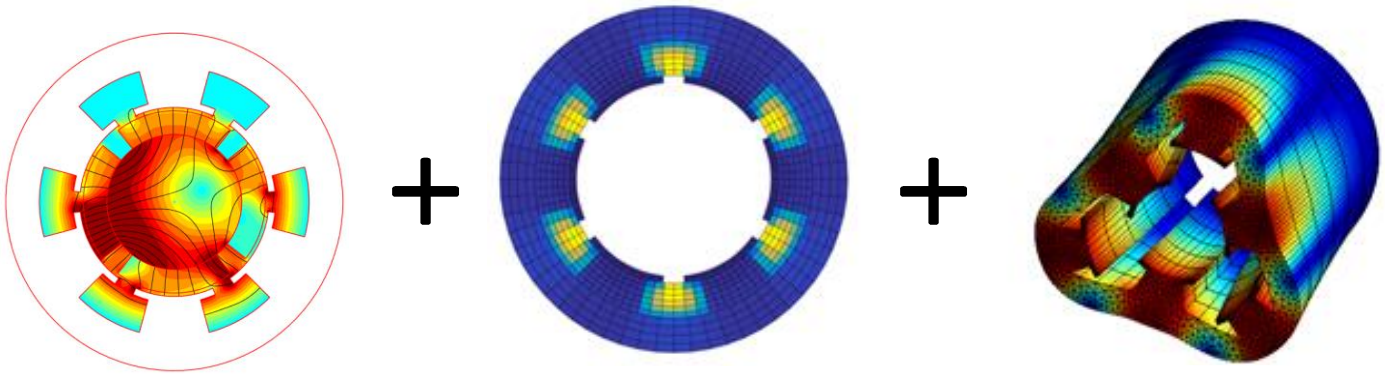
20240422

MANATEE FOR ELECTRICAL ENGINEERS



e-NVH challenges for Electrical Engineers

- +/- 20 dB **impact** of early topology and slot/pole combination
- Strong variation of magnetic excitations with **control and switching strategy**
- **Electromagnetic performance reduction** during noise mitigation solution (e.g. skewing)
- **Large computing time** of electromagnetic fields and forces, including parasitic harmonics
- Multiphysics design: **electromagnetics + heat transfer + e-NVH**



electromagnetics *heat transfer* *vibro-acoustics*

Manatee key features for Electrical Engineers

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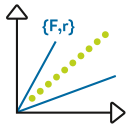
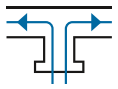
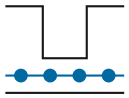
Electrical machine definition using templates and .dxf import



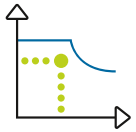
Quick Campbell diagram of magnetic forces for early e-NVH risk assessment



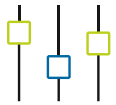
Import of third-party electromagnetic software results



Fast magnetic & NVH models in basic & detailed design



Fast and accurate calculation of magnetic forces in whole torque/speed plane

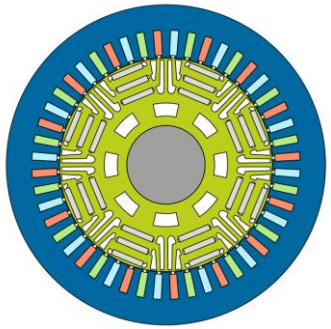


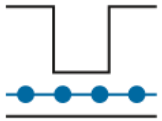
Parameter sweep on magnetic circuit design parameters

Electromagnetic modelling levels at different design stages

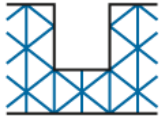
- Linear hybrid Permeance Magnetomotive Force (PMMF) model is proposed in early design phase, non linear magnetostatic simulations is proposed in detailed design phase
- Current harmonics can be manually added in sinusoidal-driven simulations, and flux distribution can be imported

Synchronous Machines



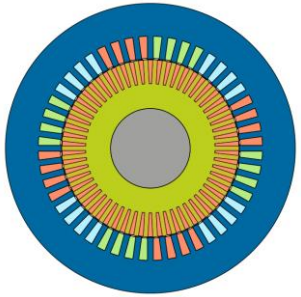


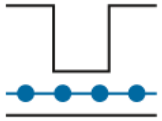
2.5D PMMF
(current-driven,
no-load, linear)



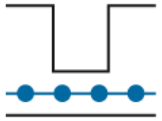
2.5D FEA
(current-driven,
non-linear)

Induction Machines

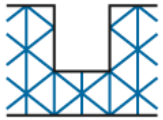




2.5D PMMF
(current-driven,
no-load, linear)

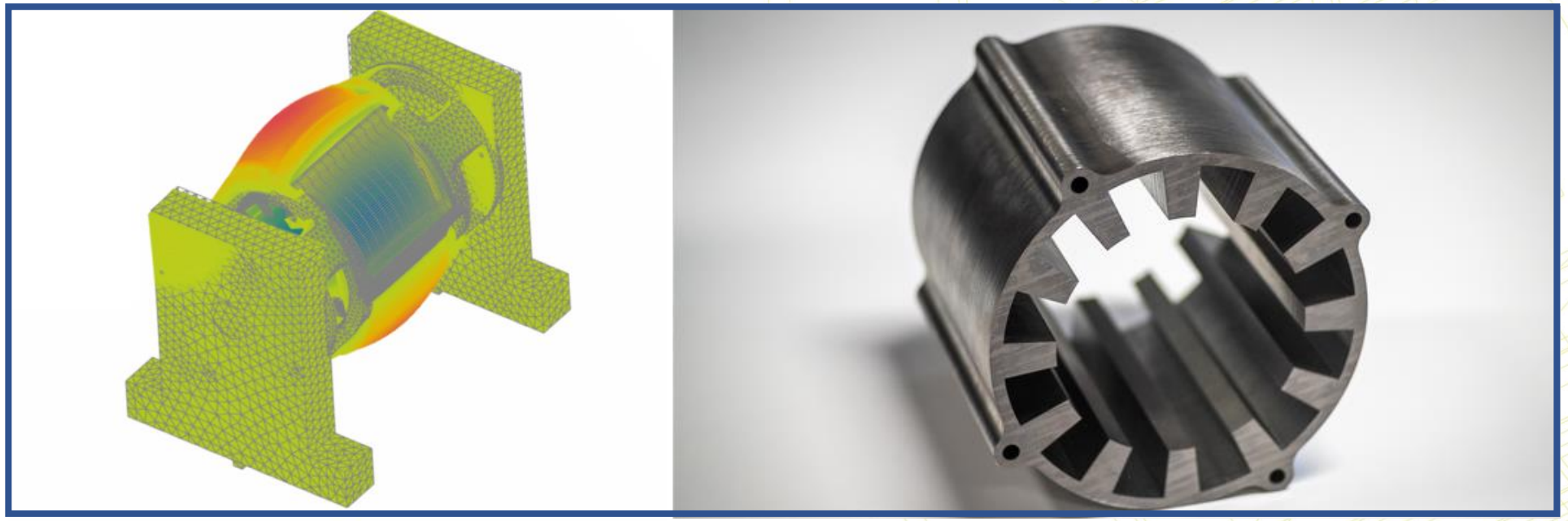


2.5D PMMF
(voltage & slip driven,
full load, linear)



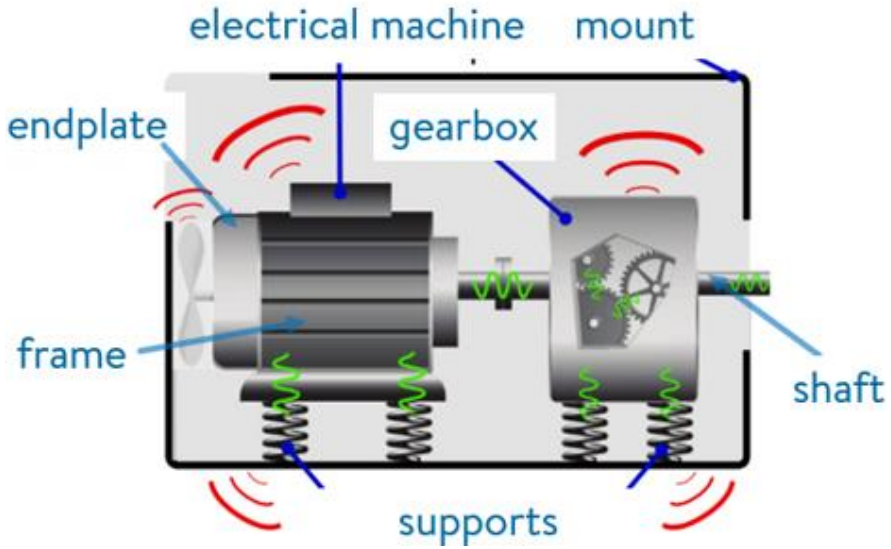
2.5D FEA
(voltage & slip driven,
circuit-based, non-linear)

MANATEE FOR MECHANICAL ENGINEERS



e-NVH challenges for Mechanical Engineers

- **Complexity of e-NVH transfer paths** resulting in more difficult NVH troubleshooting
- High influence of **mechanical tolerances** (e.g. eccentricity, uneven airgap) on magnetic forces
- High impact of boundary conditions on structural modes and e-NVH resonances
- Potential interactions between **e-motor and gearbox design**



