EVS32 A world of E MOTION 2019 MAY 19-22
INTERNATIONAL ELECTRIC VEHICLE SYMPOSIUM & EXHIBITION

Advanced experimental NVH analysis of e-powertrains under electromagnetic excitations

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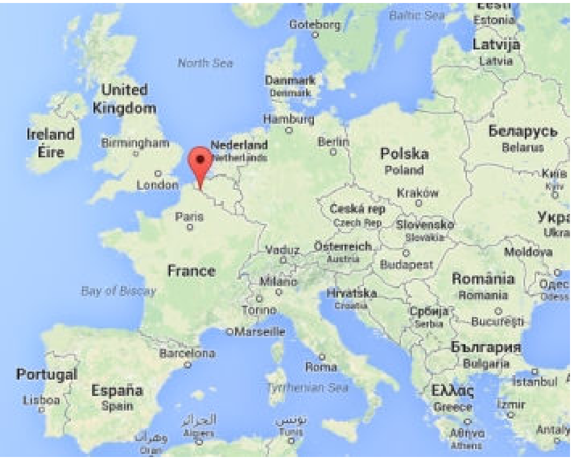
1 EOMYS | ENGINEERING CONSULTING RESEARCH

2 L2EP Laboratoire d'électrotechnique et d'électronique de puissance de Lille

3 OROS MEASURING NOISE & VIBRATION

Who is EOMYS ENGINEERING?



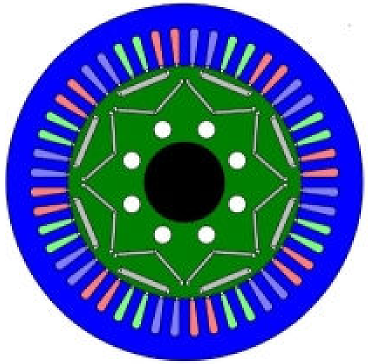
- Created in 2013 in Lille, North of France
- **Engineering consultancy** specialized in **electrical NVH (e-NVH)**
  - NVH studies (troubleshooting, optimization…)
  - Technical trainings
  - Experimental measurements
- e-NVH Software

manatee by EOMYS

- **90% of export turnover** in transportation, energy, industry,…

Context

Magnetic forces → Vibrations of external yoke from 20Hz to 20kHz → High level of noise



