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Advanced experimental NVH analysis of e-powertrains under electromagnetic excitations

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Executive Summary

This paper presents several Noise, Vibration, Harshness (NVH) post-processing techniques used on a dynamic aquisition system to troubleshoot acoustic noise and vibration issues due to electromagnetic forces in electric powertrains. Standard NVH post processing techniques based on Order Tracking (OT), Operation Deflection Shapes (ODS) and Experimental Modal Analysis (EMA) are presented. Those well-known methods efficiently discriminate the frequencies of magnetic forces responsible for NVH issues. However they do not filter the different wavenumbers of vibration waves. Some special NVH post processing techniques are introduced to go deeper in the analysis and quickly capture electromagnetically-excited NVH root cause. They are based either on "spatiogram" or on special post processing of flux sensor and current waveforms. "Spatiogram" relies on the Discrete Fournier Transformation of the accelerations measured on the machine along the machine circumference and length. It aims at introducing a space information besides the standard time and frequency information. It can be seen as an extension of the spectrograms done at variable speed as it efficiently discriminate the wavenumbers of magnetic forces responsible for NVH issues. This advanced post-processing technique can be applied on both experimental and simulation data. Experimental measurements run on a Permanent Magnet Synchronous Motor (PMSM) are interpreted and confirmed by simulation results. Similarly flux sensor waveforms can be post-processed to quantify geometrical and magnetic asymmetries, to estimate radial magnetic forces per tooth and derive Frequency Response Functions (FRF) of stator teeth under radial electromagnetic excitations.

1 Introduction

Electromagnetic forces in e-powertrains are a source of so-called electromagnetically-excited acoustic noise, or electromagnetic noise, which can be a major issue to tackle on site or at a design stage. This paper show how standard Noise, Vibration, Harshness (NVH) post-processing can be used to better understand specific e-NVH (electromagnetic NVH) phenomena, and demonstrates some new post-processing to more quickly capture the root cause of e-NVH harmonics.

2 Standard NVH post processing techniques

2.1 Spectrograms

Principle

As a reminder, a spectrogram is a 2D representation of three parameters (see Figure 2):

- x-axis: frequency
- y-axis: time, rotating speed (preferably) or supply frequency of the machine
- color: magnitude of the quantity (e.g. Sound Pressure Level in dB) displayed as a colormap

Spectrograms are generally obtained using a Short Time Fourier Transform of the time waveform of measured quantity, therefore requiring to find a tradeoff between frequency resolution and time resolution. They can be drawn on vibration levels (displacement, velocity or acceleration in radial, axial or tangential directions) or sound levels (in this case, the term sonogram or sonagram is sometimes used). They can also be applied to electrical machine phase currents. Spectrograms also sometimes called waterfall, but is should reserved for the 3D plot of a 2D spectrogram, taking the amplitude of the signal as z-axis to draw a 3D surface. The term Campbell diagram should be reserved to schematic plots of excitation frequencies and structural natural frequencies without considering the magnitude of the system response. Spectrograms are also sometimes called abusively “colormaps” referring to the graphical post-processing.

Interpretations

Spectrograms are generally displayed as a function of speed rather than time, based on a tachometer signal. In this case, all the excitations proportional to the speed cross the origin of the graph. If the run-up is linear (constant acceleration), these excitations appear as straight lines. This is the case of electromagnetic excitations due to pole/slot interactions, but necessarily the case of electromagnetic excitations due to switching (Pulse Width Modulation), which can appear as V-shape excitations.

Structural mode natural frequencies appear as vertical bands in a spectrograms: even if electromagnetic excitations are purely harmonic, there is always a broad-band excitation source coming from mechanical or aerodynamic forces which amplifies the response of the electric powertrain independently of speed. This vertical bands are therefore very informative; depending on the position of the sensor and the direction of the vibration, one may guess the modal shape that is associated to this particular frequency.

2.2 Order Tracking (OT)

Principle

Order Tracking technique consists in processing a spectrogram to extract the signal magnitude at multiples of the rotational frequency (named orders k), which appear in linear run-up spectrograms as straight lines crossing the origin. The equivalent of a spectrogram can be drawn as an ordogram, where the y-axis directly represents the orders k instead of the frequency.