Manatee key features for Mechanical Engineers

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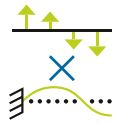
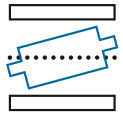
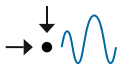


Unit magnetic load case projection onto structural modal basis

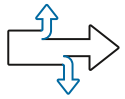


Quick modelling of mechanical tolerances (inclined eccentricities, uneven airgap)

Import of third-party 3D FEA mechanical modal basis (**up to 6 billion nodes**)



Electromagnetic vibration synthesis to accelerate e-NVH calculations



Load case contribution for an efficient transfer path analysis

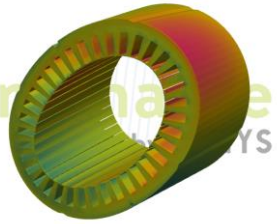
Vibration spectrograms and order cuts to visualize and investigate resonances

Mechanical modelling levels at different design stages

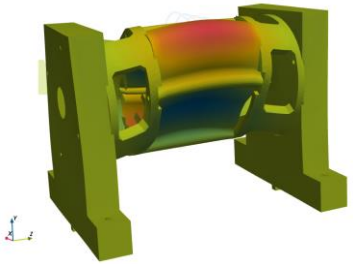
- Mechanical model can be adapted to each stage of the development
- Electromagnetic vibration calculation is extremely fast even when using a 3D FEA model of a full electric drive

2.5D outer rotor or stator
Analytical cylindrical shell

2.5D stator
Beam Element Model



3D FEA
stator only



3D FEA
stator + rotor
+ bearings + housing

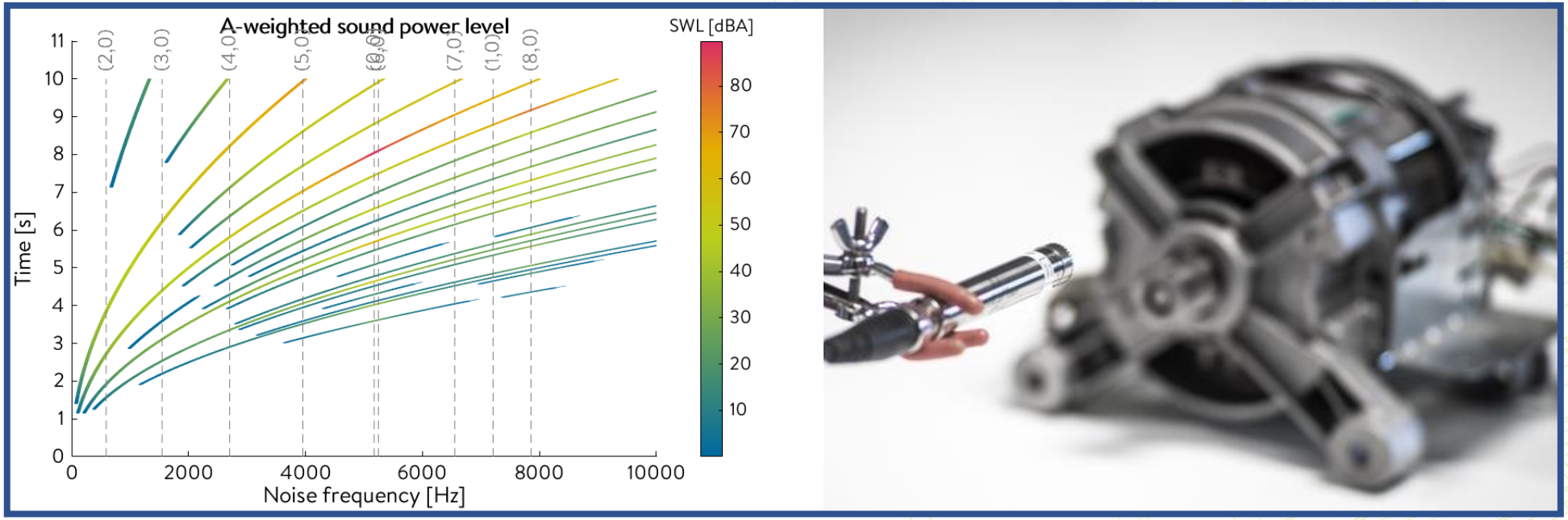
3D FEA
Electric Drive Unit incl. gears

...

Use of mechanical properties from machine object
Free-free boundary conditions

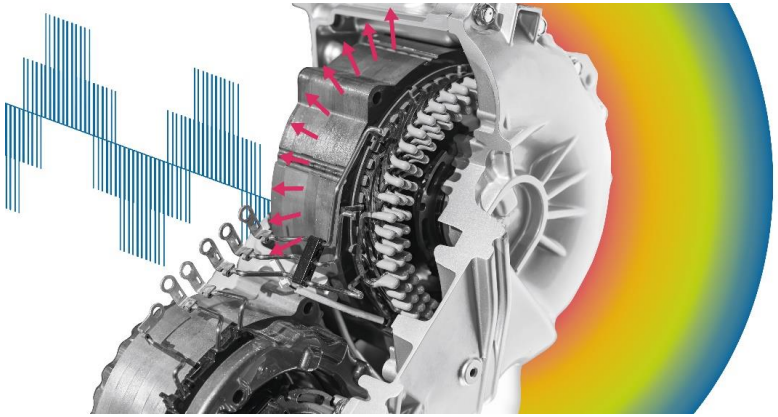
No use of mechanical properties from machine object
(import from third party 3D FEA mechanical software)
Any type of boundary conditions

MANATEE FOR ACOUSTIC / NVH ENGINEERS

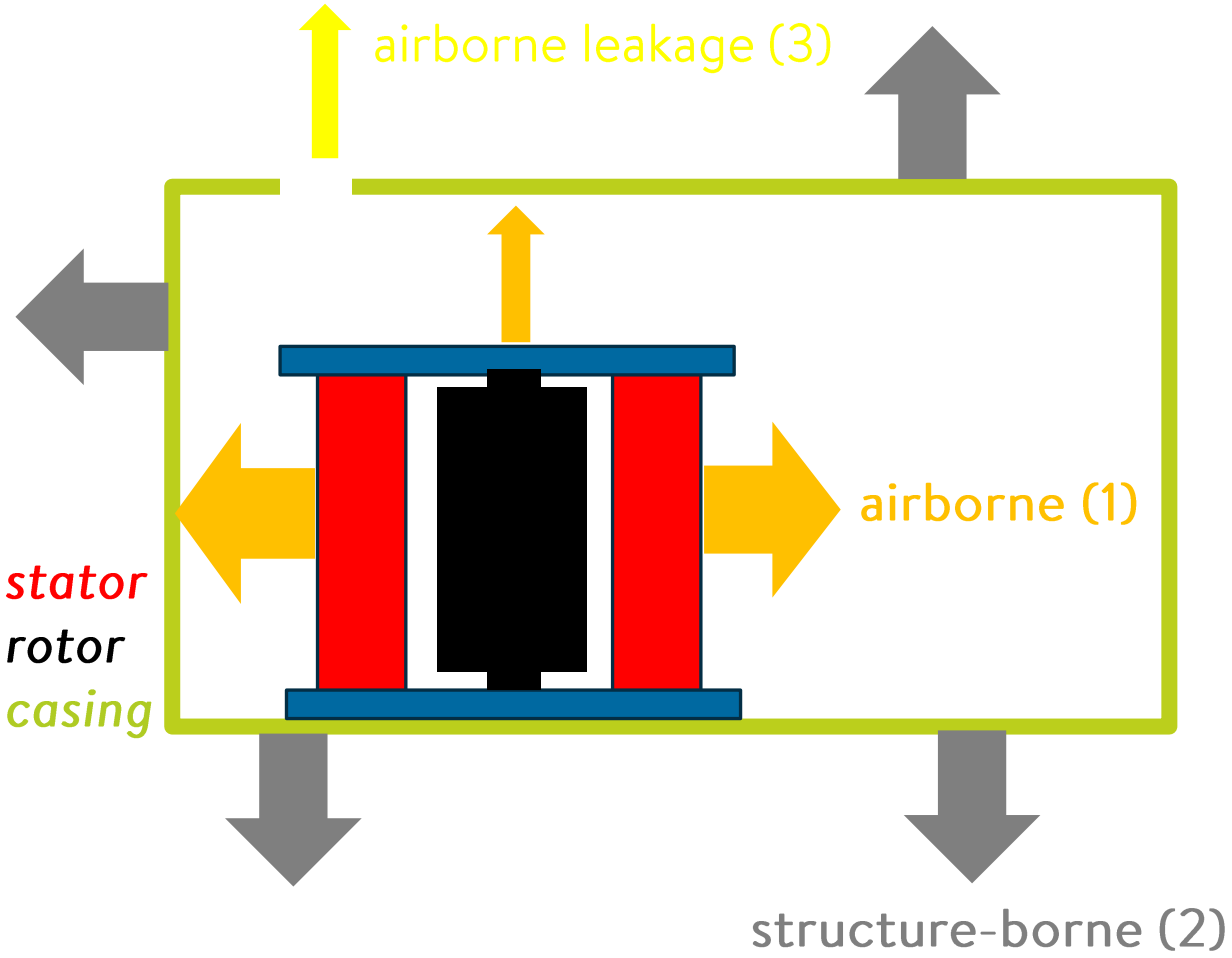


e-NVH challenges for Acoustic / NVH Engineers

- **Target setting** in presence of combined magnetic, mechanical and aerodynamic noise sources
- **Acoustic standards fulfilment** of electrical system in terms of Sound Power Level
- Assessment of structure-borne and airborne noise, as well as potential acoustic leakages
- **Sound quality** design including psychoacoustics
- Handling **large computing time** related to high frequency noise or complex acoustic environments



