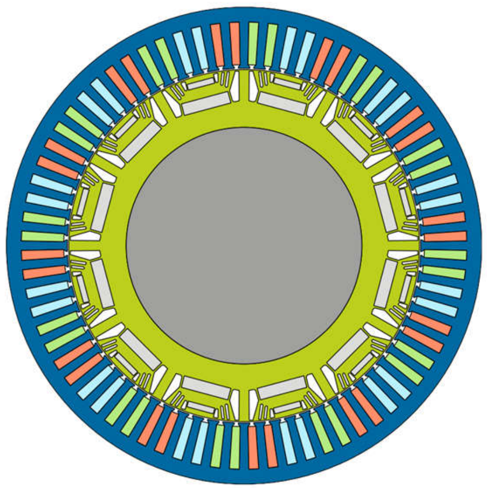
Manatee® e-NVH CAE collaborative platform

Solutions for electrical systems engineering challenges

From e-machine geometry & control parameters…



… to system-level electromagnetic noise and vibrations

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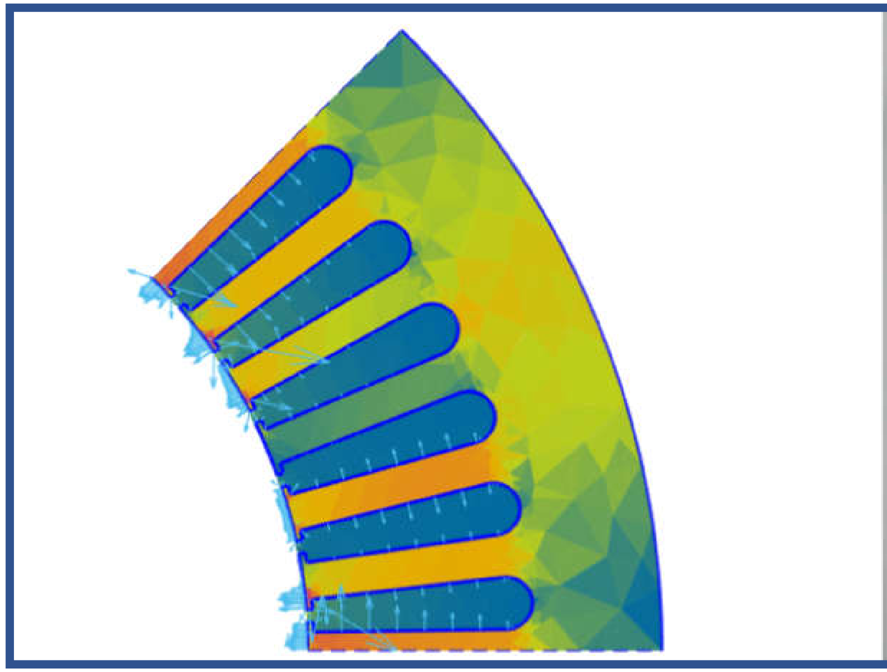
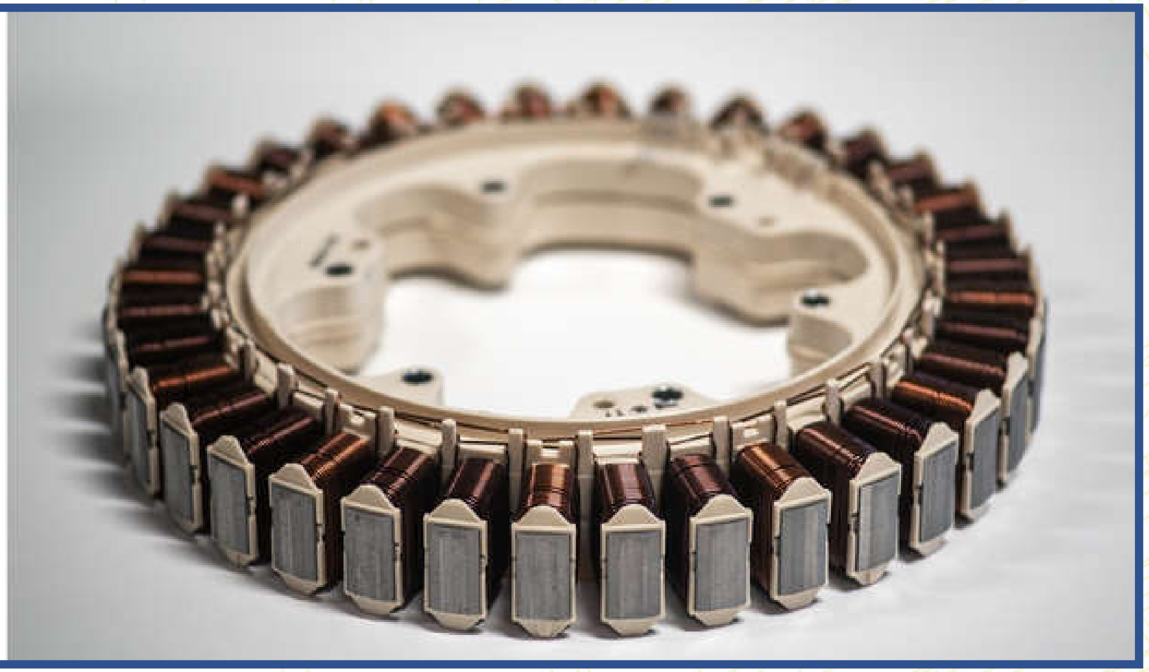
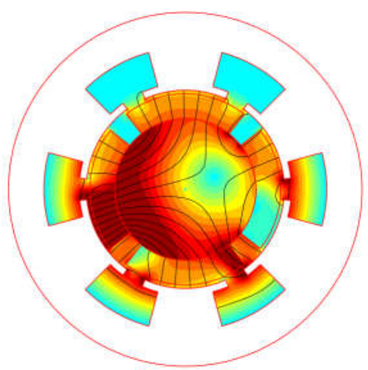
MANATEE FOR ELECTRICAL ENGINEERS





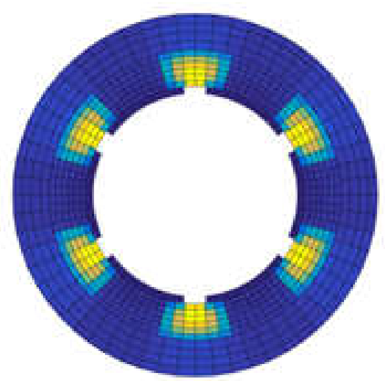
e-NVH challenges for Electrical Engineers