Interpretations

Order tracking analysis allows to identify what is the exact expression of the electromagnetic forces frequency as $f=kf_R$ (using f: frequency of the excitation force, k: “mechanical order”, f_R: mechanical rotation speed). For instance, electromagnetic excitations may only appear at $48f_R$ and $96f_R$ (also called H48 and H96 respectively) on a specific machine. This information is very valuable because there is a correlation between the frequency of the electromagnetic excitation and its spatial distribution along the airgap of the electrical machine – this spatial frequency is called a “wavenumber” (or spatial order) and noted r, some example of wavenumbers are given in Figure 1. r=0 corresponds to a pulsing vibration wave ; r=1 to an Unbalanced Magnetic Pull (UMP), the magnetic equivalence of a mechanical imbalance (that would typically occur at H1 if the rotor is not mechanically balanced) ; other vibration patterns due to electromagnetic forces always rotate, even in case of Pulse Width Modulation (PWM).

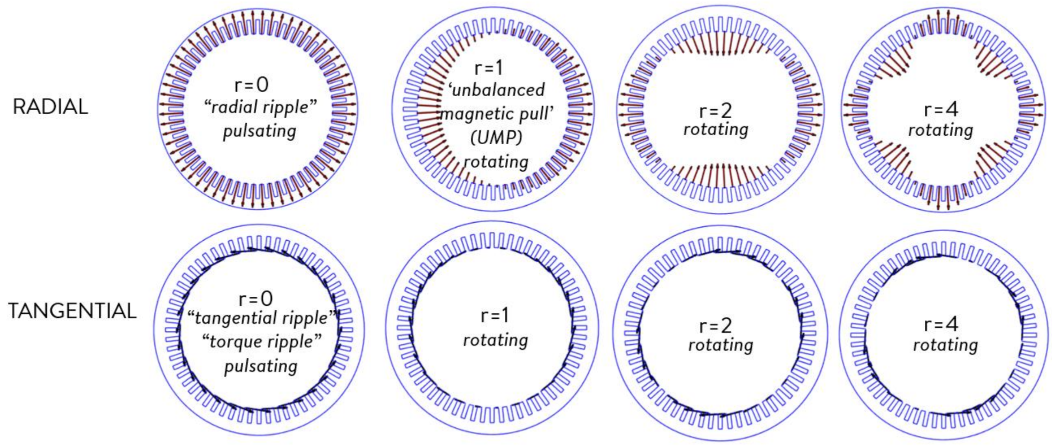

Figure 1: Examples of different patterns of electromagnetically-excited radial vibration waves along the electrical machine circumference (r=0: pulsing, r=1: UMP)

The correlation between the excitation frequency f and the wavenumber r noted (f,r) can be known analytically but it depends on the load state, e-motor topology, airgap roundness and overall magnetic and geometrical asymmetries. Numerical simulation with MANATEE software can be also used to make this correlation.

Using the OT, the plot of the magnitude of a given vibration velocity order as a function of speed can give an indication on the presence of resonance. In particular, if the electrical machine is supplied so that magnetic forces remain constant over the full speed range (case of induction machine during constant flux operation, or permanent synchronous machine during open-circuit operation or fixed current angle and magnitude operation), the order tracking analysis of a radial acceleratomer on the stator stack gives an image of the dynamic mechanical transfer function of the stator, and both natural frequencies and damping can be estimated by looking at this response.

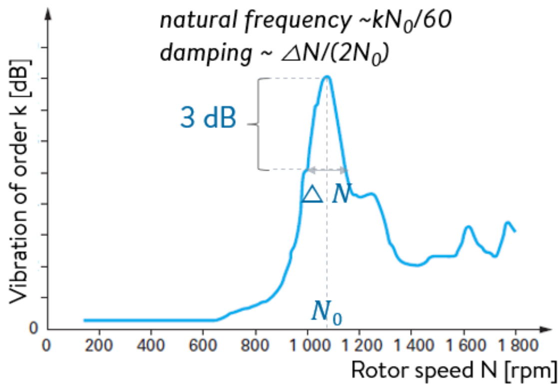

Figure 2: Example of the result of an Order Tracking analysis on the H48 radial acceleration of the stator

An important feature of e-NVH is that large resonances occur at two conditions: the electromagnetic excitation frequency must match a natural frequency, and the electromagnetic excitation wavenumber must match the corresponding modal shape of the stator or rotor. This means that in a spectrogram, some excitation orders might cross some natural frequencies (vertical bands) without resonance. Therefore, the combination of the Order Tracking analysis and the identification of the natural frequencies present in the spectrogram can give some clues of the electromagnetic force wavenumber responsible for a given resonance.