Manatee key features for Acoustic / NVH Engineers



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(1) sound power assessment with Manatee V2
(2) sound power & pressure assessment with Manatee V2
(3) not included from Manatee V2 GUI (can be assessed within a consulting project)

Manatee key features for Acoustic / NVH Engineers

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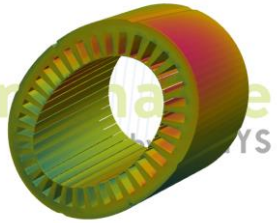
- Fast semi-analytic acoustic models suitable for high frequency calculations
- A-weighting and third octave band spectra for acoustic standards
- Sound power level order cuts to visualize and investigate resonances
- Sound quality metrics calculation, sound synthesis and .wav export
- Import of external (non magnetic) sources of noise
- Coupling with Actran to perform acoustic FEA calculations *Starting from V2.3*

Acoustic modelling levels at different design stages

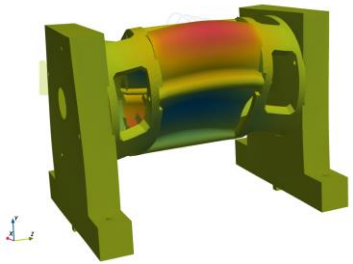
- Acoustic model depends on structural model
- Coupling with Actran FEA can be carried in scripting mode (consulting project)

2.5D Analytic
stator only

2.5D stator
Beam Element Model



3D FEA
stator only



3D FEA
stator + rotor, bearing + housing

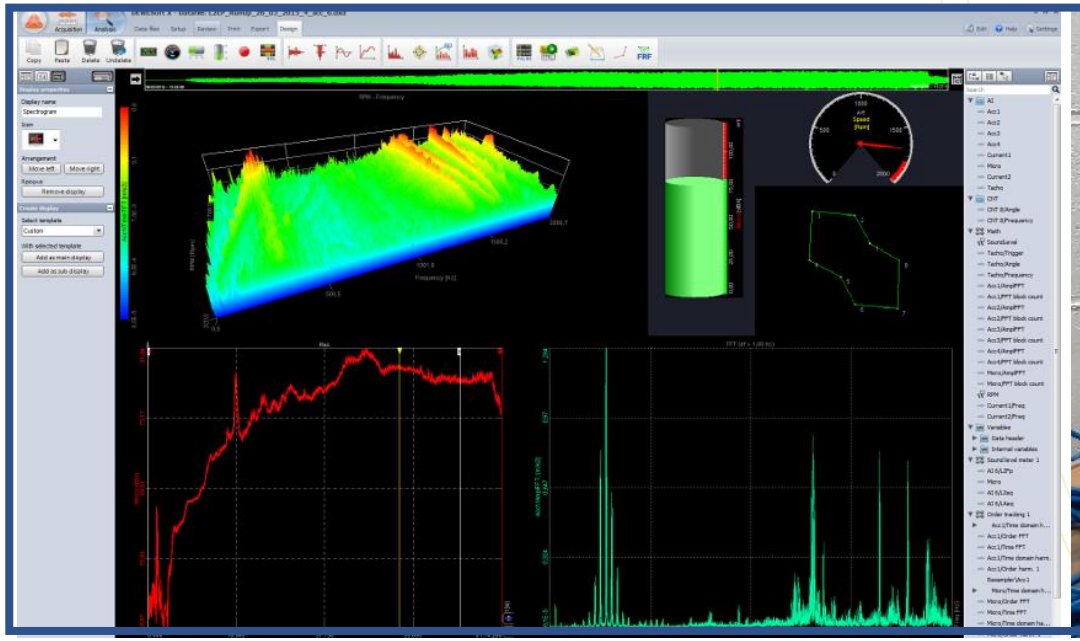
3D FEA
Full Electric Drive Unit

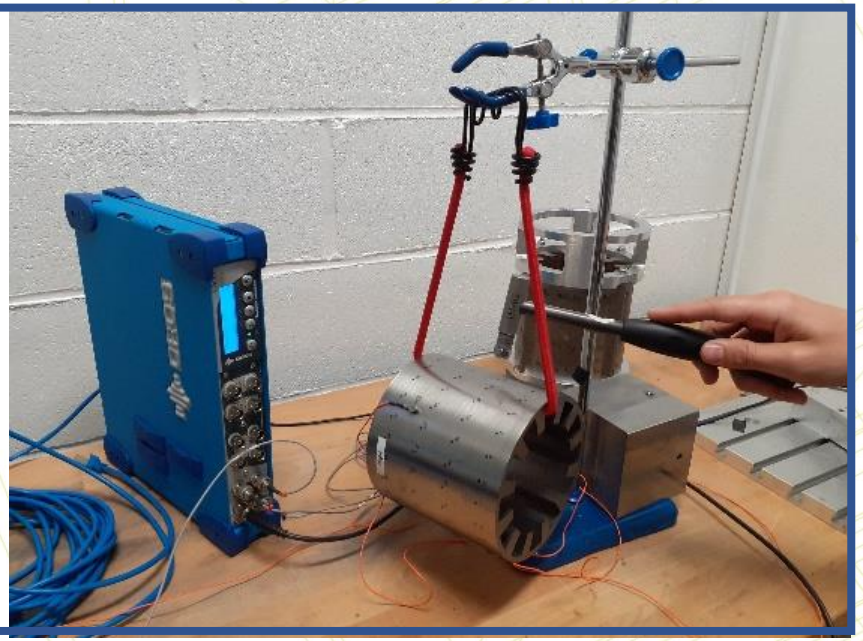
...

Semi-analytic radiation factors
Equivalent monopole for Sound Pressure Level

Equivalent Radiated Power
Equivalent monopole for Sound Pressure Level

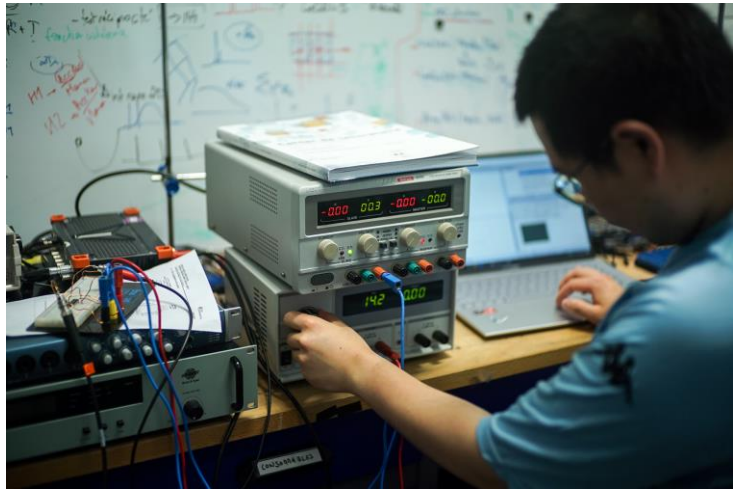
MANATEE FOR NVH TEST ENGINEERS





e-NVH challenges for NVH Test Engineers

- Identification of the **physical origins** of main orders and resonances from NVH test data
- Experimental characterization of **structural modes** excited by magnetic forces
- **Correlation** of simulation and measurements to build digital twins
- Characterization of operational electric, magnetic and geometrical **non idealities** affecting test Vs simulation comparison (e.g. uneven magnetization, current unbalance)



Manatee key features for NVH Test Engineers

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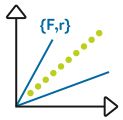
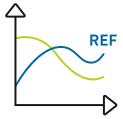
Import of experimental test data into Manatee environment *Starting from V2.3*