- **+/- 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**



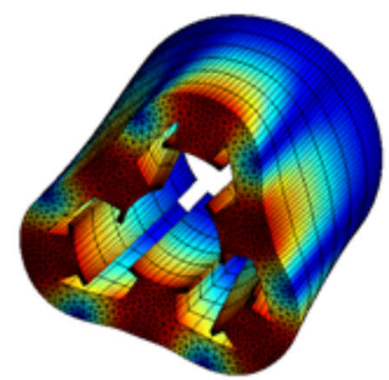
electromagnetics

+



heat transfer

+



vibro-acoustics

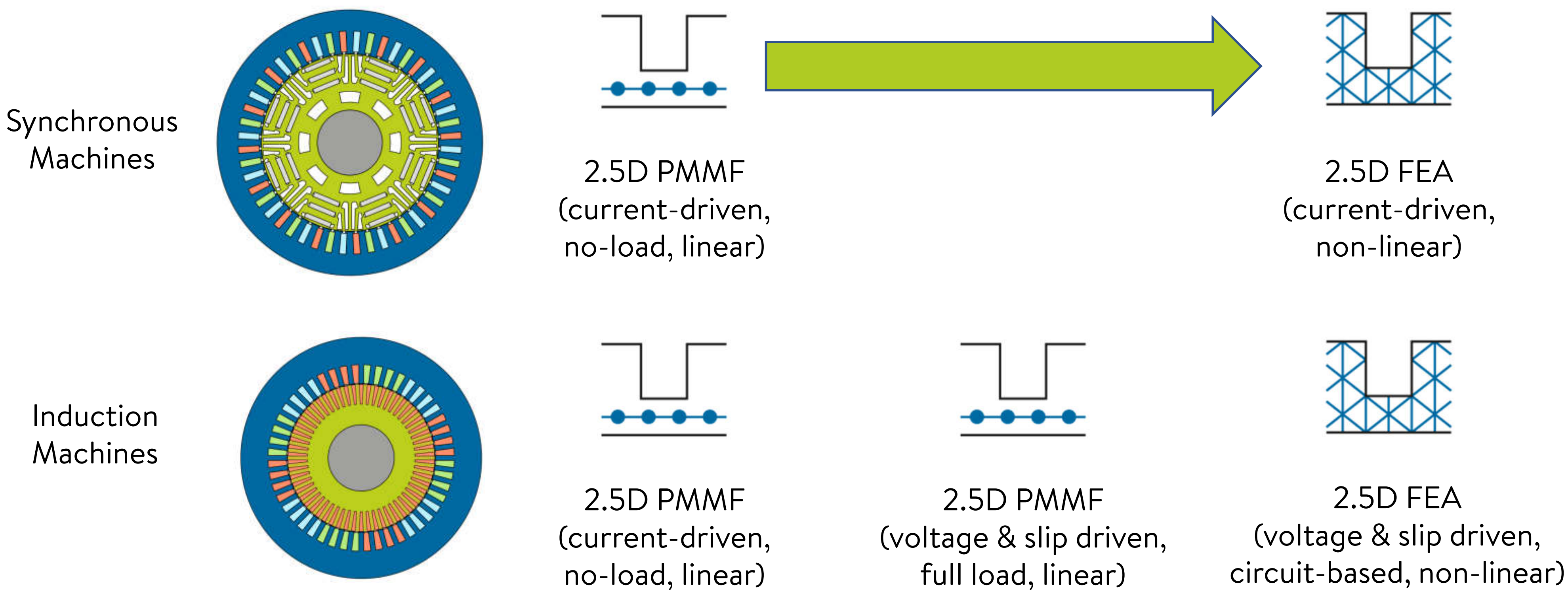
Manatee key features for Electrical Engineers

- 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

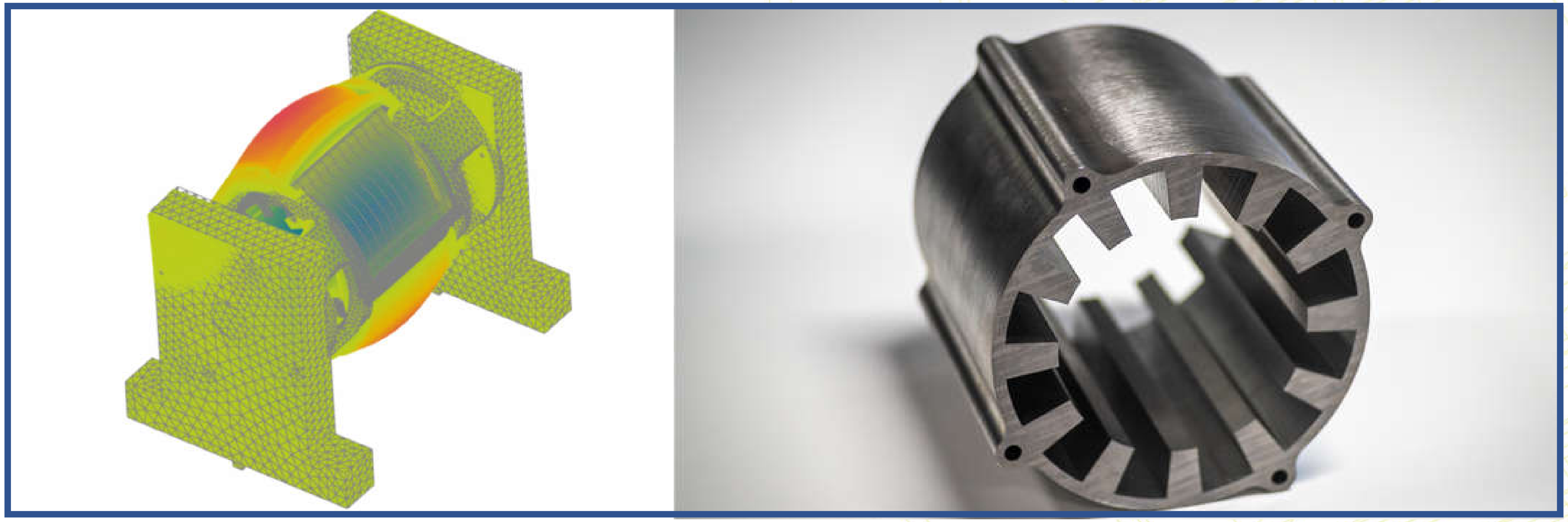
manatee by EOMYS

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

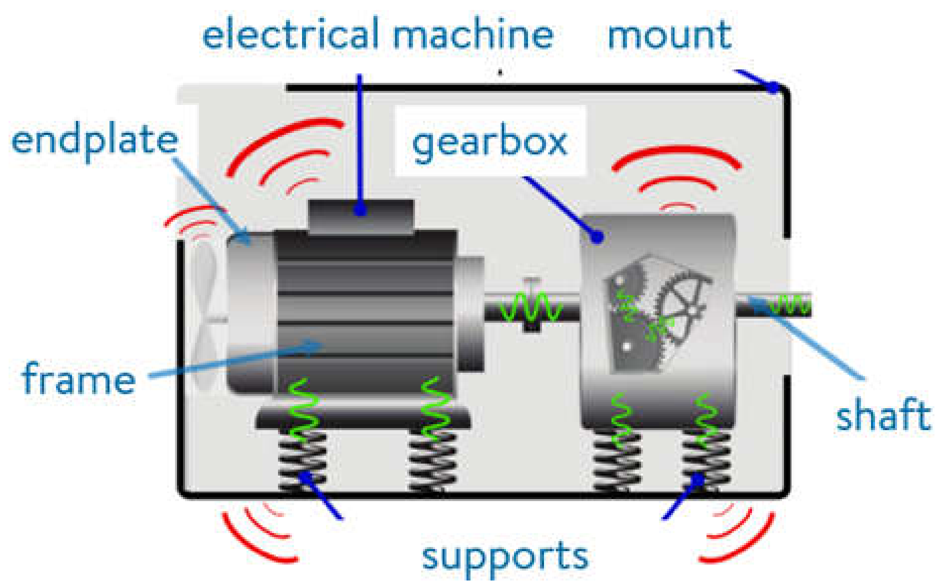


MANATEE FOR MECHANICAL ENGINEERS



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

- 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

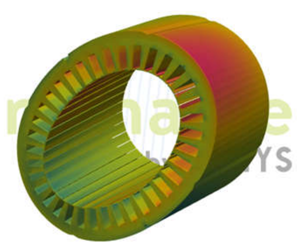
manatee by EOMYS

Mechanical modelling levels at different design stages

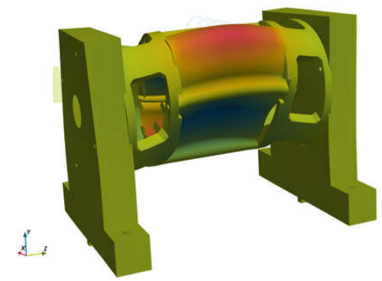
- Mechanical model can be adapted to each stage of the development
- Electromagnetic vibration calculation is extremely fast even when using a 3D FEA model of a full electric drive