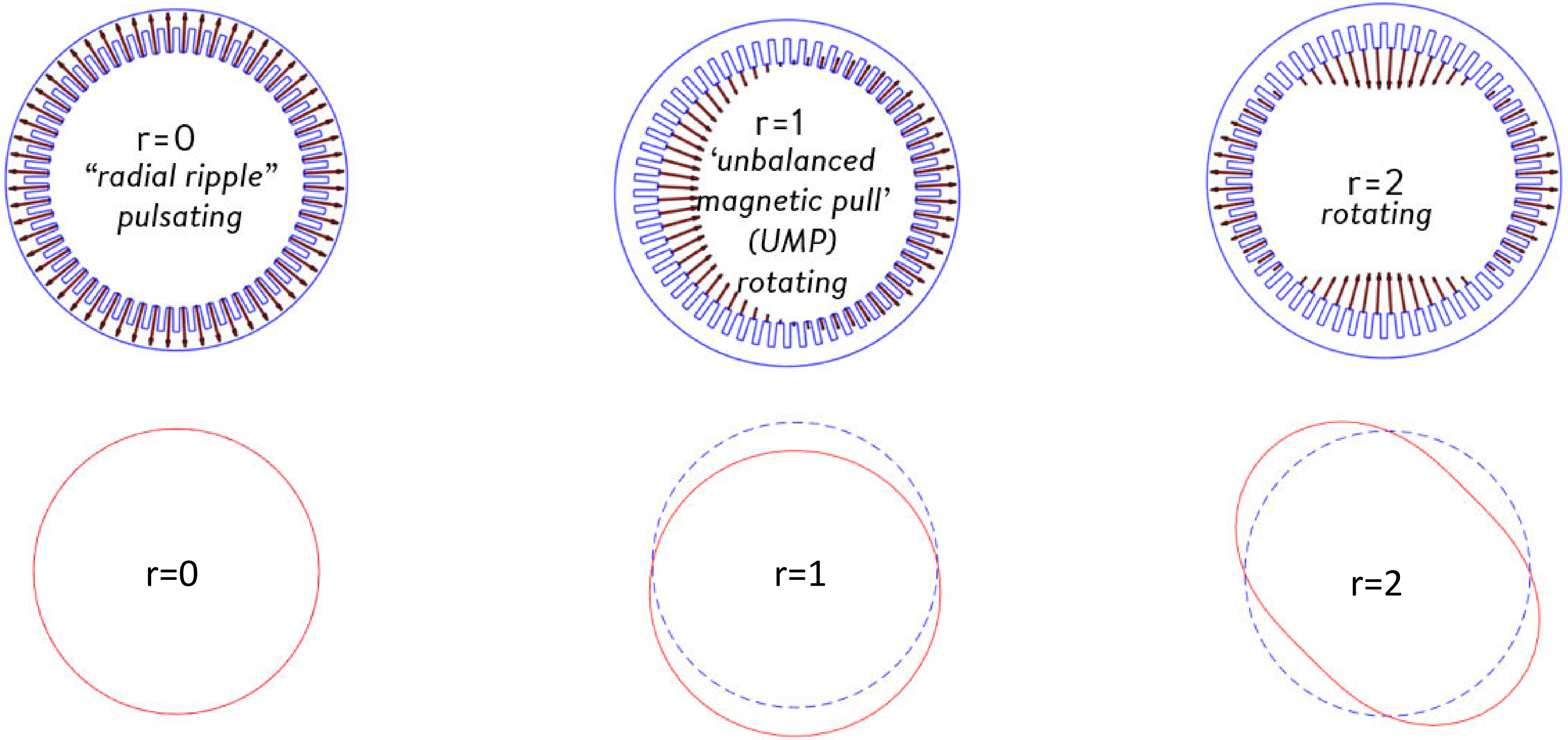
IPMSM
Nissan Leaf

- Need to understand root cause of e-NVH harmonics

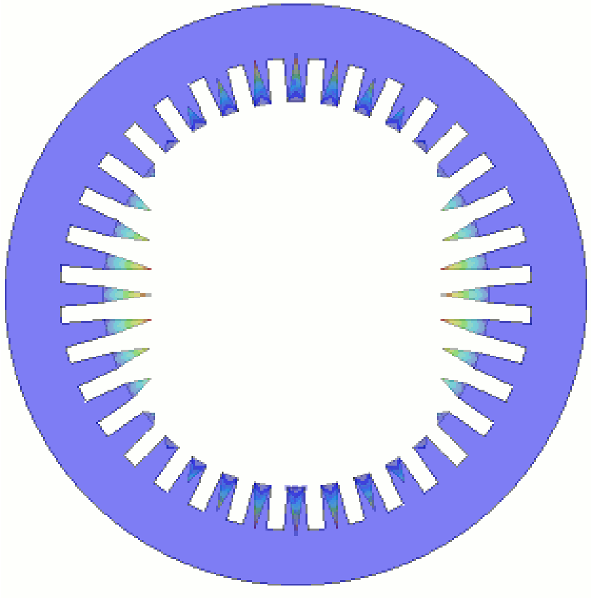
  => caracterisation of (f, r) ***: frequency***

  : wavenumber

Radial magnetic force waves



Resonance



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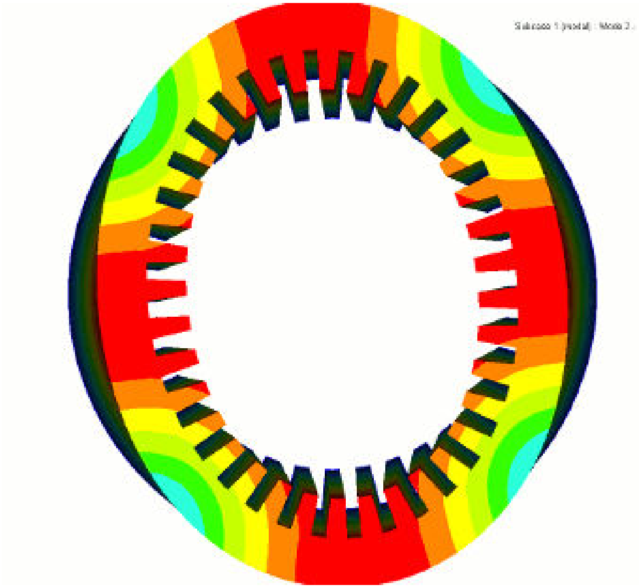

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RESONANCE

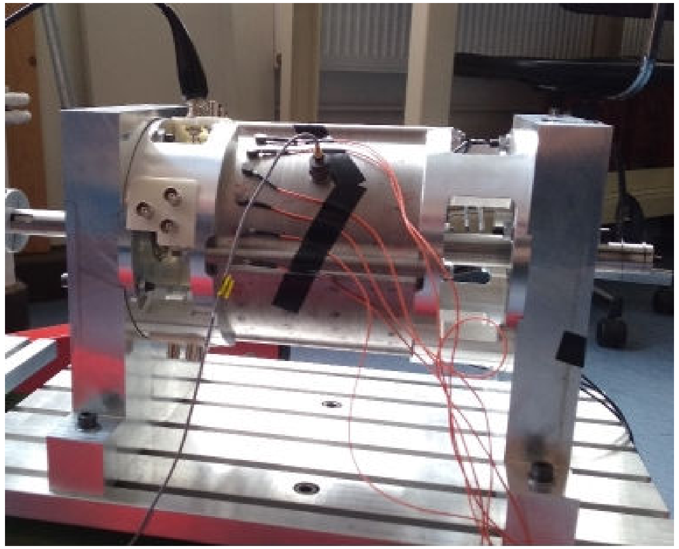
Magnetic excitation (f, r)
of r = 2 at f_{nat}

Structural modal shape
(2,0) at f_{nat}

Benchmark experimental set-up

SPMSM 12s10p

(12 stator slots, 5 pole pairs)



- Equiped with accelerometers & tachometer
- Measurements during run-up & at constant speed
- Post-processings:
  - Spectrogram (standard)
  - **Spatiogram (advanced)**

Spectrograms

- Principle: 2D plot of vibration vs freq. & speed
- Key outputs:
    - Vibration through a wide range of excitation frequencies

