VIBRO-ACOUSTIC SIMULATION OF ELECTRICAL MACHINES
Numerical challenges and application with MANATEE® software

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INTRODUCTION: EOMYS ENGINEERING & e-NVH
Who is EOMYS ENGINEERING?

- **Young Innovative Company** created in 2013 in Lille, North of France
- Engineering consultancy specialized in electrical system NVH (e-NVH)
- 10 engineers (electrical engineering, vibro-acoustics, scientific computing)
- 90% of export turnover in transportation (automotive, railway, marine, aeronautics), energy (wind, hydro), home & medical appliances, industry
- More than 80 customers worldwide and up to 40 dB reduction

*"Jeune Entreprise Innovante": the French government recognises that EOMYS runs significant R&D activities*
What do we call **electromagnetic acoustic noise and vibration** (e-NVH)?

- Noise and vibrations coming from variable electromagnetic forces
- Forces arising from the presence of a variable magnetic field: Maxwell & magnetostriction

1. **Variable current source**  
   - Always present in e-motors  
   - **ex:** Tesla S

2. **Rotating permanent magnets**  
   - Only present in magnet-based motors  
   - **ex:** Nissan Leaf

3. **Rotating DC current source**  
   - Only present in wound rotors  
   - **ex:** Renaut Zoe
What do we call electromagnetic acoustic noise and vibration (e-NVH)?

Interior Permanent Magnet Synchronous Machine (IPMSM)
- rotor shaft
- magnet (pole)
- stator yoke
- stator tooth
- stator slot
- stator outer diameter
- stator inner diameter / bore diameter
- airgap
What do we call electromagnetic acoustic noise and vibration (e-NVH)?

E-powertrain overall noise = Mechanical noise + Aerodynamic noise + Slot/pole interaction electromagnetic noise + Pulse Width Modulation electromagnetic noise

Strong harmonic/tonal nature of pole/slot effects + roughness of PWM effects
How electromagnetic noise is generated?

- Magnetic forces excite both stator and rotor, resulting in airborne and structure-borne noise
- Resonance occurs when magnetic forces frequency + shape match with a natural frequency + modal shape
How electromagnetic noise is generated?

- It is therefore important to identify magnetic force wavenumbers \( r \) and frequency \( f \) as well as to identify modal shapes, and vibro-acoustic transfer path.
What is so special about e-NVH?

- Depends on e-motor topology, load state, fault state and control strategy
- e-NVH problem solving requires skills in both electrical engineering & NVH
- e-NVH transfer path can be complex (structure-borne + air-borne, 3D excitations)
- e-NHV numerical simulation is very challenging (multiphysics + variable speed, high frequency effects)
EOMYS e-NVH services

A. Troubleshooting and solving of NVH issues on electrical systems

B. NVH design optimization of electrical systems

C. Technical trainings on vibroacoustics of electrical systems

D. MANATEE software leasing including e-NVH support
e-NVH SIMULATION CHALLENGES
e-NVH NUMERICAL CHALLENGES

- **Mutiphysics + high frequency (PWM) + variable speed** - high CPU time
- Maxwell tensor approach is very sensitive to airgap mesh, numerical noise appears especially in 3D electromagnetic FEA ("remeshing ripple")
- **Spurious inter harmonics** may appear in sound spectrum (continuous sound spectrum Vs discrete excitation) due to force spectrum leakage and acoustic solver interpolations
- Any parasitic force harmonic can be amplified by structural dynamics leading to unphysical results
e-NVH NUMERICAL CHALLENGES

- To avoid “mesh ripple”, some FEA software freeze the airgap discretization and synchronize rotor rotation with the mesh ("blocked step technique" or "rotating mesh")

- For a fixed number of timesteps the maximum frequency increases with speed
  \( \Rightarrow \) mesh fineness tends to infinity to catch high frequency effects at low rotation speed \( f_R \)

- High frequency, low speed noise & vibration are wrongly estimated (e.g. resonances, or PWM)
APPLICATION WITH MANATEE SOFTWARE
MANATEE® SIMULATION SOFTWARE
Magnetic Acoustic Noise Analysis Tool for Electrical Engineering
WHY ANOTHER SOFTWARE?

- e-NVH numerical challenges are not solved by “multiphysics software suites” (Ansys Workbench, Comsol Multiphysics, Altair Program, Simulia etc)

- General purpose multiphysics software take a long time to be set-up for a particular problem

- Once the computation is finished, you don’t know much about why your motor is noisy, and you need to implement your own post processing, diagnosis tools and noise minimization methods

- Vibroacoustic level is highly determined in early design phase where fast models are needed -> no time to iterate on a multiphysic numerical model

Ex: effect of rotor slot number Zr in a SCIM
MANATEE simulation software can be used for the electromagnetic design optimization of electrical machines including the analysis of magnetic vibrations and acoustic noise due to Maxwell forces (“e-NVH”).