2.5D Analytic
stator only

2.5D stator
Beam Element Model



3D FEA
stator only



3D FEA
stator + rotor
+ bearings + housing

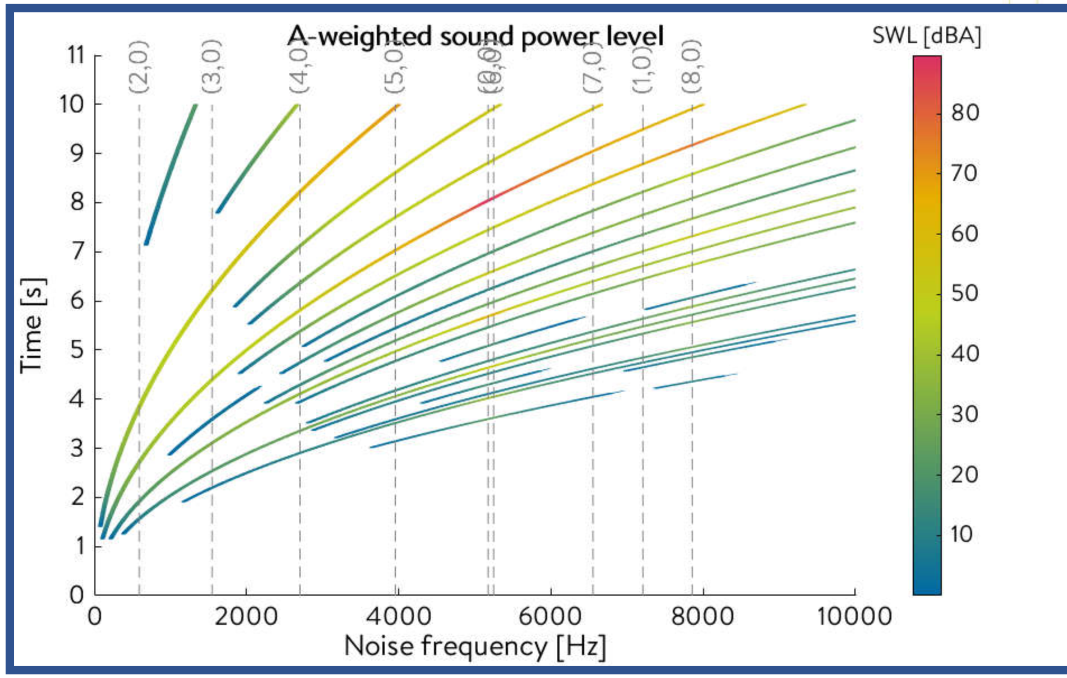
3D FEA
Full Electric Drive Unit

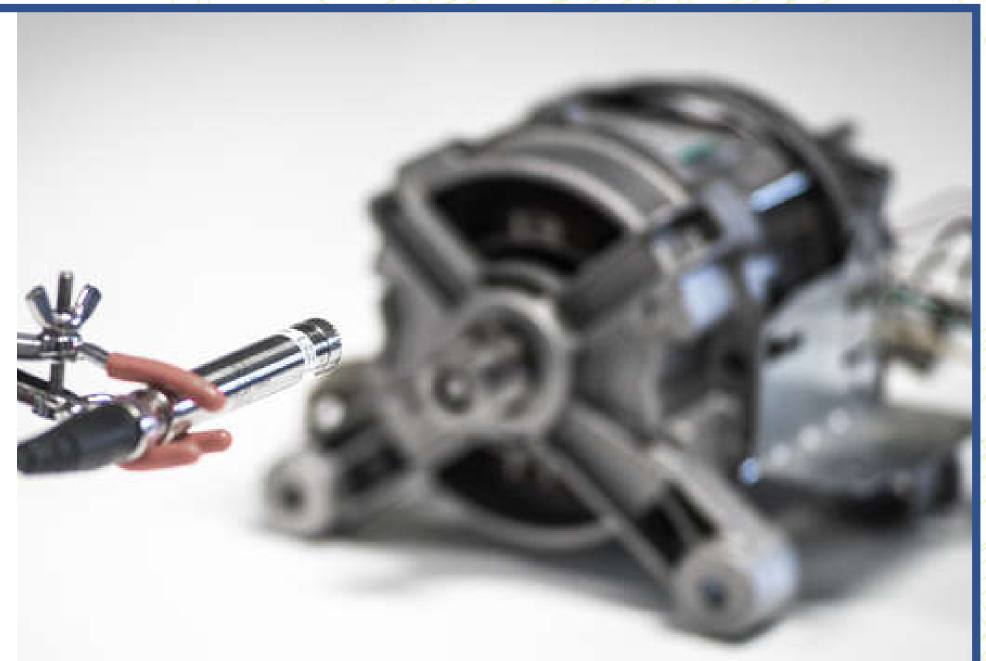
...

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

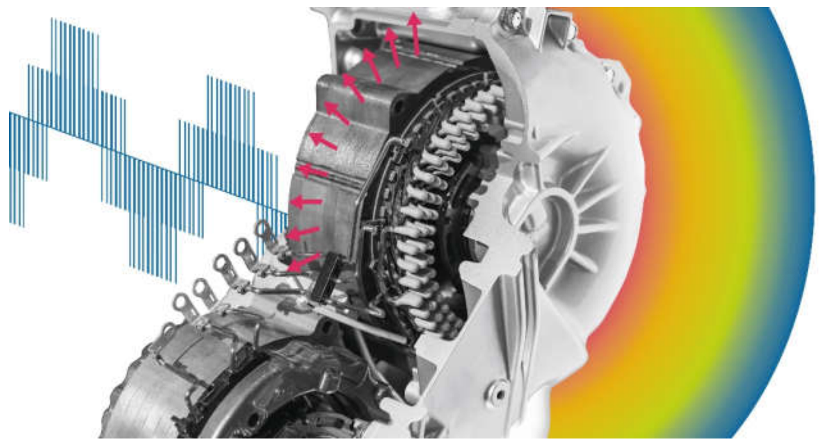
MANATEE FOR ACOUSTIC / NVH ENGINEERS



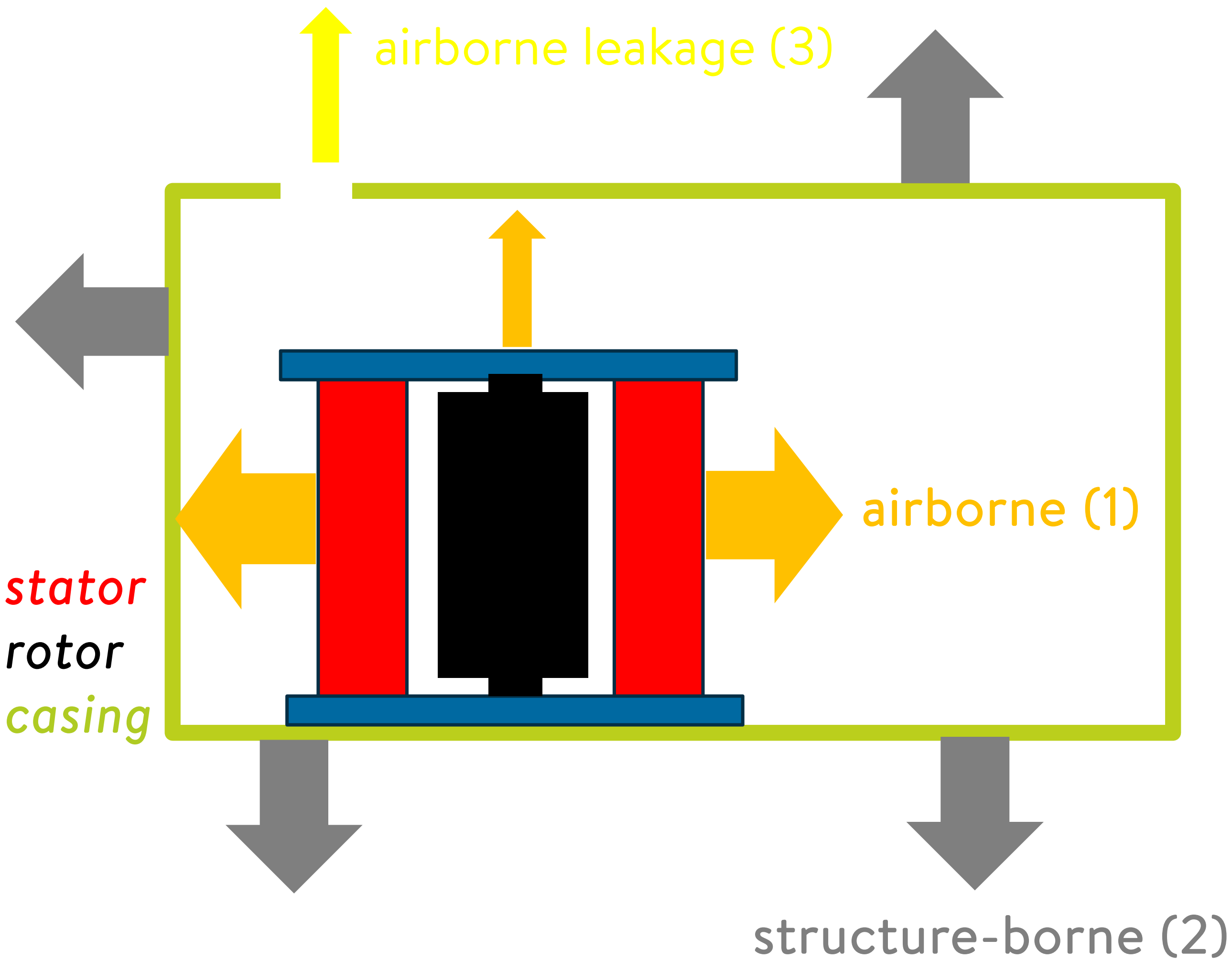


e-NVH challenges for Acoustic / NVH Engineers

- **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

- 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*

manatee by EOMYS

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)