      Main force excitation at $f=2f_s$
      & other excitation at $f=10f_s$

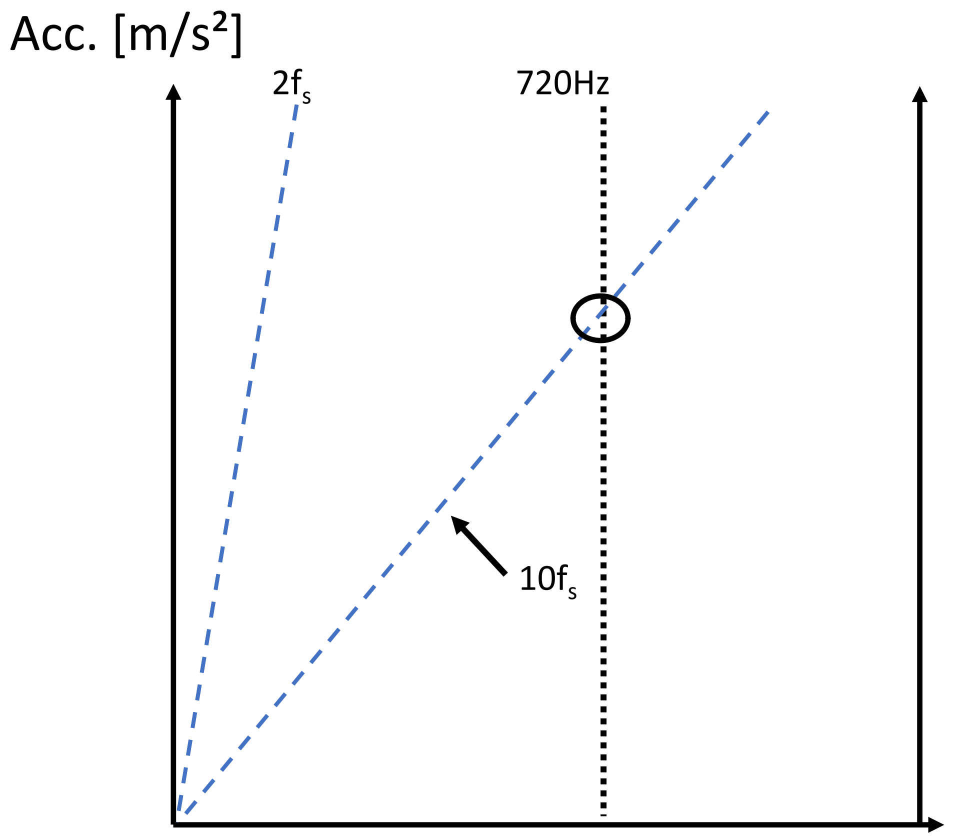
    - Nat. Frequencies

      1 mode at 720Hz

    - Resonances

      1 resonance at 850RPM between $f=10f_s$ and mode at 720Hz

Schematic example



Spectrograms

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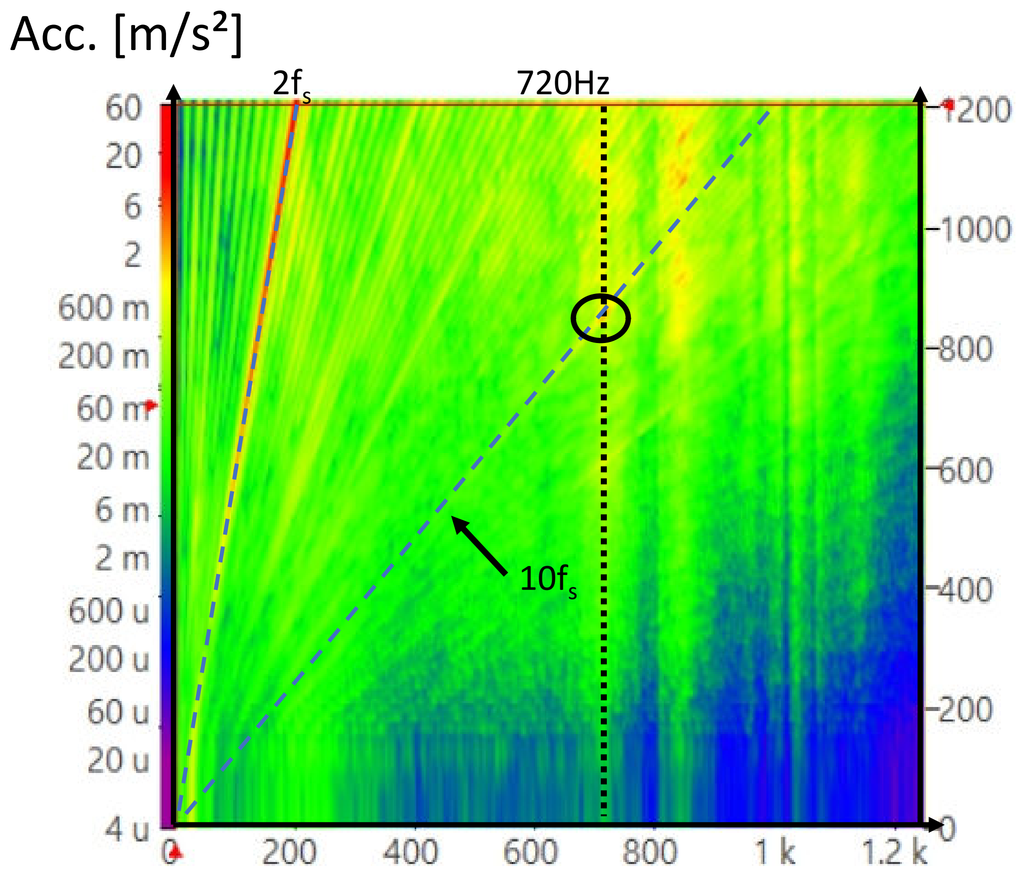
    & other excitation at $f=10f_s$
  - Nat. Frequencies

