Noise & vibrations due to magnetic forces in electrical machines

Root cause analysis and mitigation using MANATEE software

The webinar will start soon. Please check your audio/video settings (mute your microphone and do not activate your webcam) and use “Call Using Computer” option:

For technical issues and for the Q/A part of the webinar you can contact Pierre Bonneel by chat. Questions will be reviewed in the last part of the webinar. A link to the full recording of the webinar will be available at the end, including audio & video files.
Noise & vibrations due to magnetic forces in electrical machines

Root cause analysis and mitigation using MANATEE software

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EOMYS ENGINEERING

- Innovative company created in may 2013 in Lille, North of France
- Activities: **applied research in electrical engineering**
- Multidisciplinary team of R&D Engineers (electrical engineering, vibro-acoustics, heat transfer, scientific computing)
- Expertise on NVH due to magnetic forces in electrical systems
- EOMYS R&D services:
  
  *Modeling, simulation & optimization*

  *Multiphysic field measurements*

  *Technical trainings*
Part I - Magnetic noise and vibrations phenomena
Acoustic noise sources in electrical machines

Noise of an electric traction machine during starting:

- **Mechanical sources** (e.g. bearings, gearbox)
- **Aerodynamic sources** (e.g. fans)
- **Electromagnetic sources** (e.g. magnets)

- Electromagnetic acoustic noise is characterized by strong tonalities
- Depending on applications it can be at low frequency (« humming noise »), or at high frequency (« whining noise »)
Acoustic noise sources in electrical machines

What do we call *electromagnetic acoustic noise and vibration*?

- Noise and vibrations arising from variable electromagnetic forces
- Forces arising from the presence of a variable magnetic field: Maxwell & magnetostriction
- Variable current source
- Rotating permanent magnet or DC current source
• Magnetic field is “guided” by the iron of the tuning fork, creating an equivalent magnetic dipole at the fork tips

• **Maxwell force** is the magnetic attraction between the equivalent North and South poles, similarly to what happens between the opposite polarities of two magnets

• The airgap tends to be reduced by Maxwell forces
1D illustration of noise and vibration due to Maxwell forces

Forced excitation (AC current with fixed frequency)  
https://youtu.be/y9JyYLBRGnk

• Strong tonal noise is created without any mechanical contact between coil and tuning fork
1D illustration of noise and vibration due to Maxwell forces

Resonant excitation (AC current with variable frequency $f_s$)  

$\bullet$ A resonance (high noise level) is observed when feeding the coil at 200 Hz

$f_s = 200$ Hz

https://youtu.be/D5HqdXdm8Ws
What happens at resonance for $f_s=200$ Hz?

\[
I[A] \rightarrow B[T] \propto I \rightarrow P\left[\frac{N}{m^2}\right] \propto B^2 \rightarrow V\left[\frac{m}{s}\right] \propto P \rightarrow L_p[dB] \propto 20\log_{10}(V)
\]

- The tuning fork natural frequency is close to 400 Hz (first bending mode).
- The match between exciting magnetic forces and tuning fork natural frequency create a resonance (high vibration level).
- Tuning fork behaves like a linear quadrupole and radiates acoustic noise at vibration frequency of 400 Hz.
2D illustration of noise and vibration due to Maxwell forces

Airgap reluctant (Maxwell) forces

Modal basis of the magnetic circuit

http://www.acs.psu.edu/drussell/Demos/TuningFork/fork-modes.html

2D illustration of noise and vibration due to Maxwell forces

*Forced excitation (rotating magnet)*

- Magnets create a fundamental flux $B$ with 1 minium and 1 maximum ($p=1$ pole pair) along the airgap, but the stator deformation (so magnetic force) has 2 minima and 2 maxima.
- Magnetic force $F$ is proportional to the square of flux density and has therefore $2p=2$ pole pairs (two maxima & two minima) – $r=2p$ is called wavenumber.
- Quadratic relationship between $B$ and $F$ affects both time (cf. tuning fork) and space domains.
- Ferromagnetic materials can be deformed under Maxwell stress, resulting in forced vibration and acoustic noise.

$$B = B_1 \cos(p\omega_R t + p\alpha_s)$$

$$F = F_0 + F_2 \cos(2p\omega_R t + 2p\alpha_s)$$

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[Video: https://youtu.be/5489-rzCaMQ]
Resonance condition

- In 2D case, to « maintain » vibration of a fundamental mode, the excitation force has to have the right number of minima / maxima (« spatial frequency » = wavenumber) and the right rotating speed (frequency)