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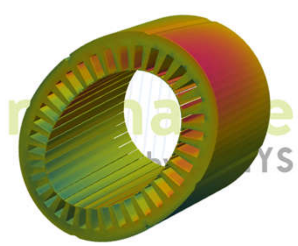
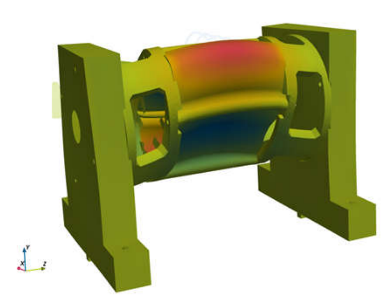
stator only

2.5D stator
Beam Element Model



3D FEA
stator only



3D FEA
stator + rotor, bearing + housing

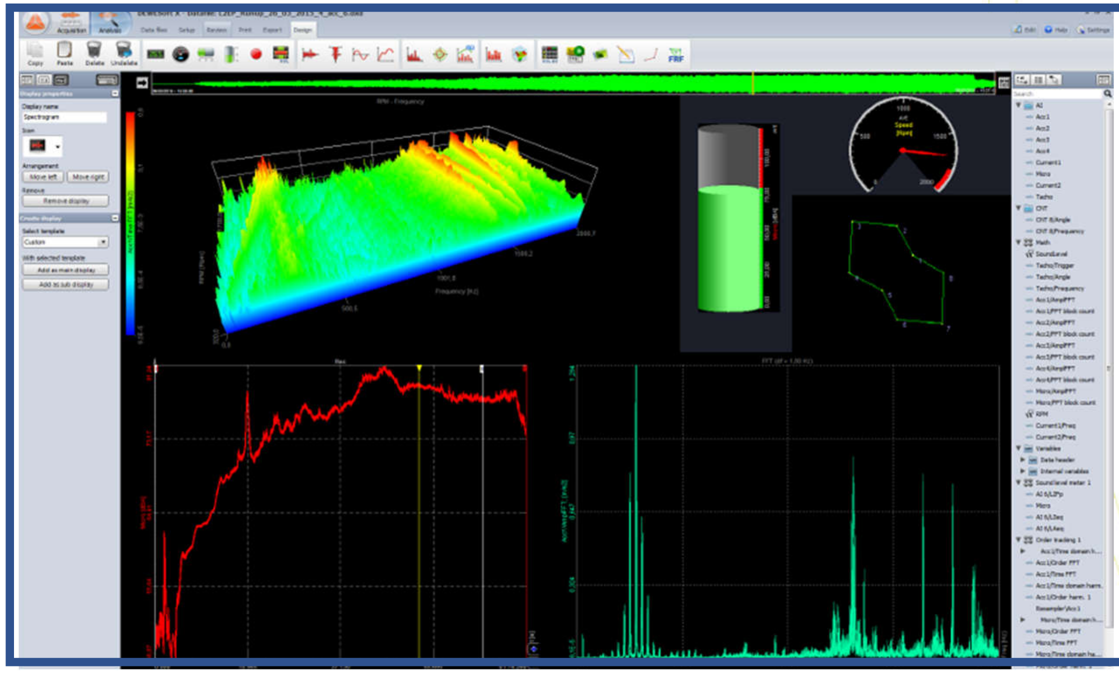
3D FEA
Full Electric Drive Unit

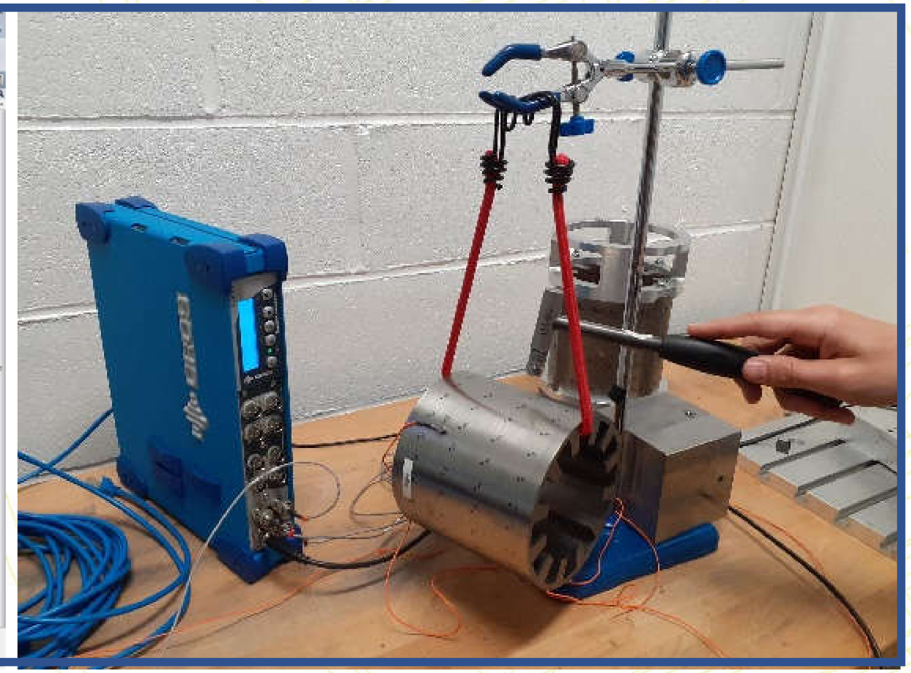
...

Semi-analytic radiation factors
Equivalent monopole for Sound Pressure Level

Equivalent Radiated Power
Equivalent monopole for Sound Pressure Level

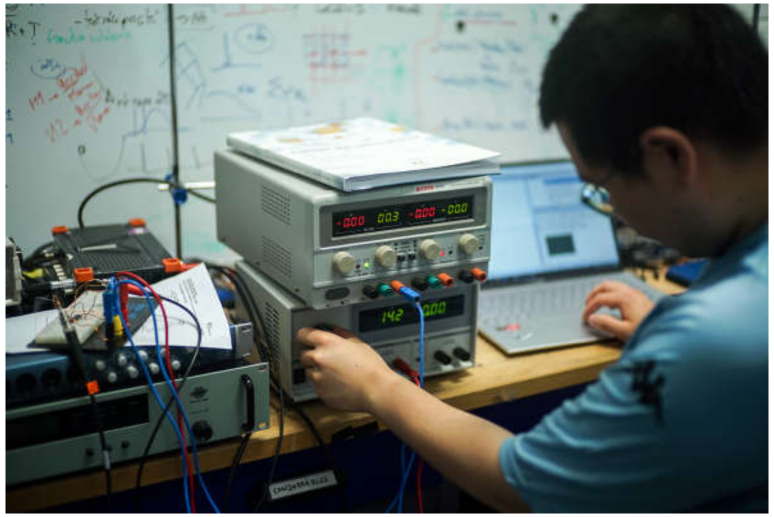
MANATEE FOR NVH TEST ENGINEERS





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)



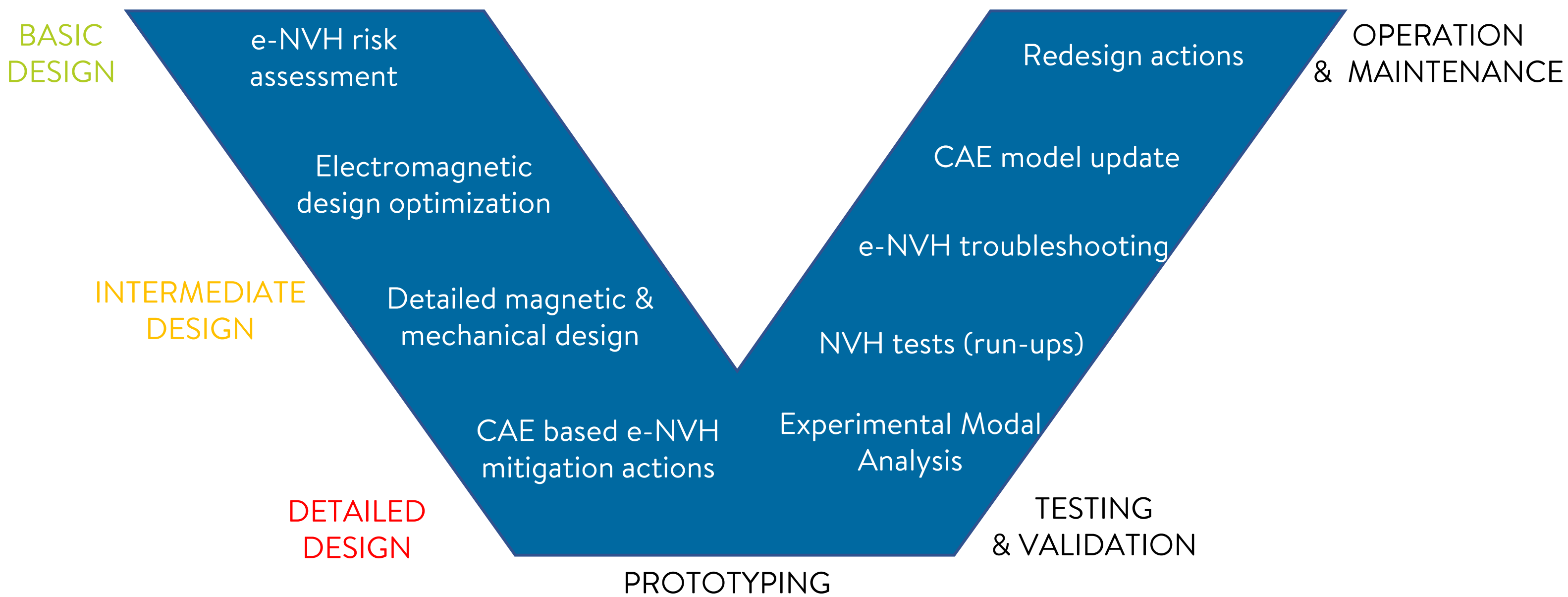
Manatee key features for NVH Test Engineers