    1 mode at 7201150Hz
  - Resonances

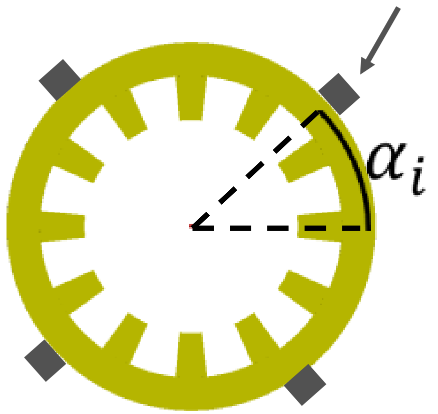
    1 resonance at 850RPM between $f=10f_s$ and mode at 720Hz

Application to SPMSM 12s10p



1 - Spatiogram

- Principle: spectrogram filtration by circumferential wavenumber



$$\mathrm{STFT}\left(A^r(t) = \frac{1}{N_{acc}} \sum_{i=1}^{N_{acc}} e^{j\alpha_i r} a_i(t) \right)$$

N_{acc} : *Number of accelerometers*

α_i : *Angle of accelerometer i [rad]*

r : *Circumferential wavenumber*

$a_i(t)$: *Radial acceleration of accelerometer i at time t [m/s2]*

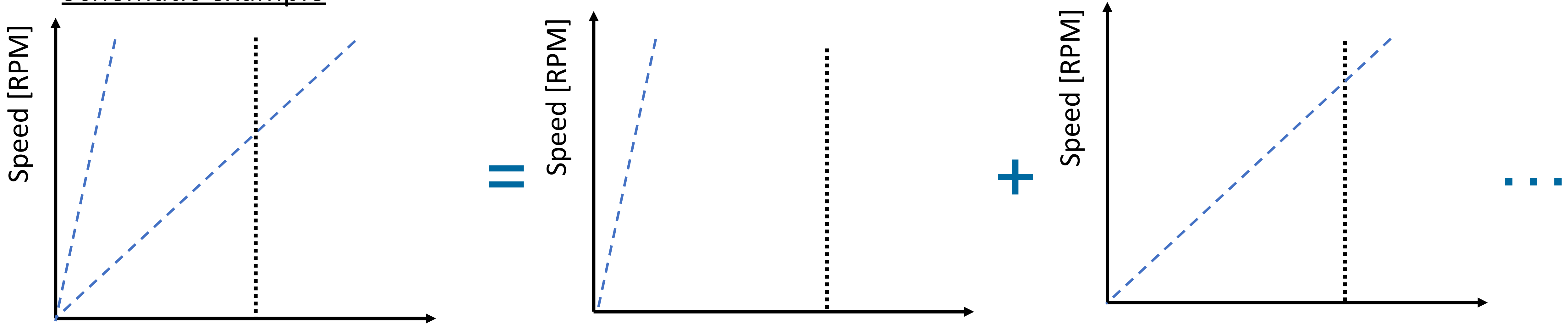
- Key outputs:

  - wavenumber discrimination & contribution

  - structural modes identification

1 - Spatiogram

- Schematic example



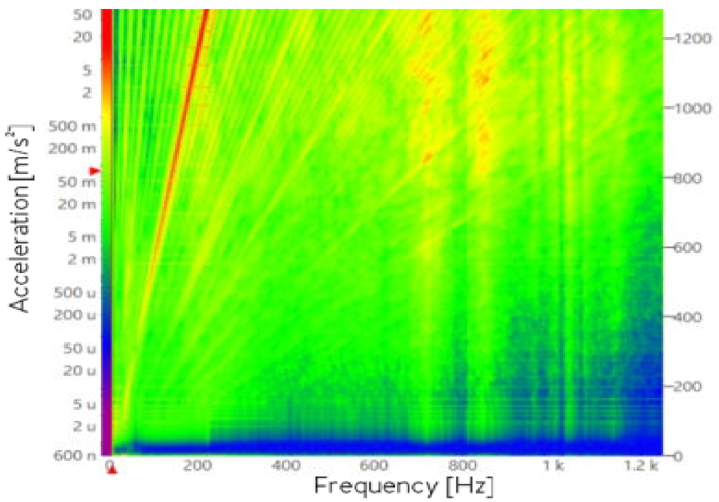
Spectrogram

Spatiogram r = -2

Spatiogram r = 2

1 - Spatiogram

- Application to SPMSM 12s10p using 20 acc (r_{max}=10)



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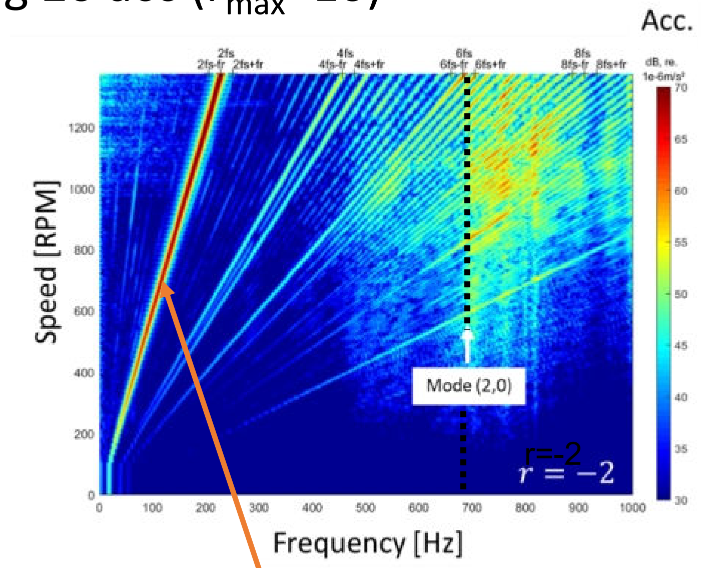