2.3 Operation Deflection Shape (ODS)

Principle

An ODS consists in visualizing the structural deflection shape on chosen degrees of freedom at a certain frequency and a certain speed, the structure being excited by its internal operational excitation forces.

Interpretations

When an ODS is carried around the e-motor stator or rotor circumference at a frequency where driving forces are mainly of electromagnetic origin, one can visually analyse the nature of the vibration wave (rotating or pulsing) and the rotation direction. Associated vibration patterns correspond to either excitation force patterns (wavenumber r, far from resonance) or modal deflection shape (at resonance). An ODS can therefore confirm the main wavenumber of a radial or tangential vibration wave of the stator yoke. Note that the distribution pattern of vibration may not only involve a single wavenumber, for instance due to eccentricities. Besides, the number of accelerometers to be put around the stator circumference must be chosen depending of the maximum wavenumber to be captured according to Shannon theorem (e.g. 20 accelerometers to capture a wavenumber r=10).

2.4 Experimental Modal Analysis (EMA)

Principle

An EMA consists in exciting a structure using an external excitation while monitoring input force and structure acceleration. Its aim is to determine modal shapes, natural frequencies and modal damping of the studied structure.

Interpretations

The EMA allows to identify in “cold” conditions (no electromagnetic loading, no thermal effect) all the structural modes of the structure. The structural modes which are the most easily excited by electromagnetic forces are the radial deflection shapes of the stator yoke (for an outer stator topology) and the bending modes of the rotor shaft, as well as torsional modes of the stator and rotor. EMA results can be used when interpreting spectrograms, as the vertical bands can be associated to structural modes identified in the EMA. Generally, in EV/HEV electric traction applications, the lowest natural frequency is the ovalization mode (potential resonance with r=2 magnetic forces) of the stator stack or coupled rotor/stator bending modes, and the highest frequency is the breathing mode of the lamination stack (potential resonance with r=0 radial forces).

EMA naturally characterizes all the structural modes of the system, even the ones which may never be excited by operational magnetic forces. Besides, the operational conditions (boundary conditions, electromagnetic & inertial loads, temperature) may not be respected. Modal damping highly depends on temperature in electrical machines, so the interpretation of damping measured in cold condition might be limited. These limitations can be removed using Operational Modal Analysis (OMA) based on several run-ups to excite the structure on a wide frequency range.

2.5 Limitations of standard NVH post-processing techniques

All those methods present some limitations to quickly and efficiently:

- discriminate the wavenumbers r (spatial order) of the electromagnetic excitation waves,
- discriminate the physical origin of the electromagnetic excitation harmonics (slotting / PWM / eccentricities),
- quantify the respective contribution of the different wavenumbers,
- identify the only structural modes which are excited by electromagnetic forces under operational conditions.

As an example, when two magnetic excitation forces of different wavenumbers are superposed at the same frequency, the ODS does not allow to quantify the contribution of these wavenumbers and the identification of these wavenumbers must be done visually by NVH test engineer, which may also be misleading as ODS animations assume a linear scale.

3 Advanced NVH post processing techniques

3.1 Spatiogram post-processing

A "spatiogram" is based on the spectrogram visualization of the vibration waves filtered by wavenumbers, and on dual-sided FFT [1]. For each wavenumber r, a discrete angular FFT is calculated from acceleration synchronized time signals (see (1)), then a standard STFT can be applied to the resulting time signal.

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

where 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]

Spatiogram allows to overcome to limitations presented in 2.5. They can be realized both along radial and tangential direction, and can be extended to the electrical machine length to capture longitudinal wavenumbers.

3.2 Flux sensor post-processing

A search coil wounded around a stator teeth allows to capture the induced voltage by time-varying magnetic flux. This signal can be integrated in a standard NVH acquisition system (similarly as acceleration is integrated to obtain the velocity) to get a picture of the average radial flux density over a given stator tooth. The radial magnetic force applied to stator teeth can be approximated as the square of the average radial magnetic flux. A Frequency Response Function can therefore be estimated by making the ratio between the radial displacement and the radial tooth force.