Campbell diagram to discriminate e-NVH sources from other sources

Automated post-processing including filters *Starting from V2.3*

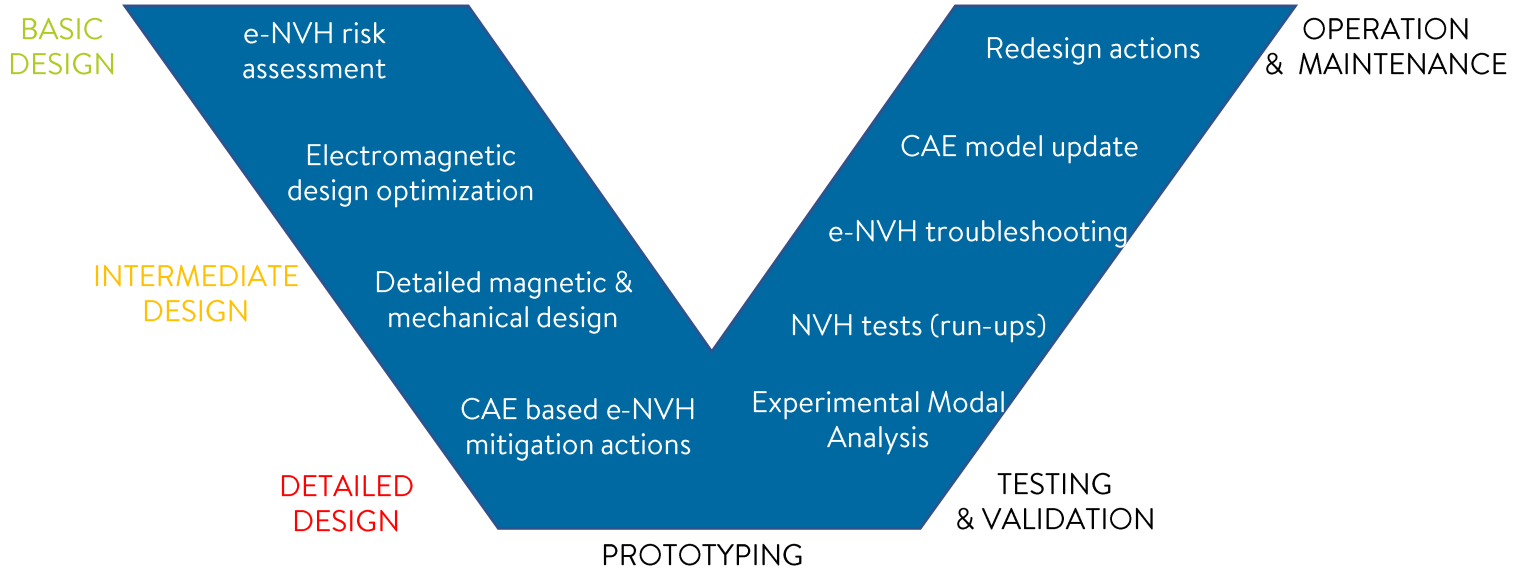


Direct comparison between experiments and simulation results *Starting from V2.3*

MANATEE FOR TECHNICAL LEADS

e-NVH challenges for Technical Leads

- Follow-up of NVH **requirements** and **efficient troubleshooting** of technical issues
- Fulfilment of **project planning and cost objectives**
- Optimization of engineering process and **CAE solutions**
- **Coordination of engineering team** to meet system requirements and reduce development time
- Management of the engineering **e-NVH know-how**



Manatee key features for Technical Leads

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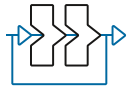


Efficient collaboration of different engineering fields through a single environment, including test & simulation iterations

Quick NVH **problem solving** combining electrical, control and mechanical mitigation actions

Import/export solutions to **ease integration with existing** CAE & validation processes

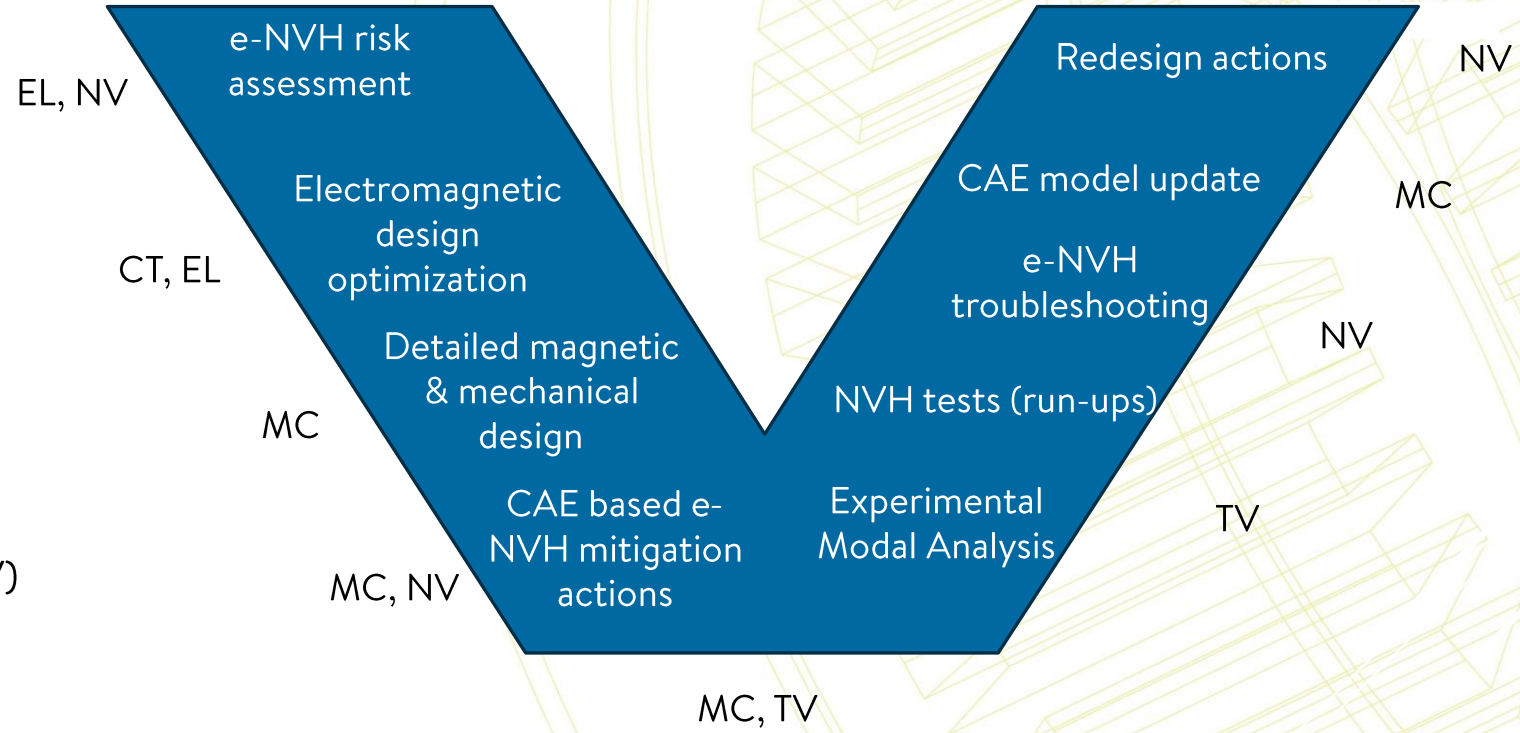
State of the art calculation methods validated on industrial cases

Flexible licensing solutions including e-NVH support

MANATEE WORKFLOW USAGE

What engineers are involved during the V-cycle development?

- Electrical Engineers (EL)
- Control Engineers (CT)
- Mechanical Engineers (MC)
- NVH Engineers (NV)
- Acoustic Engineers (AC)
- Test & validation Engineers (TV)



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Manatee e-NVH CAE collaborative platform can be used by all these engineers all along the development lifecycle of electrical machines

manatee by EOMYS joins SIMULIA

How to troubleshoot & solve e-NVH problems inside Manatee?

	ELECTRICAL ENGINEERS	CONTROL ENGINEERS	MECHANICAL ENGINEERS	NVH ENGINEERS
ANALYSIS TOOLS	**Quick Campbell** Sound power spectrogram Torque ripple spectrogram Sound power Order Tracking **Load Case contribution**	Quick Campbell including PWM Order Tracking analysis Load Case contribution	Quick Campbell with main mode position **Modal force matrix** analysis **Modal contribution**	NVH spectrogram NVH Order Tracking analysis **Load Case contribution** **Panel contribution** **Sound Quality** metrics
SOLUTION TOOLS	**Predefined noise control techniques** (e.g. skewing) focusing on magnetic circuit geometry **Parameter sweeps** on magnetic circuit design (e.g. on slot opening) **Multi-objective optimization**	**Predefined noise control techniques** (e.g. harmonic current injection) focusing on e-machine control Change of **current angle** to study torque / efficiency / NVH tradeoffs **Multi-objective optimization**	**Parameter sweeps** on mechanical structure (e.g. on yoke thickness), or on eccentricities to optimize **mechanical tolerances** **Shift of a structural mode** in a third-party 3D FEA mechanical model and update of Manatee e-NVH calculations	e-NVH **assessment** all along development cycle Update of overall **NVH targets** Optimization of **sound quality** combining e-motor & gear noise under Manatee

EOMYS

Legend of user profiles:
CT = Control Engineer
EL = Electrical Engineer
MC = Mechanical Engineer
NV = NVH Engineer
PT = Powertrain Engineer
AC = Acoustic Engineer
TV = Test & Validation Engineer

Legend of system levels:
L1 = Electrical machine
L2 = Electric Drive (emotor+gears)
L3 = System (e.g. vehicle)

Legend of Manatee versions:
[SM]: Scripting Mode, not yet in the roadmap but can be done during consulting project
[V23]: Included in Manatee V2.3 official roadmap

Legend of Manatee features:
WF4: code name of predefined multiphysic simulation workflow
[Parameter Sweep]: module of Manatee accessible through icon banner