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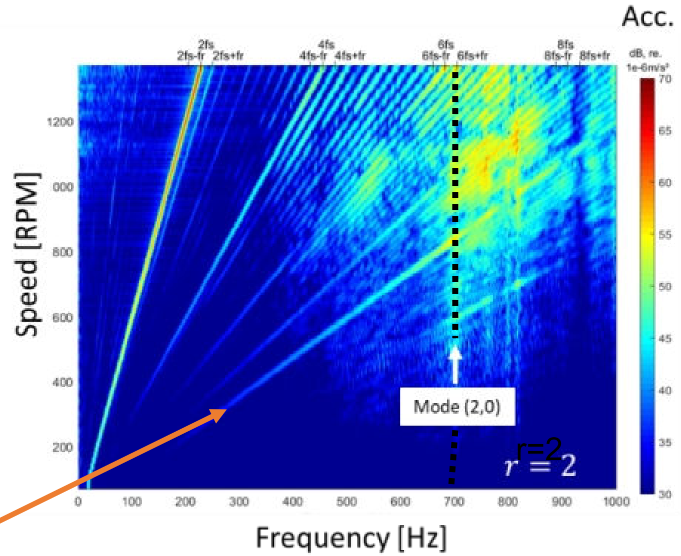


...

-excitations: $(2f_s, -2)$ and $(10f_s, 2)$

- Structural modes: (2,0) at 720Hz
- Validated with manatee by EOMYS

2 - Current weighting

- Principle for induction machine :

  - Current normalization for vibration velocity $v_{\text{norm}} \propto \frac{v}{I^2}$

  - $I[A]$ → $B[T] \propto I$ → $P[\frac{N}{m^2}] \propto B^2$ → $v[\frac{m}{s}] \propto P$

    Current → Flux → Maxwell pressure → Vibration

- Key outputs: ease interpretation of resonances (no dependency on excitation variation)

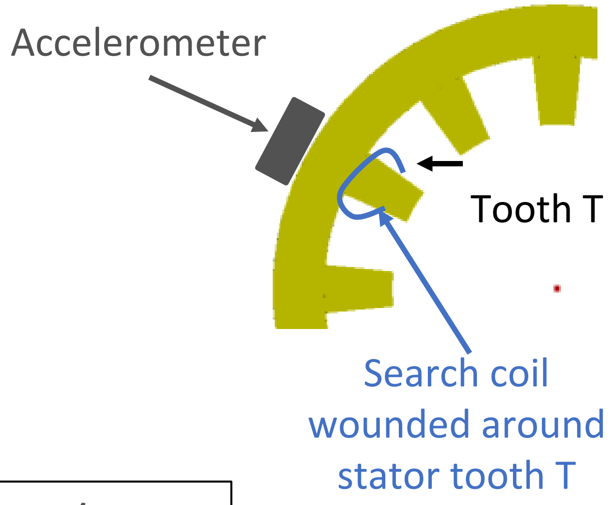
3 - Air gap flux density sensor

- Principle:

Induced V_T ($\alpha\ dB_T/dt$) $\xrightarrow{\int}$ $\sim B_{rad\_T}$ $\xrightarrow{\wedge 2}$ $\sim F_{rad\_T}$

a_{rad_T} $\xrightarrow{\iint}$ x_{rad_T}

$\sim F_{rad\_T}$, x_{rad_T} → $\sim FRF_{rad\_T} = x_{rad\_T} / F_{rad\_T}$



- Key outputs:
  - Identification of geometrical and magnetic asymmetries
  - Improvement of numerical simulation models

Conclusion

Quick and efficient post-processing tools:

- **Spatiogram** to discriminate wavenumbers of magnetic excitation waves & quantify their respective contributions -> **quicker diagnosis** -> quicker choice of mitigation strategies

- **Normalisation** with excitation magnitude to avoid resonance misleading interpretation

- **Airgap flux density sensor** to quantify asymetries and improve numerical simulation models