MANATEE unique features include:

- fast electromagnetic Noise Vibration Harshness (e-NVH) calculation in early electromagnetic design loops
- optimized e-NVH calculation in detailed design phase (coupling with structural FEA) over full operating range
- advanced post-processing for e-NVH root cause analysis
- design optimization environments of e-motor noise mitigation technique
OVERVIEW OF MANATEE SOFTWARE

MANATEE is the central point for the integrated Noise, Vibration, Harshness design process of electric powertrains (e-NVH), from basic vibro-acoustic design at e-motor level to detailed vibro-acoustic design at system level:

Third-party electromagnetic design tools

Third-party structural design tools

Third-party gearbox NVH design tools

Third-party sound quality tools

Standalone e-motor NVH solution (electromagnetics + vibro-acoustics)

Third-party NVH data acquisition tools

© Masta
© Actran
© Oros
© Jmag
© Ansys

v1.08 coupling
v1.09 coupling
MANATEE programming environment

- MANATEE solver is currently under Matlab® (R2009b or later), but does not use any Matlab toolbox
- MANATEE GUI is in Python/Qt to define the machine and simulation parameters Python
- MANATEE v2.0 will be based on PYLEECAN open-source library under Python
- PYLEECAN currently include a unified object-oriented modelling of e-machines & drives coupled to FEMM

www.pyleecan.org
MANATEE graphical environment

Scripting environment (Matlab)

GUI for simulation set-up (PyQt)

Command line post-processings (Matlab)

GUI for machine set-up (PyQt from PYLEECAN)
MANATEE demonstration: electrical machine definition

MANATEE Machine Setup - Machine Type

1. Machine Type
2. Machine Dimensions
3. Stator Lamination
4. Stator Slot
5. Stator Winding Pattern
6. Stator Winding Parameters
7. Stator Winding Conductors
8. Stator Endwinding
9. Rotor Lamination
10. Rotor Slot

Machine type: IPMSM

IPMSM (Interior Permanent Magnet Synchronous Machine) is selected with
is_innerRotor
Machine name: machine_IPMSM_A
p: 4

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MANATEE demonstration: electrical machine definition

• MANATEE built-in fast electromagnetic models are based on geometrical layouts (cf. EOMYS website)

• The following radial flux electrical machine topologies are included in MANATEE v1.08:
MANATEE software seamlessly integrates the following multiphysic modules:

- Interface between physics (e.g. mesh to mesh projections) are automatically defined
- All module inputs can be user-defined / imported if necessary, resulting in a flexible simulation workflow
- Module interface are documented for possible integration in third-party scripts
MANATEE demonstration 1: fast noise synthesis of an IPMSM (*project AC_IPMSM_03*)

- Sinusoidal currents $I_d/I_q$ curves imposed as a function of speed
- Hybrid subdomain electromagnetic models [R1]
- Cylindrical shell vibroacoustic models
- All electrical, magnetic, structural and acoustic models can be changed for different accuracy / computing time tradeoffs
MANATEE demonstration 2: Toyota Prius 2004 case

- **Objectives:** quickly identify motor whine potential issues using MANATEE software
- [R2] is based on Ansys workbench simulation, requiring several hours of simulation although acoustic noise is not calculated
- **Conclusions of [R2]:** potential resonances between H48 (48 times mechanical frequency) and H96 and breathing mode of the stack close to 3000 and 6000 rpm at open circuit; H24 appears at partial load but does not create significant resonance
MANATEE demonstration 2: open-circuit case (*project tuto_IPMSM_01*)

Ansys-based results from [R2] are found within a few seconds of calculation.

Order Tracking analysis of 10 largest orders
Ansys-based results from [R2] are found within a few seconds of calculation.

The breathing mode of the stack is driving noise radiation as in most EV/HEV [R3]

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Electromagnetic Vibration Synthesis (EVS): faster than a direct coupling, more physical insights

- **ELECTROMAGNETIC MODEL**
  - 2D or 3D external FEA software (e.g., Flux, Jmag, Maxwell, Magnet)
  - MANATEE 2,5D electromagnetic models (SDM, PMMF, FEMM)

- **HARMONIC FORCE PROJECTION**
  - Tangential and radial harmonic magnetic forces (magnitude, wavenumber, frequency, phase)
  - r=0, r=2, r=3

- **ELECTROMAGNETIC VIBRATION SYNTHESIS**
  - Complex FRFs (radial & tangential) for each force wavenumber r

- **STRUCTURAL MODEL**
  - 3D external FEA software (e.g., Optistruct, Ansys, Nastran/Actran)
  - MANATEE 2,5D structural models

- **STRUCTURAL FREQUENCY RESPONSE FUNCTIONS**
  - r=0, r=2

NUMERICAL TRANSFER PATH ANALYSIS (NTPA):
- Rotor Vs stator, radial Vs tangential, pulsating / UMP / rotating forces
- Modal contribution to noise & vibrations

- **CALCULATION OF OPERATIONAL LOADS**
  - 2D or 3D external FEA software 
  - MANATEE 2,5D electromagnetic models

- **STRUCTURAL CHARACTERIZATION**
  - Numerical Transfer Path Analysis (NTPA):
  - Modal contribution to noise & vibrations
Possibility to calculate FRF using an existing FEA model or building automatically a concept stator (orthotropic, winding mass, ideal boundary conditions):

Automatic set-up of Prius concept stator under Ansys
Conclusions

• Virtual prototyping of e-machine vibroacoustic behaviour in early and detailed design phases raises complex numerical challenges

• MANATEE is the only high-end e-NVH simulation software proposing solutions to these challenges

• MANATEE can be used at design stage or after manufacturing as an efficient e-NVH issue troubleshooting tool

• Leasing license includes a e-NVH support package and clustering options

• Regular e-NVH training sessions are organized EOMYS office in Lille (1 hour from Paris, France):
  - e-NVH training: 10-12 Sept 2019
  - MANATEE software training: 13 Sept 2019

• Training registration can be done at www.eomys-registration.com
Conclusions

• Any help is welcome on our open-source project for the electromagnetic simulation of electrical machines under Python, PYLEECAN -> see www.pyleecan.org

• EOMYS is looking for PhD Engineers in Electrical Engineering and Master’s students
  -> send us your spontaneous application at contact@eomys.com
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REFERENCES

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[R1] E. Devillers, J. Le Besnerais, "Fast calculation of the airgap flux density distribution based on subdomain and permeance magnetomotive force models of electrical machines", ISEF 2019