A-Early design phase of electrical systems

ID	Who	Objective	Inputs	Tools / WF	Outputs
A1	EL	Identify different feasible e-machine topologies achieving electromagnetic performances	Technical requirements (torque speed curve, cooling capacity, max weight / cost, max diameter)	Ex: RPMxprt, MotorCAD, FluxMotor	- Magnetic circuit geometries of different topologies fulfilling requirements - Supply characteristics (e.g. Id/Id following MTPA)
A2	EL	Qualitative ranking the magnetic noise level of the different e-machines and assess e-NVH risk	- Slot pole combination - Prior knowledge of natural frequency position	Manatee [Quick Campbell]	- Comparison of e-NVH signature (frequencies, wavenumbers) - Identification of main potential e-NVH problems during run-up (e.g. resonance of breathing mode at 3500 RPM) - Identification of the origin of magnetic excitations (PM field, armature field, PWM, ...)
A3	EL	Rank the magnetic noise level of the different e-machines and assess e-NVH risk	- A1 e-machine dimensions and supply characteristics - NVH requirements (overall sound power level based on experience or standards)	Manatee WF2 Ex: use of analytic vibroacoustic model or basic 3D FEA model of the stator to compare IM Vs IPMSM noise, [Parameter Sweep] on IM rotor slot number	- Comparison of e-NVH level of different slot/pole combination & topologies - Identification of main e-NVH problems related to airborne noise
A4	EL	Optimize a chosen design finding the best trade off between electromagnetic & e-NVH performances	- chosen design based on A3 ranking - identification of noise issue based on A3 analysis	Manatee WF4 Ex: [Parameter Sweep] on V-shape angle, [Optimization] [V23] on rotor layout variables, use of [Design Explorer] to choose a final design	- Pareto optimal solutions in terms of torque, torque ripple and NVH - Optimized design in terms of electromagnetic performance and airborne magnetic noise - Operational magnetic forces in healthy conditions

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A-Early design phase of electrical systems

ID	Who	Objective	Inputs	Tools / WF	Outputs
A5	EL, CT	Optimize the PWM strategy & switching strategy finding best trade off between efficiency & e-NVH performances	- optimized design based on A4 - feasible PWM strategies and frequencies	Manatee WF4 Ex: comparison of e-NVH SWL of SVPWM and GDPWM [V23]	- Optimized PWM strategy in terms of efficiency and airborne magnetic noise
A6	NV, EL	Understand the most influent parameters to increase e-NVH knowledge of the design	- A1 e-machine dimensions and supply characteristics	Manatee WF4 Ex: [Parameter Sweep], Design of Experiments [SM]	- Most influential magnetic circuit design parameters (e.g. slot opening, pole shoe)
A7	EL	Understand the impact of different electrical faults or tolerances to increase e-NVH knowledge of the design	- A1 e-machine dimensions and supply characteristics	Manatee WF4 Ex: application of uneven magnetization [V23], application of unbalanced currents [V23]	- Ranking of different faults or tolerances in terms of dB level and more accurate specifications (e.g. level of current unbalance)

Legend of user profiles:
CT = Control Engineer
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WF4: code name of predefined multiphysic simulation workflow
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B-Intermediate design phase of electrical systems

ID	Who	Objective	Inputs	Tools / WF	Outputs
B1	MC / NV	Building of a detailed 3D FEA mechanical model at L2 level (emotor+housing+gears)	Optimized e-machine design based on A4	Ex: Altair Optistruct, Ansys Mechanical, Abaqus, Nastran… e-NVH support from EOMYS	- 3D FEA mechanical model (not yet fit with experiments) including stator, rotor, housing, gearbox casing
B2	NV / PT	Assess the gear whine noise level at e-powertrain level	Optimized gear design	Ex: Romax, Masta, Adams Gear, …	- Variable speed sound power level due to gear whine (mechanical noise)
B3	NV	Assess the aeroacoustic noise level at e-machine level	Optimized design based on A4	Ex: Ansys Fluent/CFX, Comsol…	- Variable speed sound power level due to aerodynamics (aeroacoustic noise)
B4	MC / NV	Quantify the torque ripple / axial ripple constraints to fulfil structure borne magnetic noise and vibration allocation	System level (gear, e-motor) NVH allocations from NV	Ex: Romax, Abaqus	- Torque ripple constraints at 6f 12f etc function of speed
B5	MC / NV	Identify the structural modes which are excited by magnetic Load Case	- 3D FEA modal basis from B1	Manatee Ex: calculation of Unit Modal Force and Frequency Response Functions (in parallel of EL work)	- Vibration & Noise (ERP) levels as a function of Load Case (e.g. torque ripple on stator/rotor, UMP on stator/rotor, r=2 radial on stator…) - FRF and Unit Modal Force matrix
B6	MC / NV	Compare the impact of different mechanical integration options in terms of airborne and structure borne noise	- 3D FEA modal basis from B1 - emachine model from A1 or A4 (slot/pole combination to identify magnetic Load Cases)	Manatee Ex: modal basis import and comparison of FRF under unit magnitude Load Case	- Effect of different mechanical integrations (nb of bolts, bearing type) on NVH requirements in terms of dB variation function of frequency

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B-Intermediate design phase of electrical systems

ID	Who	Objective	Inputs	Tools / WF	Outputs
B7	EL / NV	Refine e-NVH calculations using a more accurate 3D FEA mechanical model at L2 level, healthy condition	- A4 e-machine dimensions and supply characteristics - 3D FEA modal basis from B1 or FRF from B5	Manatee WF4 Ex: Electromagnetic Vibration Synthesis algorithm along max torque speed curve Reuse of load calculations from A3 combined with modal basis from B1, Equivalent Radiated Power	- Identification of main e-NVH problems related to airborne noise and structure borne noise (e.g. torque ripple applied on rotor) - Relation between noise and torque ripple to better specify torque ripple constraints
B8	MC	Quantify the impact of manufacturing tolerances on e-NVH level	- A4 e-machine dimensions and supply characteristics - 3D FEA modal basis from B1	Manatee WF4 Ex: [Parameter Sweep] on dynamic & static eccentricity levels, uneven airgap…	- Relationship between noise and mechanical tolerances to better specify them - Insights to choose the manufacturing technology (number of weldings, segmentation…) - Operational magnetic forces in eccentric conditions
B9	EL / NV / PT	Robust design optimization to achieve NVH requirements under tolerances	- B3 & B4 conclusions on e-NVH problems - choice of a noise control techniques	Manatee WF4 Multiobjective optimization [V23] of magnetic circuit dimensions including eccentricity	- Optimized mechanical & electromagnetic design including tolerances

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B-Intermediate design phase of electrical systems

ID	Who	Objective	Inputs	Tools / WF	Outputs
B10	NV	Check NVH requirements in the whole torque speed plane	- A4 e-machine dimensions and supply characteristics on whole torque speed plane - 3D FEA modal basis from B1 or FRF from B5	Manatee WF4 Electromagnetic Vibration Synthesis algorithm on whole torque speed plane	- Optimized mechanical & electromagnetic design including tolerances
B11	EL	Calculate the Unbalanced Magnetic Pull level under eccentricity for later use by MC in gear system simulation	- A1 e-machine dimensions and supply characteristics	Manatee [SM]	- UMP harmonics function of operating points and eccentricity level
B12	EL / CT	Application of noise mitigation techniques if NVH requirements are not achieved in B7 or B9	- A1 e-machine dimensions and supply characteristics - - 3D FEA modal basis from B1 or FRF from B5	Manatee [Skew Optimization], Notching or Harmonic Current Injection [V23]	

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C-Detailed design phase of electrical systems

ID	Who	Objective	Inputs	Tools / WF	Outputs
C1	MC / NV	Building of a detailed 3D FEA mechanical model at L3 level (e.g. vehicle)	3D FEA mechanical model of B1	Ex: Altair Optistruct, Ansys Mechanical, Abaqus, Nastran… e-NVH support from EOMYS	- 3D FEA mechanical model (not yet fit with experiments) including EDU integration to chassis
C2	AC	Building of a detailed 3D FEA acoustic model at L3 level (e.g. vehicle)	3D CAD model at L3 level	Ex: Actran	- 3D FEA acoustic model including acoustic packaging
C3	NV	Estimation of structure borne noise at L3 level with different mounting technologies	Magnetic forces calculated from B8 or A4	Ex: Optistruct with magnetic forces exported from Manatee	- Structure Borne Noise at L3 level due to magnetic forces - Optimized mechanical integration of L2 into L3
C4	AC	Estimation of air borne noise at L3 level with different acoustic packaging	Magnetic forces calculated from B8 or A4	Ex: Actran with magnetic forces exported from Manatee	- Air Borne Noise at L3 level due to magnetic forces - Optimized acoustic packaging
C5	NV	Refine e-NVH structure borne calculations at L2 level at “low” frequencies using 3D FEA acoustic model	- A4 e-machine dimensions and supply characteristics - 3D FEA modal basis from B1	Manatee Import of acoustic FEA modal radiation efficiency [SM] or direct call to third party acoustic FEA software Actran [SM]	- More accurate quantification of sound power/ pressure level at “low” frequency (compared to ERP model used in B7) to compare with experiments or to investigate low frequency resonance problems

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C-Detailed design phase of electrical systems