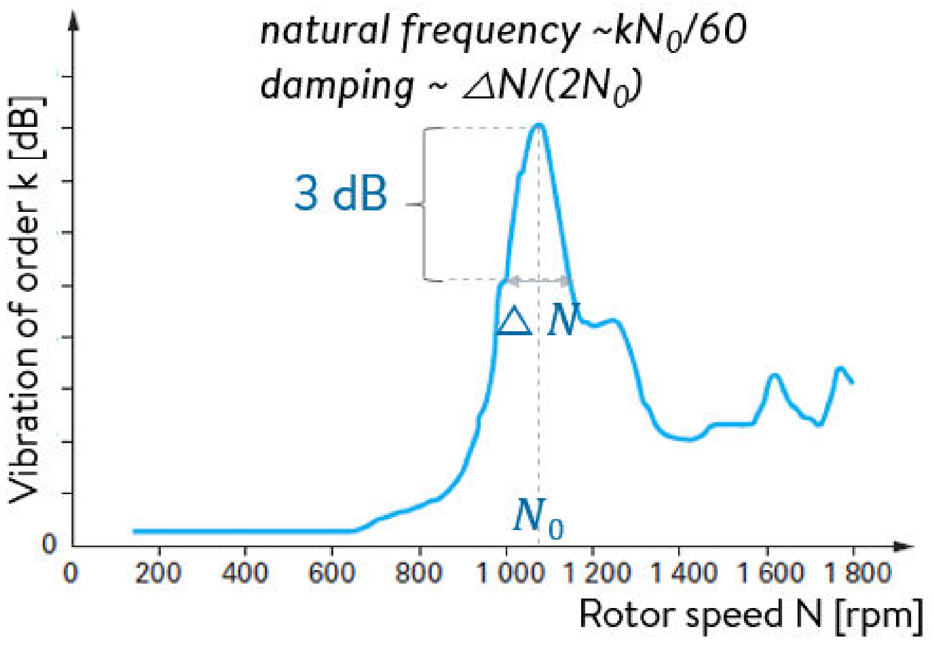
BACK UP

Order Tracking (OT)

- Principle: spectrogram signal extraction of **order k** (multiple k of f_R)

  Ex: order 50 at 50f_R = 10.p.f_R = $10 f_s$

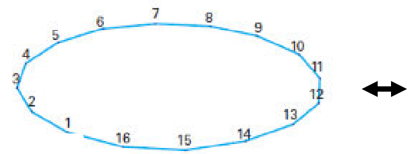
- Key outputs:
  - Resonance identification (nat. freq, damping (*))
  - Clues for wavenumber r responsible for a given resonance ($f \approx f_m \quad \& \quad r = m$)



(*) If electromagnetic forces remain constant over the full speed range

Operational Deflection Shapes (ODS)

- Principle:
  - Constant speed operation
  - Location & number of acc. depending on max wavenumber to capture



2m acc

- Key outputs: Structural deflection shapes
  - **Far from resonance:** vibration pattern matches excitation force pattern (r)

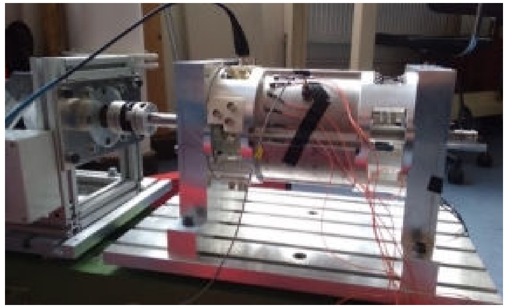
    Rotating or pulsating

    Rotation direction

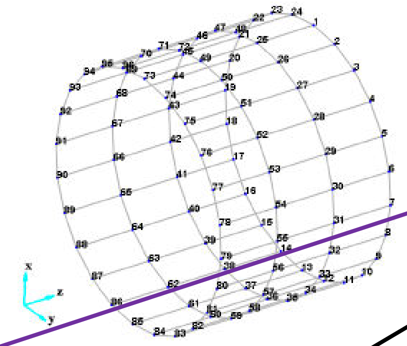
  - **At resonance:** vibration pattern matches pulsating modal shape

