NVH analysis of a 3 phase 12/8 SR motor drive for HEV applications

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Presentation Outline

- Introduction
- Experimental setup
- Vibro-acoustic study based on experimental data
  - Signature time and frequency analysis
  - Deflection shapes and time domain animation
  - Sound quality evaluation
- Conclusion
Electric motor overview:

World of Electrical Machines

DC motor
- Brush DC
  - Shunt wound
  - Separately excited
  - Series wound
  - Compound wound
  - Permanent magnet
  - Universal

AC motor
- Induction
  - Squirrel cage
  - Wound rotor
- Synchronous
  - Permanent magnet
  - Variable reluctance
  - Switched reluctance
  - Hybrid synchronous
- Linear
  - Induction
  - Synchronous
  -...

Salient advantages of SRMs:
- Simple, robust and low-cost construction
- Absence of permanent magnets = higher temperature
- High efficiency in wide speed range
- Intrinsically safe operation

Disadvantage:
- Acoustic noise and torque ripple are troublesome

12 stator poles
8 rotor poles

Organized by: Fira Barcelona, avele, AVERE, neA, Ajuntament de Barcelona, EVAAP, EDTA
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Introduction

Noise generation process of a SR-motor:

Phase currents

Radial forces in the air gap between rotor and stator

Vibrations of stator due to radial displacement

Pressure variations in the air, perceived as noise

The radial attractive force between stator and rotor is the dominant NVH source!
Objectives of this research work “Characterization of 3 phase 12/8 SRM”:

• To verify the theory that the square mode is the first excited mode in practice
  → Modal analysis & operational deflection shapes

• To identify the dominant features in different operational conditions
  → Frequency spectrum/ order sections of current, noise and vibrations signals

• To assess the tonality, loudness and sharpness of this specific 12/8 SRM
  → Sound metrics
Experimental Setup

Practical overview:

12/8 SRM under test conditions

Total measured channels: 219
Schematic overview:

- Controller
- 12/8 SRM
- 60 tri-axial accelerometers
- Microphones
- DC-BUS
- Large induction motor
- Torque sensor
- Incremental encoder

Measurement conditions:
- SRM was clamped at one side
- For modal analysis: Complete SRM including stator, rotor, end shields, cooling water,...
Frequency spectrum of a phase current profile during run-up:

In a 12/8 SRM, each of the 3 phases is excited 8 times per revolution → 8th order harmonics

The phase current $i_\alpha$, $i_\beta$, $i_c$ commutation is the main cause of the torque ripple!

8kHz switching frequency of inverters of load (i.e. IM)

8000.00
400.00
rpm
Tacho_SRM_Filt2 (T3)
-70.00
30.00
0.00
10.00

Dominant orders due to radial force excitation:

Switching frequency angle detection system

Related to ripple on the current signal
Signature Analysis

Frequency spectrum of a phase current profile during run-up:

I1, I2, I3

Filtered signal

Unfiltered signal

Waterfall spectrum of original current profile

Waterfall spectrum of modified current profile

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Frequency spectrum current versus noise and vibrations signal:

- Phase current
- Acceleration
- Sound

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Acceleration</th>
<th>Sound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order 8 and multiples</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Resonances</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
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</tbody>
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Resonances
Frequency spectrum current signal versus noise and vibrations:

- Torque level: 6%
- Torque level: 49%
Modal analysis

Ovalization mode of the mounted 12/8 SRM:

1324 Hz (damping: 1.45%)
1425 Hz (damping: 1.65%)
Ovalization mode of the mounted 12/8 SRM:

- **Theoretically**, when a phase is excited, 4 stator poles are loaded at the same time => ovalization mode shouldn’t be excited during run-up measurement

- **In practice**, it turns out that the ovalization mode are excited
  - Visible in all orders, but best in order 24
  - Ovalization happens at both flanges. Both flanges move in phase which each other.

Order 24
3370 rpm

Ovalization of free end shield

Ovalization of clamped end shield
Deflection Shapes

Square mode of the mounted 12/8 SRM:

- **Theoretically**, when a phase is excited, 4 stator poles are loaded at the same time => square mode should be excited.
- **In practice**, visible in all orders but best in order 56.

Screenshots:

- Order 56
  - 5120 rpm
  - 5960 rpm

- Square deflection of free end shield
  - Clamped end shield: Square deflection
  - Clamped end shield: deflection less pronounced
Sound Quality Evaluation

Tonality/sharpness/Loudness:

- **Tonality**
  - 0%
  - 6%
  - 49%

- **Sharpness**
  - 0%
  - 6%
  - 49%

- **Loudness**
  - 49%
  - 0%
  - -49%
Prominence ratio is a metric related to the detection and evaluation of prominent discrete tones in noises emissions. In the Prominence ratio method, a discrete tone candidate is said prominent if the average SPL of the "critical band" centered on the tone is at least 9dB higher than the average SPL of the adjacent critical bands.
• The **theoretical assumption** that the ovalization mode is **not** excited in 12/8 configuration could **not** be confirmed with measurements. **Not only the square mode, but also the ovalization mode is excited during run-ups:**
  - Square mode dominates in acceleration signals
  - Ovalization mode dominates in microphone signals!

• Objective evaluations like sound metrics confirm the high **tonality** of the SRM

• **Order 8 with his harmonics** are excited in 12/8 SRM configuration due to the geometry of the rotor and phase excitation principle
  - Order 24 is dominant in the sound (ovalization mode)
  - Order 40 and 56 in the accelerations (square-mode)

• Finally, all these NVH tools can help automotive engineers to obtain insight in the vibro-acoustic behavior of electric machines to optimize significant NVH motor characteristics
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http://www.asterics-project.eu/
http://www.green-cars-initiative.eu/projects/asterics
Questions and answers