- 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

- **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

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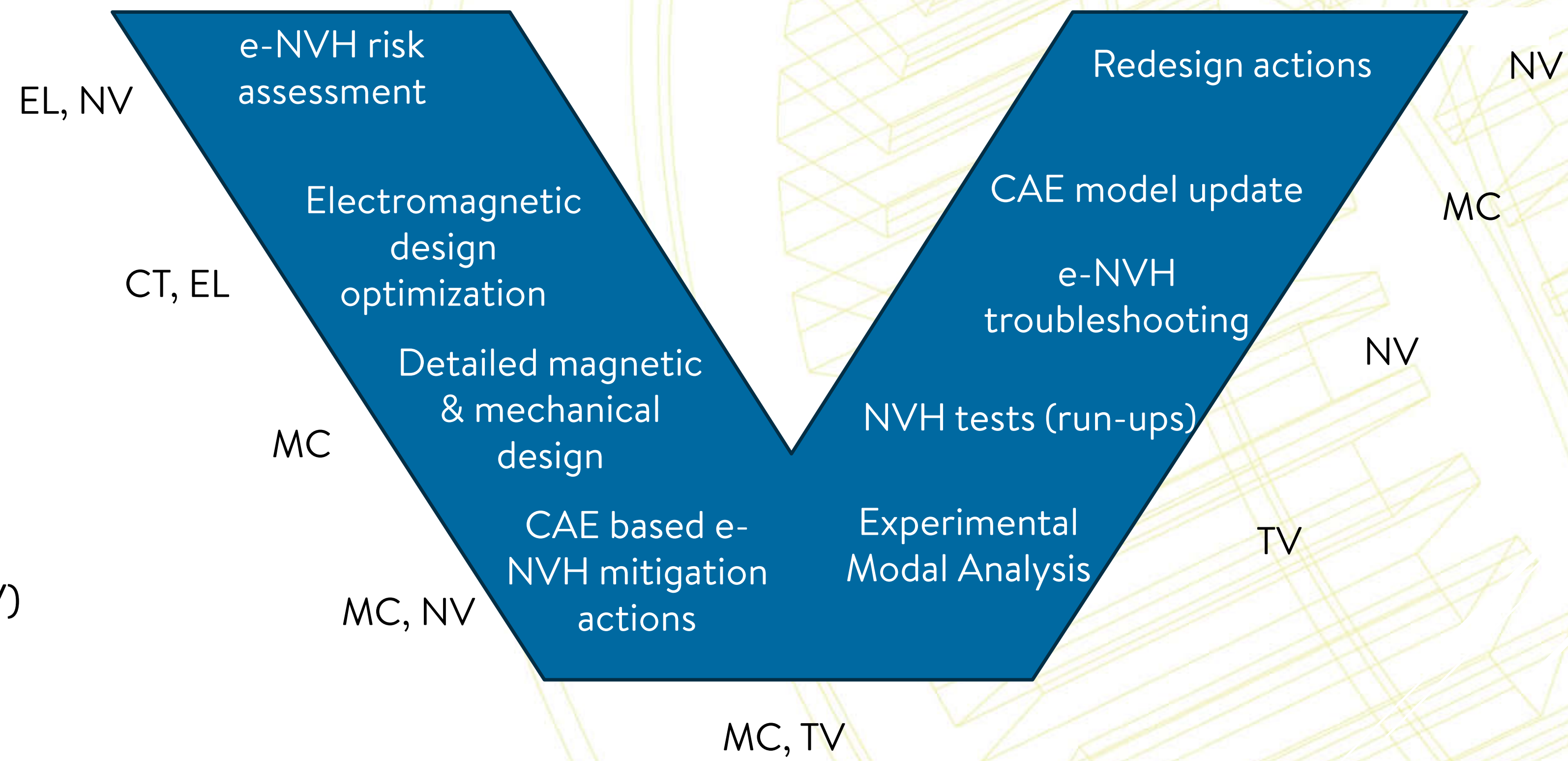
MANATEE WORKFLOW USAGE

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

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

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	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

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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)

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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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[Parameter Sweep]: module of Manatee accessible through icon banner

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

__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

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)

How to troubleshoot & apply noise reduction techniques?

ELECTRICAL ENGINEERS

- **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**

CONTROL ENGINEERS

- **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**

MECHANICAL ENGINEERS

- **Modal force matrix** analysis
- **Parameter sweeps** on mechanical structure (e.g. on yoke thickness)
- **Parameter sweeps** on eccentricities to optimize **mechanical tolerances**
- Shift of a structural mode or stiffening (e.g. adding ribs, change of bearing type) in a third party 3D FEA mechanical model, **update of modal basis** used in Manatee, calculation of **modal force matrix** or re-run of e-NVH calculations using vibration synthesis

NVH ENGINEERS

- **Parameter sweeps** on mechanical s (e.g. on yoke thickness)
- **Parameter sweeps** on eccentricitie optimize **mechanical tolerances**
- Optimization of the **sound quality** i non magnetic noise sources (e.g. im gear whine) Shift of a structural mode or stiffen adding ribs, change of bearing type party 3D FEA mechanical model, **up** **modal basis** used in Manatee, calcu **modal force matrix** or re-run of e- calculations using vibration synthes

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**

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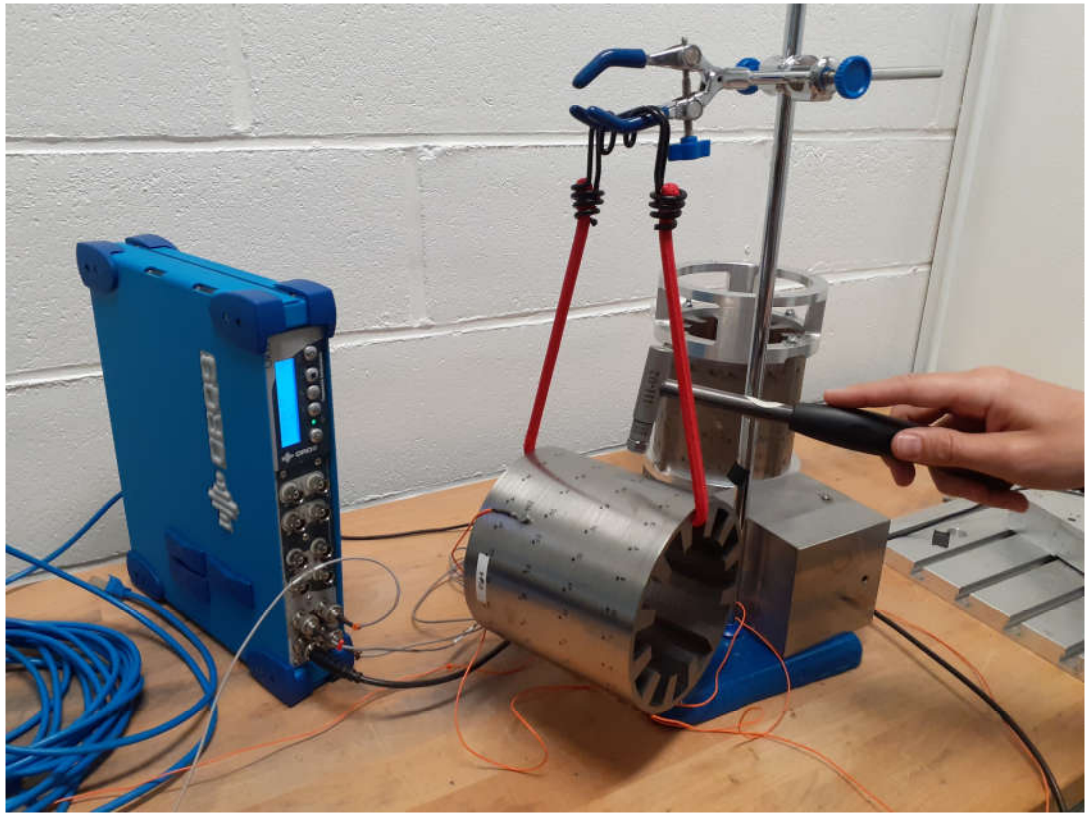
Back-up slides – Manatee software validations