Operational Deflection Shapes

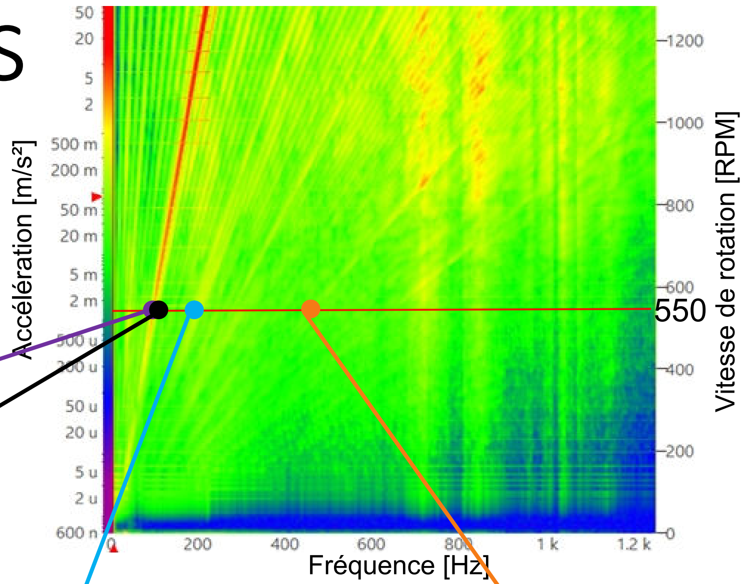
- <u>Application to SPMSM 12s10p</u>

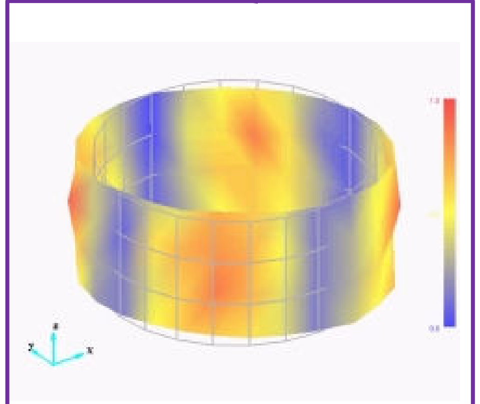


PMSM with 6 acc

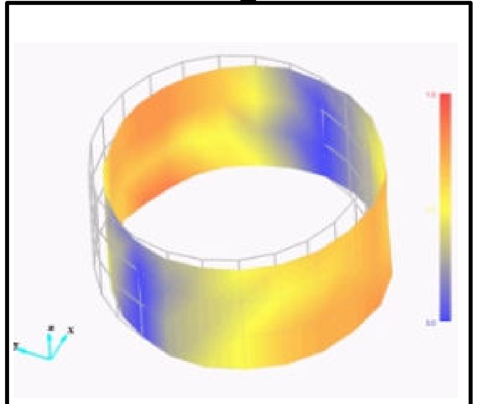


96 point mesh

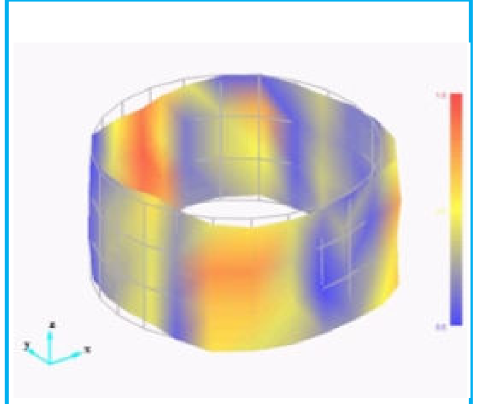




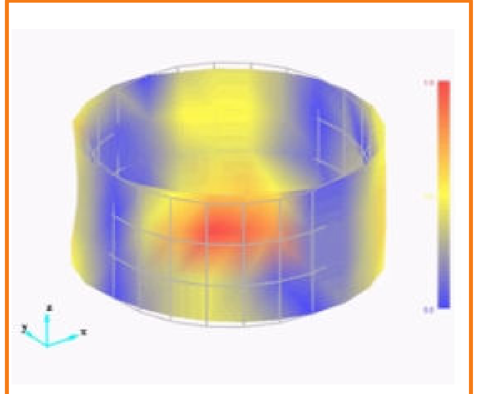
$(2f_s, -2)$



$(2f_s + f_R, -1)$



$(4f_s, -4)$

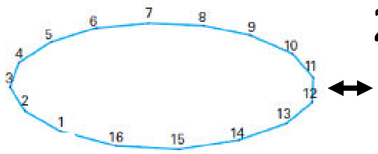


$(10f_s, 2)$

Experimental Modal Analysis (EMA)