ID	Who	Objective	Inputs	Tools / WF	Outputs
C6	EL	Refine e-NVH calculations using strong coupling between electromagnetics & electric circuit	- A4 e-machine dimensions and supply characteristics - 3D FEA modal basis from B1	Manatee Import of a third party electromagnetic SW flux solution including strong coupling (Ansys, Flux, Jmag…)	- More accurate quantification of e-NVH levels due to strong coupling effects (e.g. dead times, back emf, inverter non idealities)
C7	NV	Assess overall NVH behaviour combining all noise sources, including sound quality metrics	- e-motor whine levels from B4 or C1 - gearwhine level from B2 - aeroacoustic level from B3	Manatee Import of non magnetic noise sources	- Sound quality analysis of the overall noise level including all excitations sources, to account for masking effects - Identification of NVH hot spots
C8	MC / NV	Find the operational eccentricity level function of speed due to strong coupling between magnetics & mechanics (UMP + centrifugal forces)	- bearing stiffness function of speed - UMP calculated in B10 - “cold” eccentricity levels - mechanical imbalance level	Manatee Iterations between mechanical model and magnetic force [SM]	- Hot eccentricity level starting from cold eccentricity level - Prediction of rotor/stator interferences

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D-Testing, validation & operation phase of electrical systems

ID	Who	Objective	Inputs	Tools / WF	Outputs
D1	MC	Refine 3D FEA mechanical model based on measurements	- numerical modal analysis of prototype B1 - experimental modal analysis	Ex: Optistruct, LMS, Ansys e-NVH support from EOMYS	- Updated 3D FEA mechanical model of stator, rotor, housing assembly including experimental modal damping
D2	NV, AC	Discriminate magnetic noise from other noise sources in test results	- run-up NVH measurements	Manatee [Quick Campbell] Import of test data and automated order extraction at emachine frequencies [SM]	Split of magnetic noise from other noise sources (mechanical & aerodynamic noise) [V23]
D3	EL, NV	Refine e-NVH calculations using updated 3D FEA mechanical model fit with experiments	- 3D FEA modal basis from D1	Manatee Import of measured modal basis [V23] Set of measured modal damping [SM]	More accurate evaluation of sound pressure level due to magnetic forces
D4	NV	Compare tests & simulations	- run-up NVH measurements	Manatee Import of test data and automated order extraction at emachine frequencies [SM] Comparison of test & simulations [V23]	- Identification of gaps between tests & simulation (e.g. uneven magnetization, unbalanced currents, uneven airgap…) - Explanation of experimental NVH hot spots
D5	MC	Redesign of the electrical machine based on test results	- 3D FEA modal basis from D1	Manatee Application of complementary noise mitigation techniques such as [Skew Optimization], Notching or Harmonic Current Injection [V23]	- Updated mechanical & electromagnetic design to tackle noise issues that were eventually not identified during virtual prototyping phase (e.g. due to inaccurate 3D FEA mechanical model, or asymmetries in the real motor)

CONCLUSION

- Manatee provides **high productivity gains** as it is >1000 faster than general purpose FEA software:
  - > 10x faster for simulation set-up
  - > 10x faster for e-NVH calculations
  - > 10x for post processing and application of noise reduction techniques

- Manatee is the **most advanced solution** to tackle electromagnetic noise problems **throughout system development lifecycle**

Commercial inquiries

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manatee by EOMYS

joins

SIMULIA

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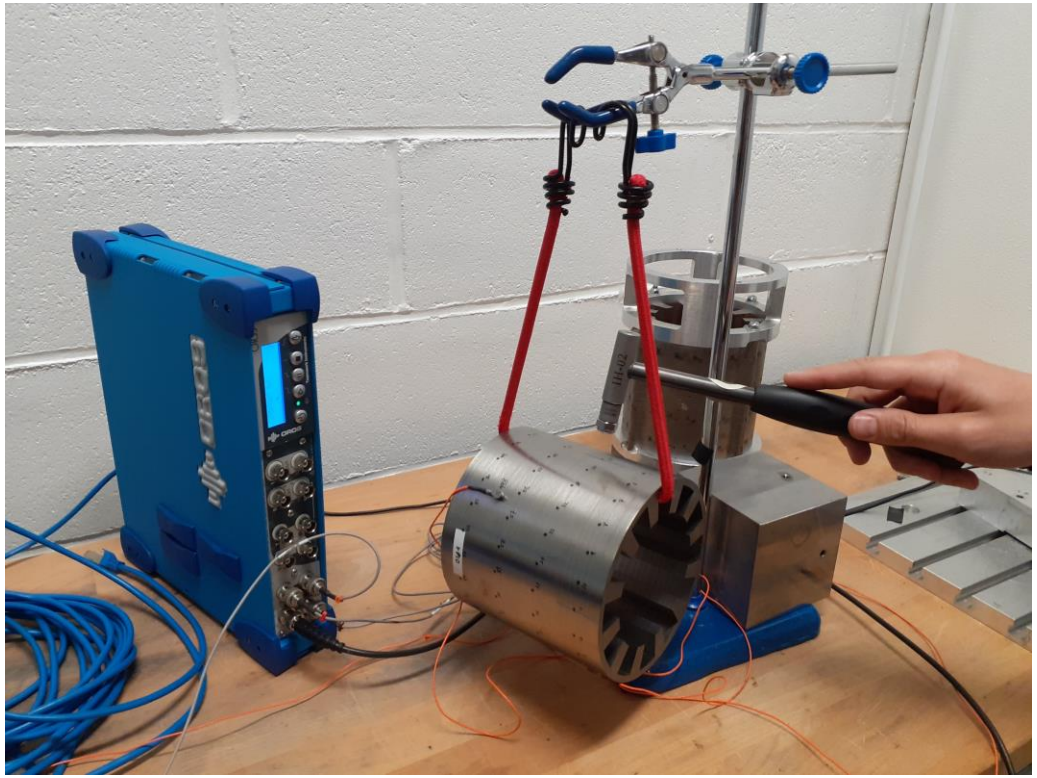
Back-up slides – Manatee software validations

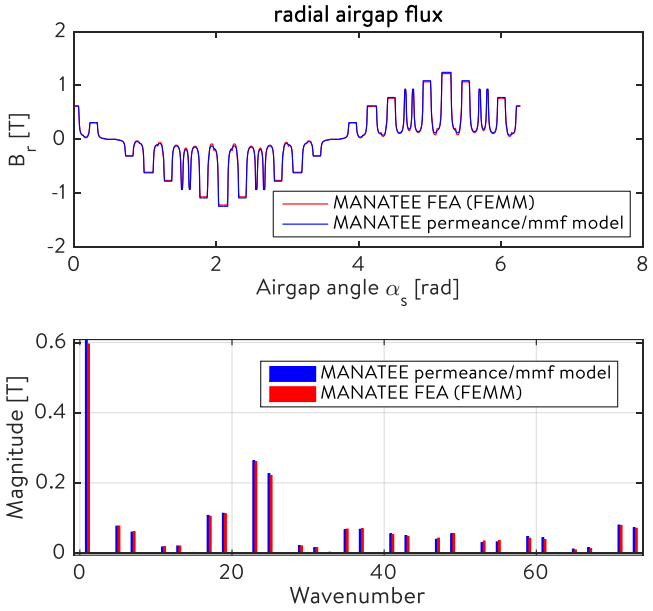


Fast hybrid electromagnetic models

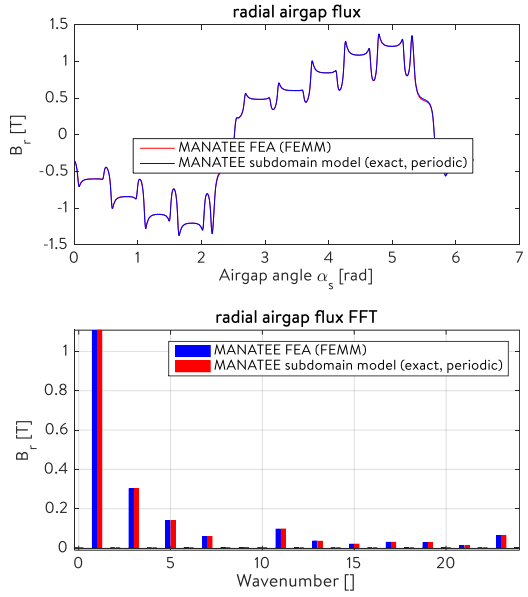
- hybrid magnetic model combines permeance / magnetomotive force model and FEA calculations
- used for induction machines and IPMSM early design phase

$$B(t, \alpha^s) = \Lambda(t, \alpha^s) \left(f^r_{mm}(t, \alpha^s) + f^s_{mm}(t, \alpha^s) \right)$$

Permeance/mmf model on SCIM:

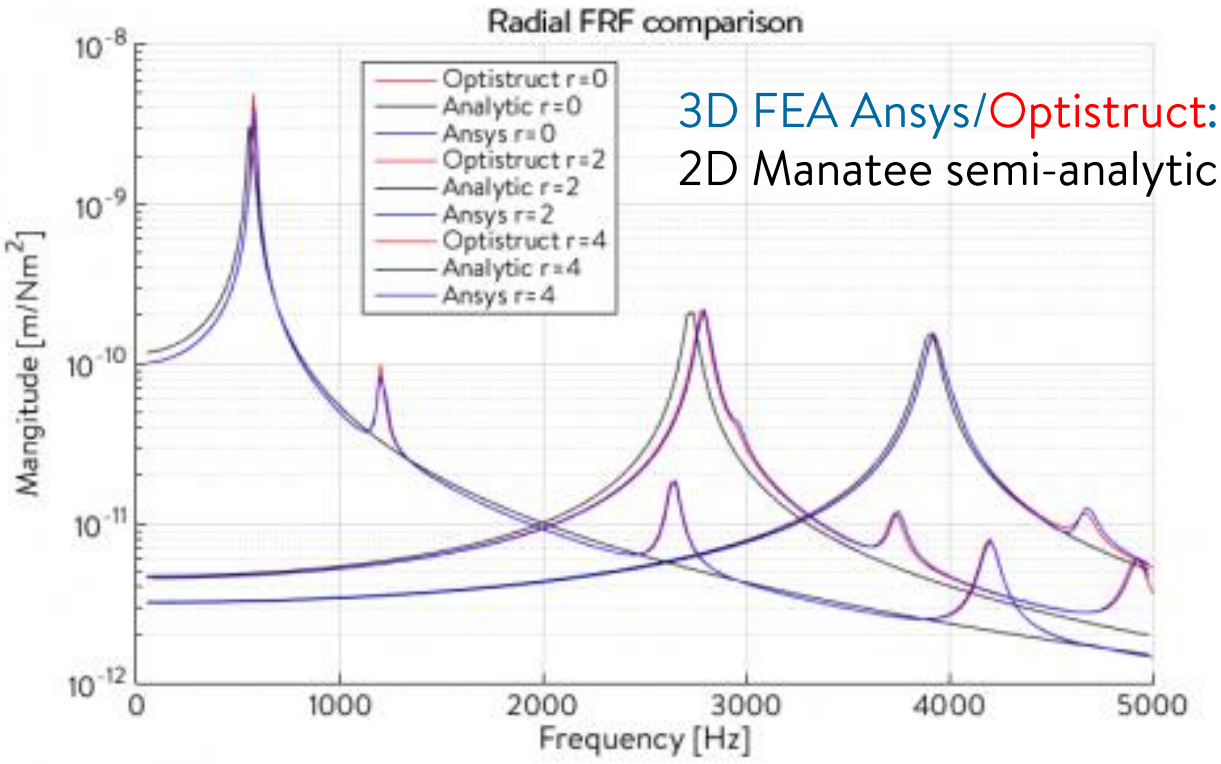


Permeance/mmf model on SPMSM:



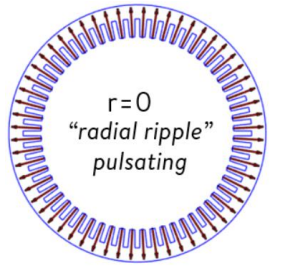
Fast semi-analytic vibro-acoustic model

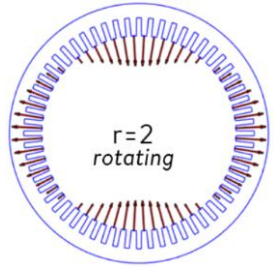
- comparison of Manatee semi-analytic model and Ansys/Optistruct mechanical FEA on EV HEV electric motor under variable frequency Maxwell stress harmonic of wavenumber r=0, 2, 4

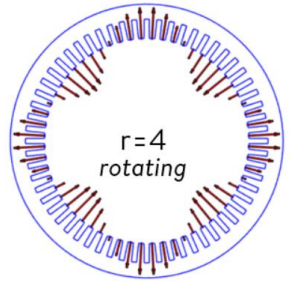


3D FEA Ansys/Optistruct: ~10 mn

2D Manatee semi-analytic: ~1 sec



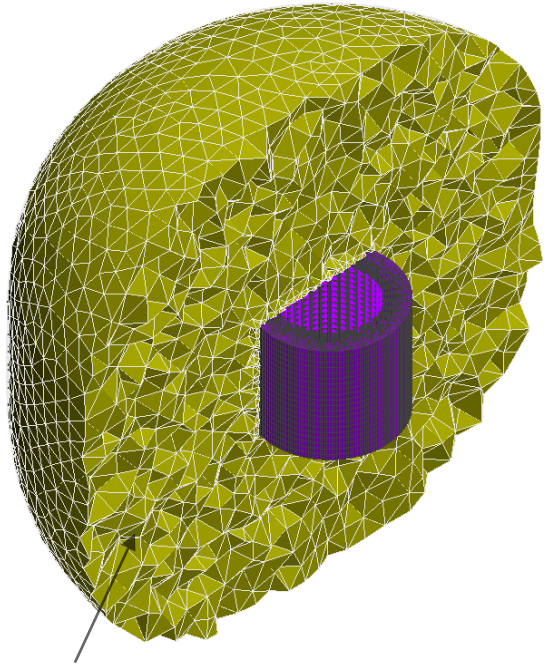




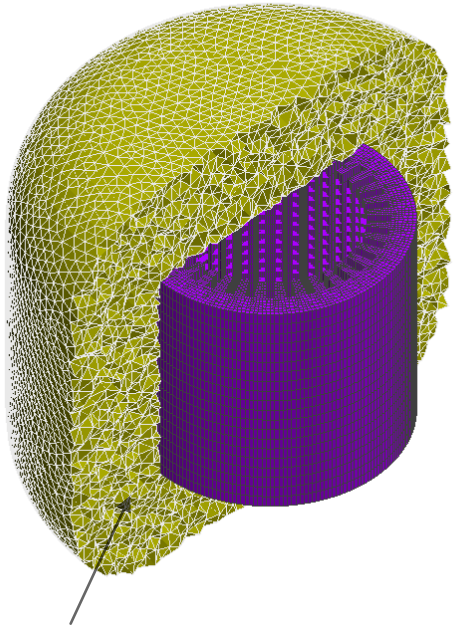
Fast semi-analytic vibro-acoustic model

manatee by EOMYS *joins* SIMULIA

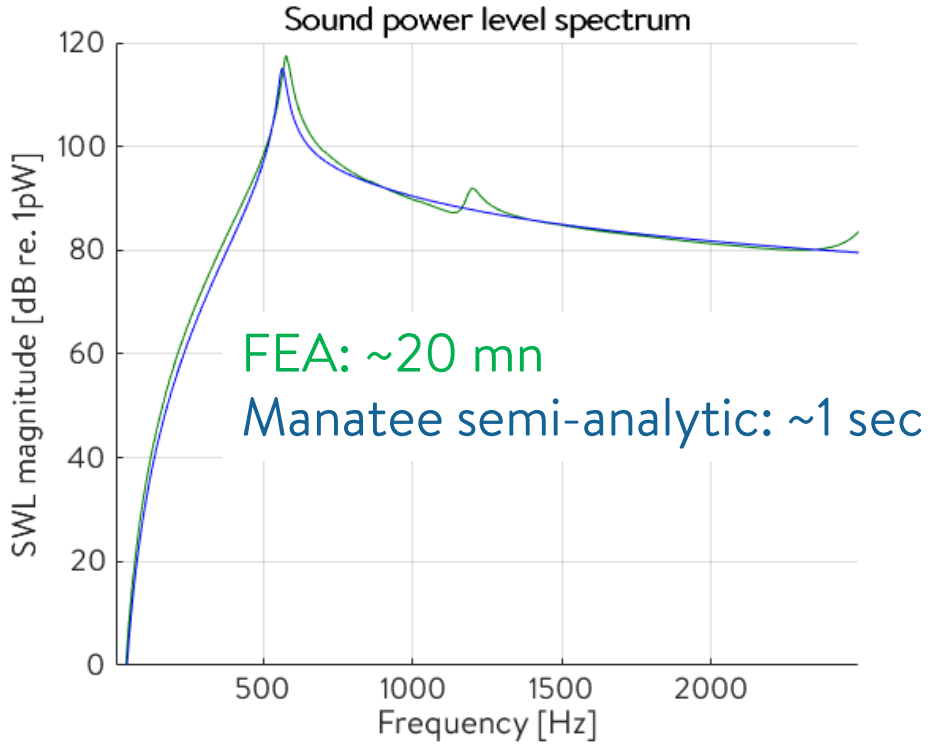
- comparison of Manatee semi-analytic model and 3D FEA on EV HEV e-motor under variable frequency Maxwell stress harmonic of wavenumber r=2