**EXCITED STRUCTURE**
Elliptical mode of the stator stack (m=2) of natural frequency $f_2$
$U = U_2 \cos(2\pi f_2 t) \cos(m\alpha_s)$

**EXCITATION FORCE**
One pole pair (r=2 pole pairs) excitation rotating at $f/r$
$F = F_2 \cos(2\pi ft + r\alpha_s)$

In 2D resonances (high vibration and noise amplification) occur at two conditions:
- match between the exciting force frequency $f$ and the structural mode natural frequency $f_m$: $f = f_m$
- match between the exciting force pattern $r$ and the structural mode shape $m$: $r = m$
Analysis of magnetic noise and vibrations

To analyze the NVH behavior of electric motors one must therefore at least carry two analysis:

- **structural modal analysis** (modal shapes $m$ and natural frequencies $f_m$)
- **2D Fourier transform** of the airgap Maxwell stress (wavenumbers $r$ and exciting frequencies $f$)

The analysis can be restricted to « low » magnetic force wavenumbers (maximum between 4 and 18 depending on the application): the larger the force wavenumber, the stiffer the structure
Noise and vibration mitigation actions

1. Lower excitation magnitude
   - skewing
   - current angle
   - magnet shaping
   - pole shifting / pairing
   - slot opening
   - short pitch winding
   - magnetic wedges
   - current injection
   - notches / slits
   - etc...

2. Lower structural response
   - stiffening
   - damping
   - frame/lamination contact
   - etc...

3. Avoid resonances between excitation and structure
   - slot/pole combination
   - winding topology
   - natural frequency
   - operating speed
   - etc...

All these NVH mitigation actions can be studied in MANATEE software.
Part II – Illustration with MANATEE software
MANATEE simulation environment

- fast electromagnetic design optimization of electrical machines including the analysis of magnetic vibrations and acoustic noise due to Maxwell forces
- Matlab® (R2009b or later) with a Python/Qt GUI – no toolbox needed
- possibility to couple it with your own Matlab scripts
- electromagnetic model is based on templates (no CAD import) but new topologies can be included upon request
MANATEE simulation models

- Integrated hybridation of multiphysic analytical, semi-analytical & numerical models
- Numerical optimization (e.g. spectrogram synthetization, symmetries, field reconstruction, harmonic analysis)
Example of experimental validation

Case of a concentrated winding PMSM with interior magnets at partial load (traction motor):

**MANATEE**

-40 dB

-40 dB

**TESTS**

Sound level during a run-up
(MANATEE simulation without converter harmonics)
~20 sec on a laptop

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

FEA is not necessary to avoid large vibroacoustic resonances due to magnetic forces in the early electromagnetic design loops
Case study 1: squirrel cage induction machine (using GUI v1.6.01beta)

Default_proj at no-load with U=200V
Case study 1: squirrel cage induction machine (using GUI v1.6.01beta)
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Effect of stepped mmf harmonic removal

Effect of rotor slotting

Effect of rotor slot number from $Z_r=24$ to $30$

Effect of rotor slot opening
Case study 2: surface permanent magnet synchronous machine at full load

Cf tutorials & validation cases of website tuto_SPMSM_03

Effect of magnet stepped-skw
Thank you for your attention.

Question & Answers

Request your free trial of MANATEE at http://www.manatee-software.com
BACK UP SLIDES
Vibroacoustic transfer paths

- Tangential and radial force harmonics (r>0) generate radial vibrations propagating to the external frame.
- Radial average force (r=0) also generates radial vibration of the yoke and frame.
- Torque harmonics (r=0) can propagate through rotor shaft as torsional vibrations, and efficiently radiated (large surface / normal vibrations) like gearbox frame or mount.
- Unbalance forces (r=1) harmonics generate shaft bending vibrations which propagate to bearing & frame.
- Axial forces make endplates axial vibrations.
Torque ripple Vs noise minimization

- Torque ripple corresponds to $r=0$ tangential forces, if the stator is circular it cannot create noise through stator vibrations as torsional vibrations cannot radiate acoustic noise.
- In PMSM cogging torque is related to $r=0$ radial force and the minimization of cogging torque can be correlated to acoustic noise minimization if noise is dominated by $r=0$ deflection of the yoke.
- At load in PMSM torque ripple and radial force harmonic $r=0$ correlation has not been proven yet.