- Principle:
  - External excitation

  - Accelerometers

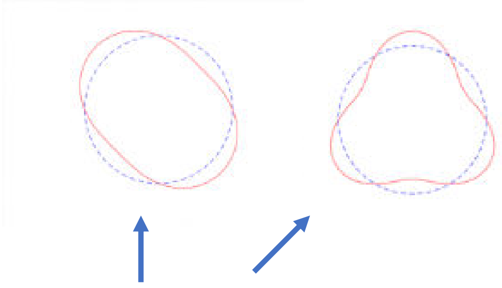


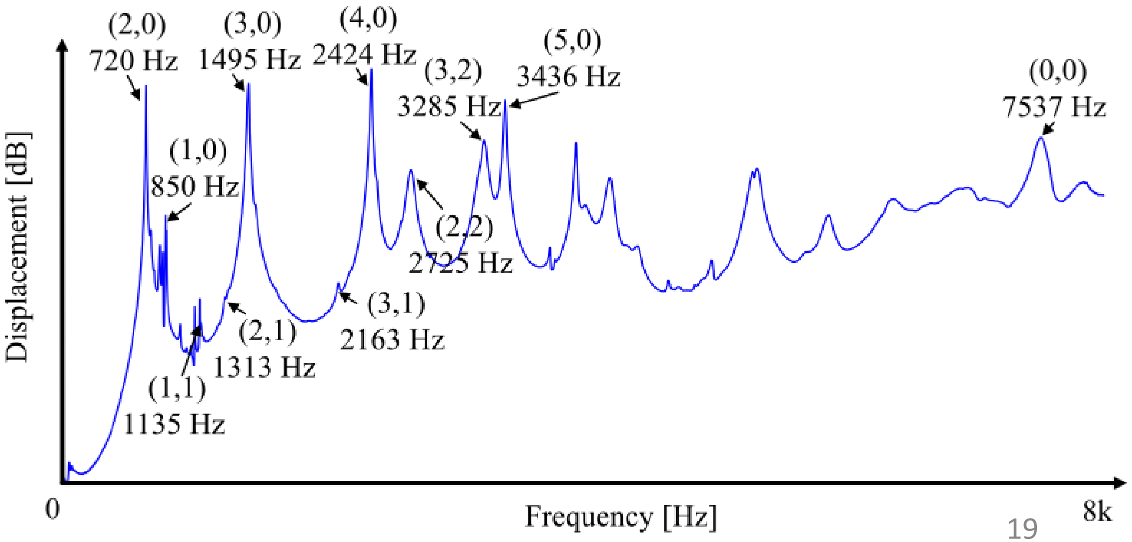
2m acc

modes

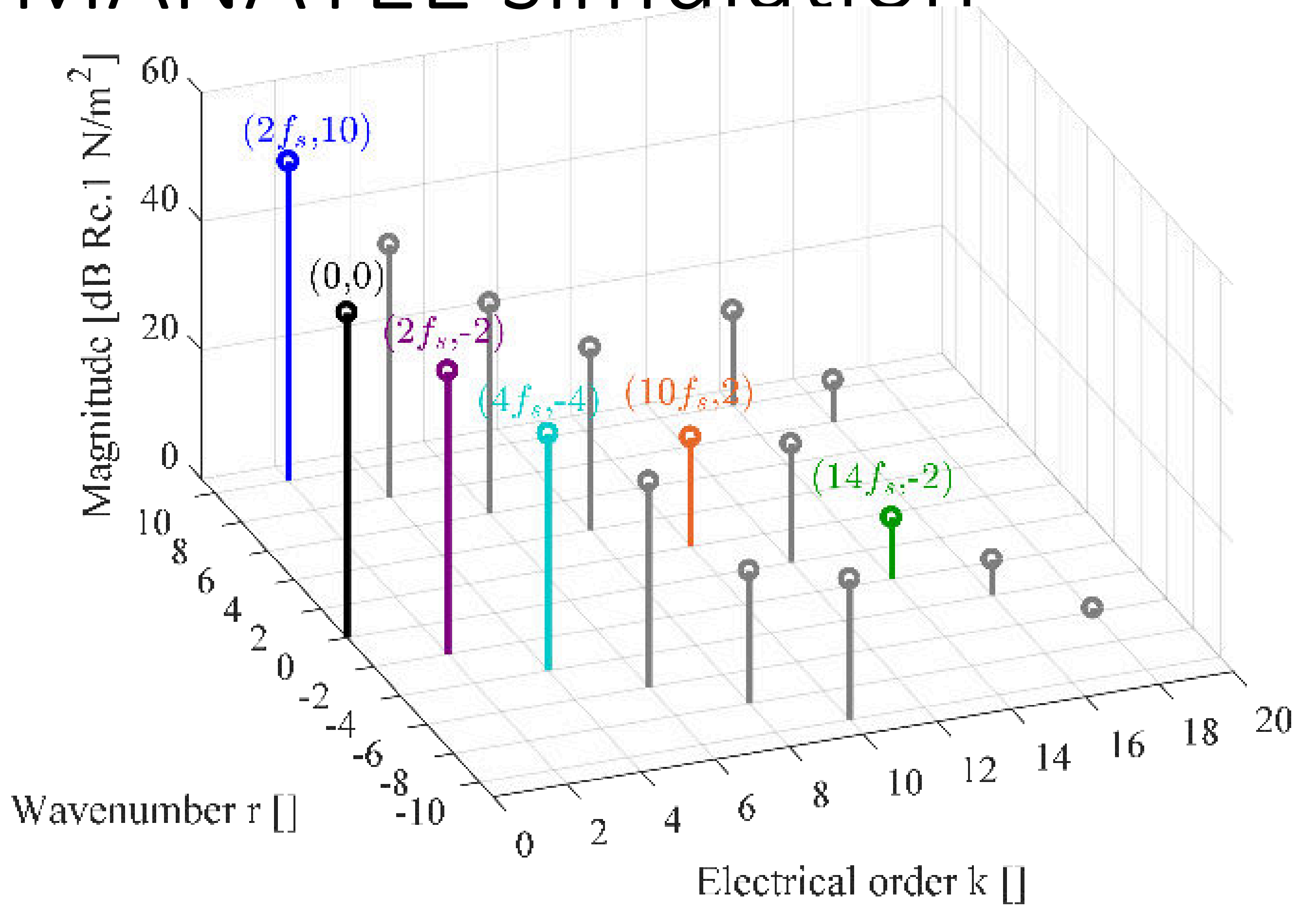
- Key outputs:
  - Natural frequencies
  - Modal shapes
  - Modal damping

- Application to SPMSM 12s10p





MANATEE simulation



Main stress harmonic σ_i	(kf_s, r)	Main stress harmonic σ_i	(kf_s, r)
σ_1	$(2f_s, 10)$	σ_1	$(2f_s, 10)$
σ_2	$(2f_s, -2)$	σ_2	$(2f_s, -2)$
σ_3	$(4f_s, -4)$	σ_3	$(4f_s, -4)$
σ_4	$(10f_s, 2)$	σ_4	$(10f_s, 2)$
σ_5 (*)	$(2f_s + f_R, -1)$	σ_5 (*)	$(2f_s + f_R, -1)$

Main stress harmonic σ_i	(kf_s, r)	Main stress harmonic σ_i	(kf_s, r)
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σ_3	$(4f_s, -4)$	σ_3	$(4f_s, -4)$
σ_4	$(10f_s, 2)$	σ_4	$(10f_s, 2)$
σ_5 (*)	$(2f_s + f_R, -1)$	σ_5 (*)	$(2f_s + f_R, -1)$

X

Main stress harmonic σ_i	(kf_s, r)	Main stress harmonic σ_i	(kf_s, r)
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σ_2	$(2f_s, -2)$	σ_2	$(2f_s, -2)$
σ_3	$(4f_s, -4)$	σ_3	$(4f_s, -4)$
σ_4	$(10f_s, 2)$	σ_4	$(10f_s, 2)$
σ_5 (*)	$(2f_s + f_R, -1)$	σ_5 (*)	$(2f_s + f_R, -1)$

✓

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✓

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✓

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σ_5 (*)	$(2f_s + f_R, -1)$	σ_5 (*)	$(2f_s + f_R, -1)$

✓

(*) including dynamic eccentricity

Comparison between tests and MANATEE

- Good match for $(2f_s, -2)$, $(4f_s, -4)$, $(10f_s, 2)$ and $(2f_s + f_R, -1)$

- Predicted deflection at $(2f_s, 10)$ is not seen on experimental results:
  - Structure filtration of high wavenumber r=10
  - Modulation by the 12 stator teeth $(2f_s, 10)$ => $(2f_s, -2)$