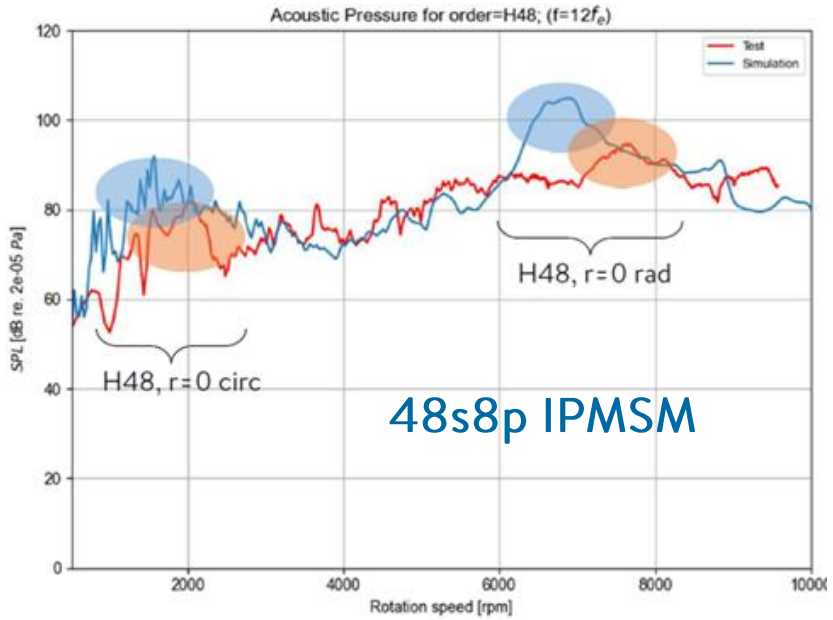
Acoustic mesh at 590Hz



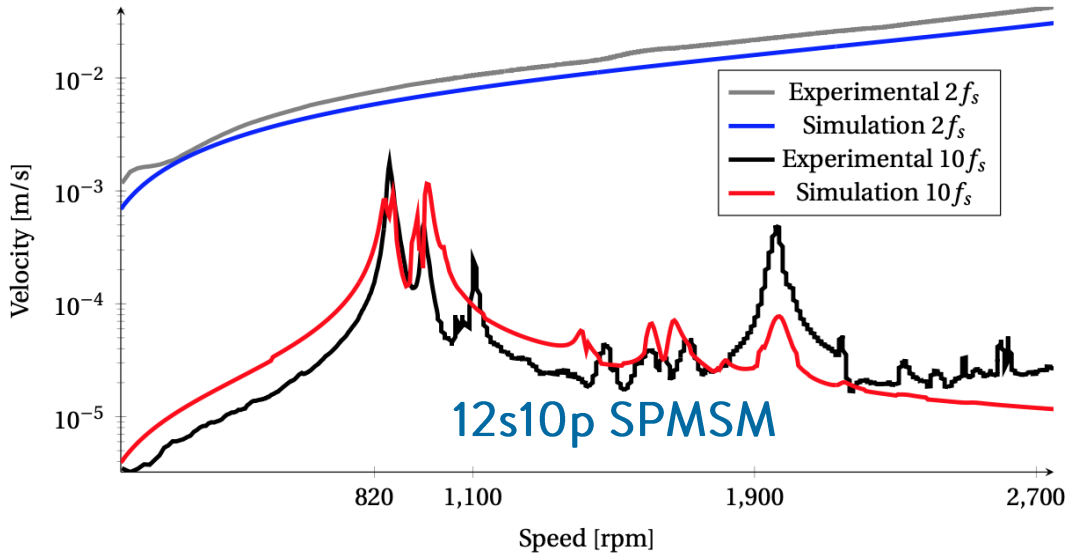
Acoustic mesh at 2116Hz



Manatee validation – intermediate design models of PMSM (automotive)



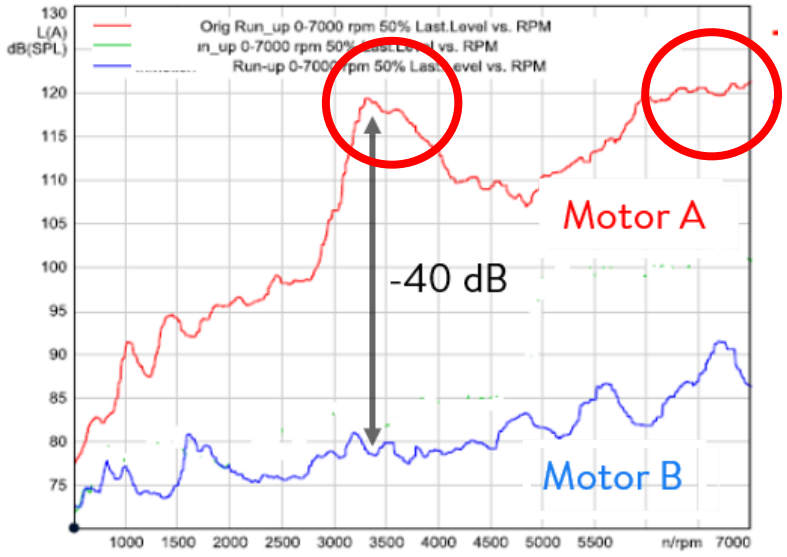
/!\ 3D FEA model not fitted with tests
Damping frozen to 2%
/!\ no 3D FEA acoustics



/!\ 3D FEA model not fitted with tests
Damping frozen to 2%

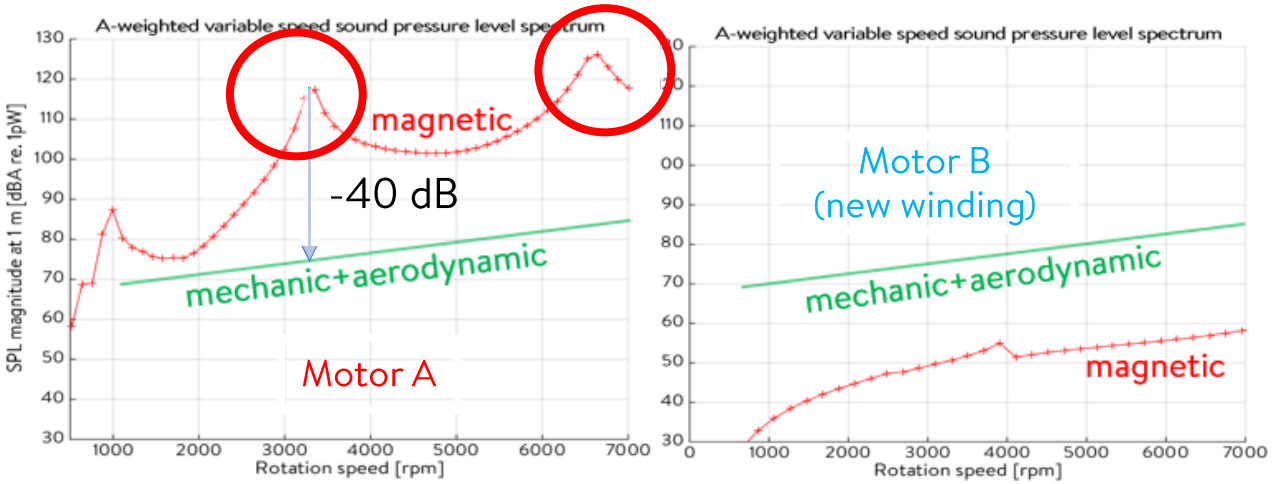
Manatee validation – early design models of PMSM (automotive)

Experimental measurements



Sound level during a run-up (experiments with gearbox+water-cooling+converter harmonics)

Manatee quick e-NVH models

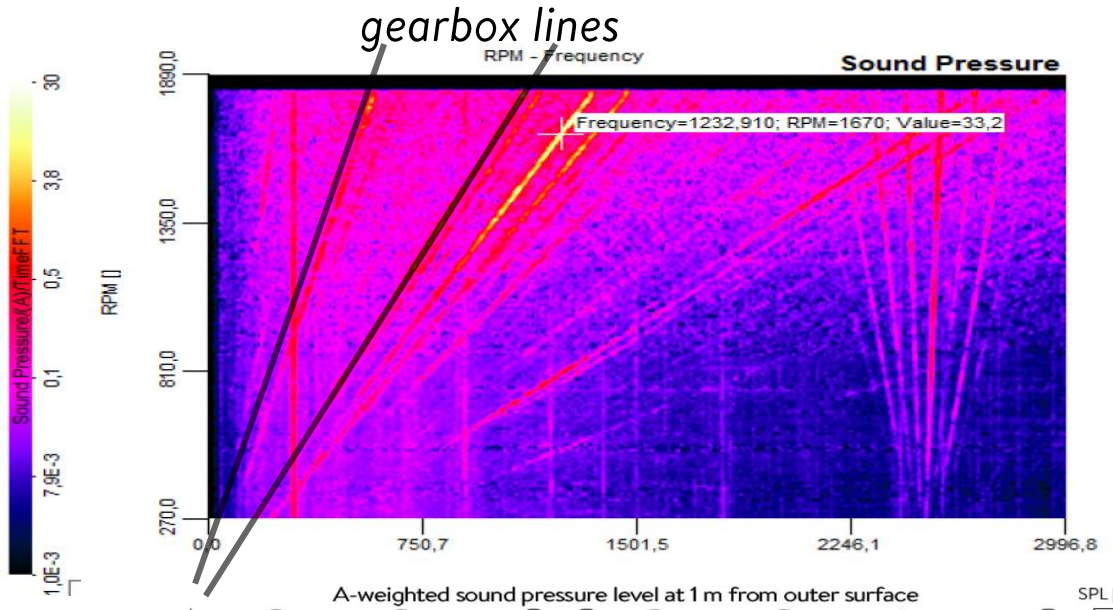


Sound level during a run-up (quick e-NVH model <u>without</u> PWM)
~10 sec on a laptop

Manatee validation – early design models of IM (marine propulsion)

TESTS

Sound level during a run-up (experiments with PWM + gearbox +air-cooling)



Manatee

Sound level during a run-up (quick e-NVH model <u>without</u> PWM)

~10 sec on a laptop