**Figure 6.18:** Surface normal velocity integral due to combined excitation at 6045rpm 3% slip

[B25]
<table>
<thead>
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<th>Permeance/ MMF</th>
<th>Subdomain</th>
<th>FEMM</th>
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<td>Calculation time</td>
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<tr>
<td>Overall accuracy</td>
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<tr>
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<td>Eccentricities &amp; uneven airgap</td>
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<td>No</td>
<td>No</td>
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<tr>
<td>Saturation</td>
<td>--</td>
<td>--*</td>
<td>+</td>
</tr>
<tr>
<td>Faults (e.g. short circuits, broken bar, demagnetization)</td>
<td>Yes</td>
<td>No*</td>
<td>No*</td>
</tr>
<tr>
<td>Topologies</td>
<td>IPMSM**, SPMSM, SCIM, DFIM</td>
<td>IPMSM**, SPMSM, SCIM, DFIM</td>
<td>IPMSM, SPMSM, SCIM (no-load), DFIM</td>
</tr>
</tbody>
</table>

*can be modelled but not included yet in MANATEE  
**hybridation with FEA

Preferred model for fast vibroacoustic analysis in healthy variable speed operation
Option 1: 3D ANALYTICAL PERMEANCE / MMF MODEL

\[ B(t, \alpha^8) = \Lambda(t, \alpha^8) \left( f_{mm}^r(t, \alpha^8) + f_{mm}^s(t, \alpha^8) \right) \]

Option 2: 3D SEMI-ANALYTICAL SUBDOMAIN MODEL

\[ \sum_k [A_2(k)r^k + B_2(k)r^{-k}] \cos(\kappa) + \sum_k [C_2(k)r^k + D_2(k)r^{-k}] \sin(\kappa) \]

Option 3: 2.5D FINITE ELEMENT MODEL (FEMM)

User defined flux distribution

Airgap time and space flux distribution

Phase current waveforms

Harmonic magnetic forces

Analytical permeance incl. geometrical asymmetries (e.g. uneven airgap, eccentricities)

FEA permeance incl. saturation, magnetic wedges, notches...

FEA mmf including non linearities

Analytical mmf in linear case using winding function model

PROJECTION TOOL

Radial and tangential forces FFT 2

r=2

r=3

...
IV. STRUCTURAL MODEL

Option 1: 2,5D ANALYTICAL CYLINDER MODEL

Natural frequencies of the circumferential modes of an equivalent ring

\[ Y_{n	ext{u}} = \frac{12R_{\text{ext}}R_{\text{cyl}}}{E_h h_y(m^2 - 1)^2} \]

Dynamic radial deflections

\[ Y_{n\text{u}}^{d} = Y_{n\text{u}}^{1} \left(1 - \frac{f^2}{f_{m}^2}\right)^{2} + 4\xi_{m}^{2}f^2/f_{m}^{4} - 1/2 \]

Static radial deflections incl. tooth-induced moments

Option 2: 3D FINITE ELEMENT STRUCTURAL MODEL

GetDP (free) or Optistruct (commercial)

Vibration synthesis of radial deflections

FRF calculation of main spatial orders of magnetic forces

Harmonic magnetic forces

User defined natural frequencies (e.g. experimental data)

Natural frequencies automatically calculated by FEM (GetDP) on a 3D model

Dynamic radial deflections
Coupling with structural FEM tool Altair Optistruct:

- Possibility to automatically couple an existing FE model of Optistruct with any other electromagnetic software, or to rebuild a lamination model from scratch:
  - Circular lamination with any slot geometry (possibility to simplify the slot geometry to have a lighter structural model)
  - Application of physics: orthotropic properties, winding mass
  - Application of boundary conditions (e.g. clamped/clamped, free/clamped, fixed nodes)
  - Meshing based on the number of nodes in the different regions
- Automated magnetic force application (load collectors)
- Vibration synthesis post-processing
Coupling with structural FEM tool based on open-source GetDP software:

- Automated mesh generation using Gmsh
- Automated identification of coupled circumferential / longitudinal modes with different boundary conditions
- Modal shape selector to visualize the modes and validate the automated modal identification

![Diagram showing various modes and frequencies](image)
APPENDICES – SOUND & VIBRATION SYNTHESIS

ELECTROMAGNETIC MODEL

3D airgap time and space flux distribution

HARMONIC DECOMPOSITION

Tangential and radial harmonic magnetic forces (magnitude, wavenumber, frequency, phase)

r=0
r=2
r=3

VIBRATION SYNTHESIS

Spectrograms
Vibration level
Operation Deflection Shapes
Modal contribution
Radiating surface velocities

STRUCTURAL FEA MODEL

Unit harmonic loads for wavenumber r = 0, ±2, ±4...

Motor and frame modal basis

STRUCTURAL FREQUENCY RESPONSE FUNCTIONS

Complex FRFs (radial & tangential) for each wavenumber r

r=0
r=2