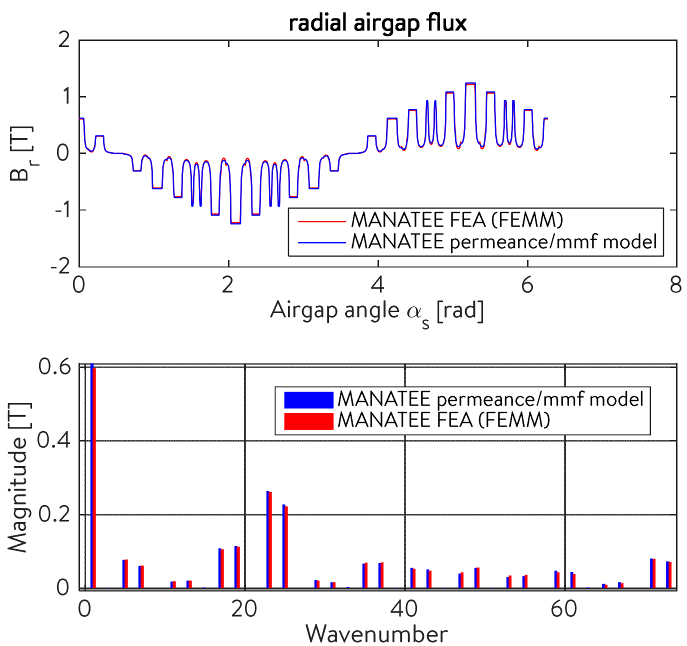


Fast hybrid electromagnetic models

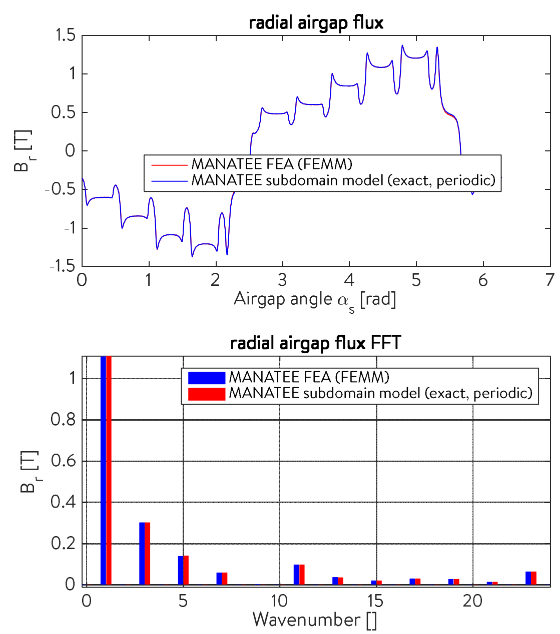
- hybrid magnetic model combines permeance / magnetomotive force model and FEA calculations
- used for induction machines and IPMSM early design phase

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

Permeance/mmf model on SCIM:



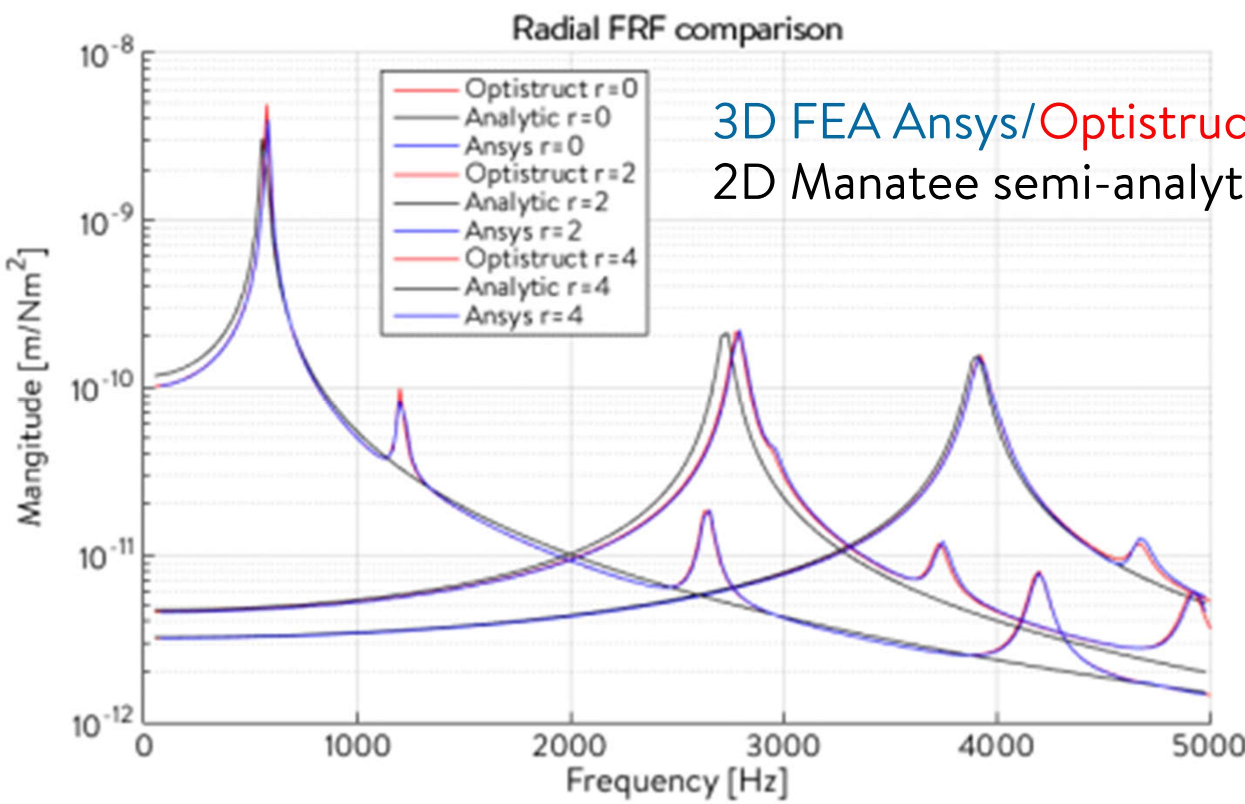
Permeance/mmf model on SPMSM:

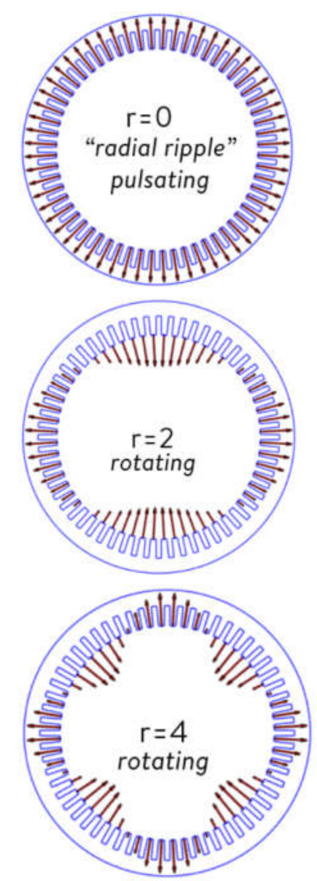


Fast semi-analytic vibro-acoustic model

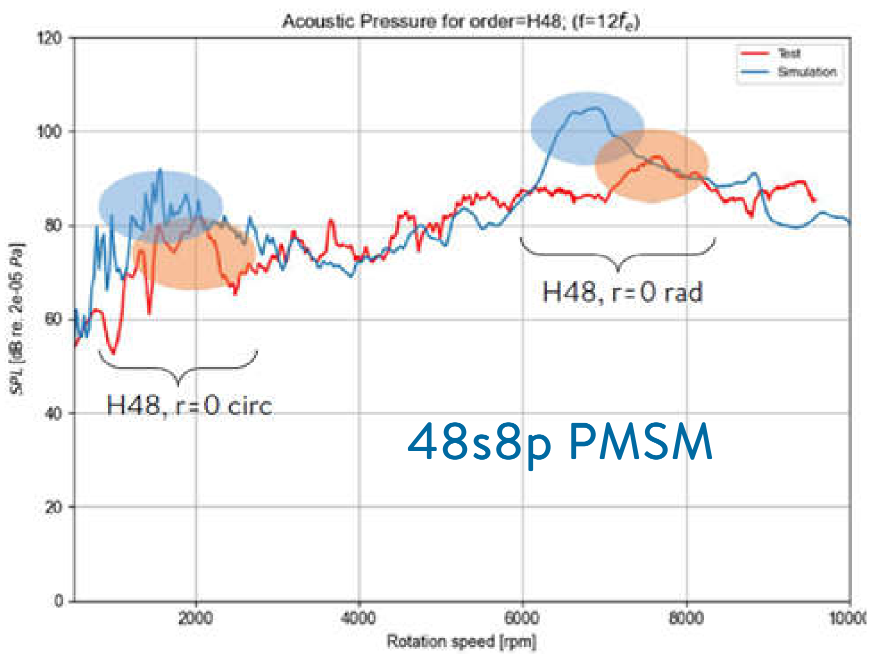
- comparison of Manatee semi-analytic model and Ansys/Optistruct mechanical FEA on EV HEV electric motor under variable frequency Maxwell stress harmonic of <u>wavenumber r=0, 2, 4</u>

3D FEA Ansys/Optistruct: ~10 mn
2D Manatee semi-analytic: ~1 sec

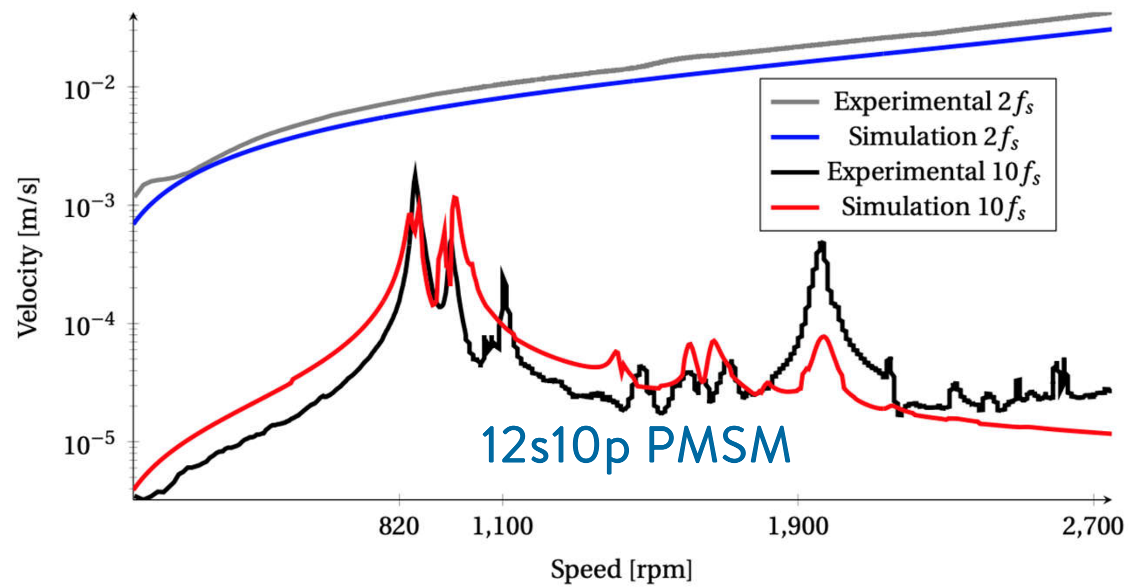




Manatee validation – intermediate design models of PM



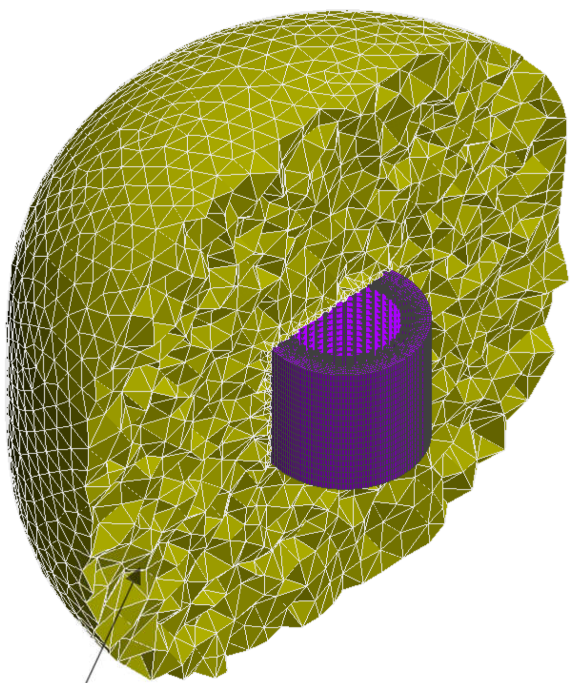
/!\ 3D FEA model not fitted with tests
Damping frozen to 2%
/!\ no 3D FEA acoustics



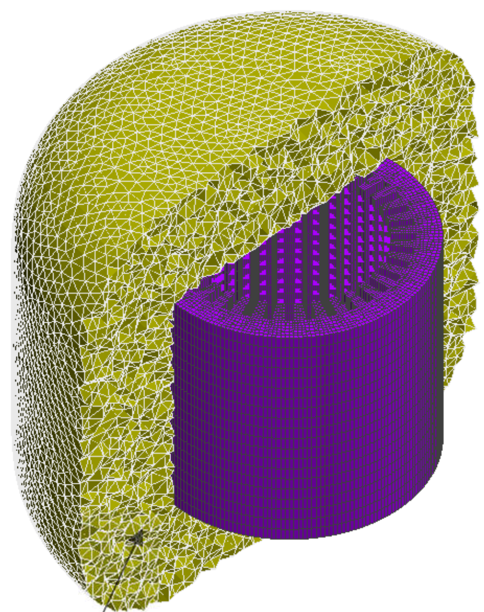
/!\ 3D FEA model not fitted with tests
Damping frozen to 2%

Fast semi-analytic vibro-acoustic model

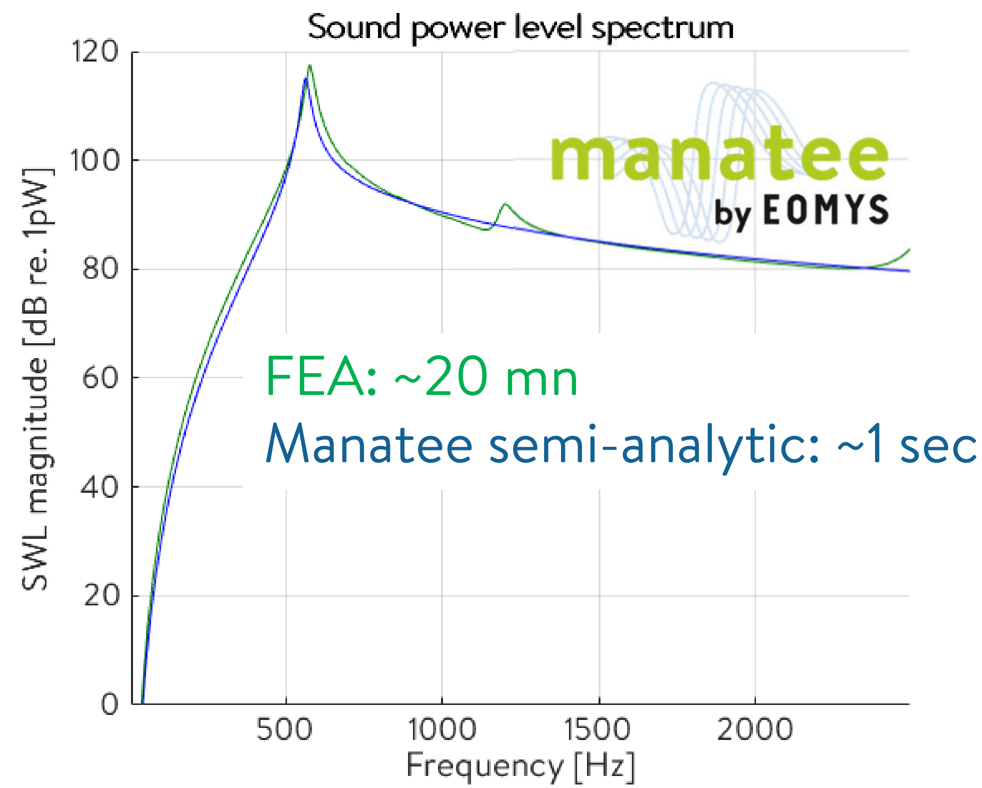
- comparison of Manatee semi-analytic model and 3D FEA on EV HEV e-motor under variable frequency Maxwell stress harmonic of wavenumber r=2



Acoustic mesh
at 590Hz

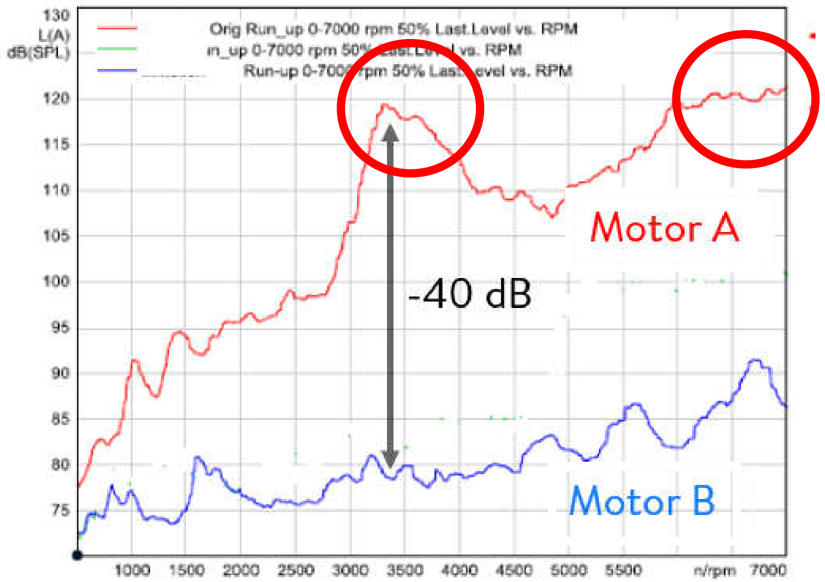


Acoustic mesh
at 2116Hz



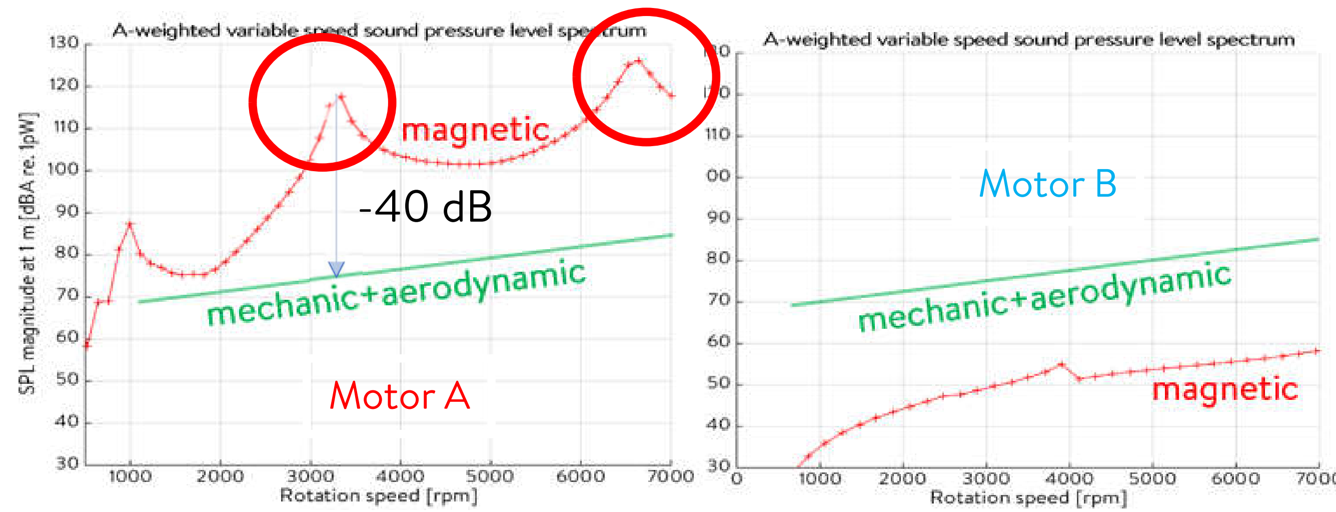
Manatee validation – early design models of PMSM

Experimental measurements



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

Manatee quick e-NVH models



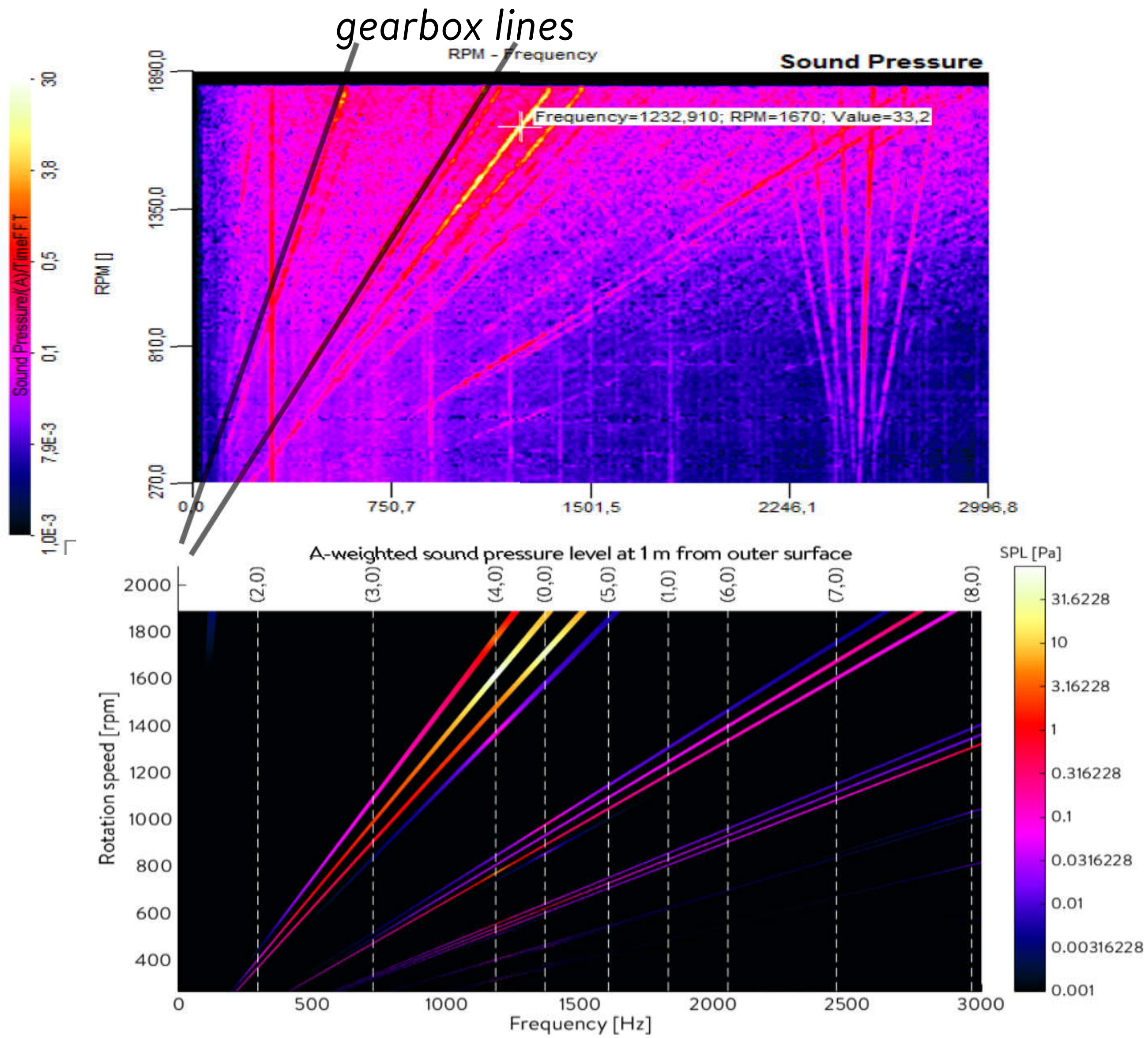
Sound level during a run-up (Manatee simulation without converter harmonics)

~10 sec on a laptop

Manatee validation – early design models of IM

TESTS

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



Manatee

Sound level during a run-up (simulation <u>without</u> PWM)

~10 sec on a laptop