3.3 Current weighting post-processing

Maxwell stress electromagnetic forces are a quadratic function of the flux density. Depending on load state and electrical machines topology, the excitation force might be proportional to the current or to the current squared. To obtain the structural response of the e-motor independently from variations of the excitation levels, one can therefore normalize the NVH levels to the current or the current squared to ease interpretations of resonances.

4 Application

4.1 Experimental analysis

A PMSM machine is equipped with accelerometers, a microphone and a tachometer. The chosen topology is 12s10p, i.e. with 12 stator slots ($\boldsymbol{Z_s = 12}$) and 10 poles ($\boldsymbol{2p = 10}$). All e-NVH measurements are carried with OROS OR35 10+2 channel acquisition system.

Some no-load run-ups and ODS at specific speeds are carried. Several post processings are performed to identify the vibration waves responsible for acoustic noise, namely spectrograms, order tracking analysis, operation deflection shapes and "spatiograms".

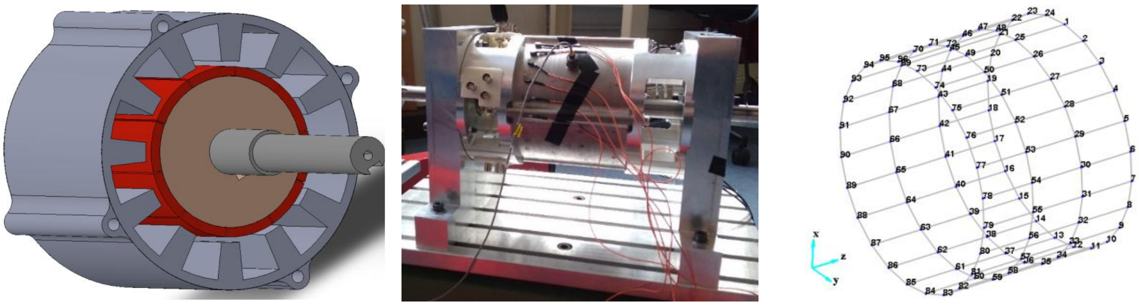

Figure 3: Rotor and stator lamination stack (left), experimental set-up with 6 miniature accelerometers around the yoke circumference (middle) and associated 24x4 geometry meshing (right)

- Spectrogram: Rotating speed of the PMSM is increased linearly between 0 and 1200RPM over 40s. Acceleration of the outer yoke in radial direction is recorded during the linear ramp-up. The resulting spectrogram is depicted in Figure 4.

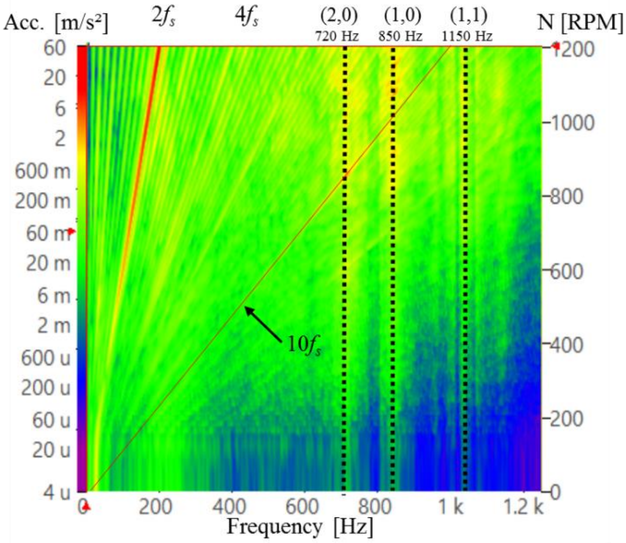

Figure 4: Radial acceleration spectrogram

The main forced excitation which appears as straight line crossing the origin of the graph, occurs at $2f_s$ (f_s, electric frequency). Other excitations occur at $4f_s$ and at $10f_s$. Three distinct structural mode natural frequencies of the stator yoke appear as vertical bands on the spectrogram: modes at 720 Hz, 850 Hz and 1150Hz. A resonance between a force excitation occurring at $10f_s$ and the mode at 720 Hz is clearly noticeable at 850 RPM.

- Order Tracking Analysis: an Order Tracking at the order 50 is performed to investigate further the resonance at $10f_s$=10.p.$f_r = 50f_r$ (f_r, mechanical frequency). Both natural frequencies and damping factor can be estimated.

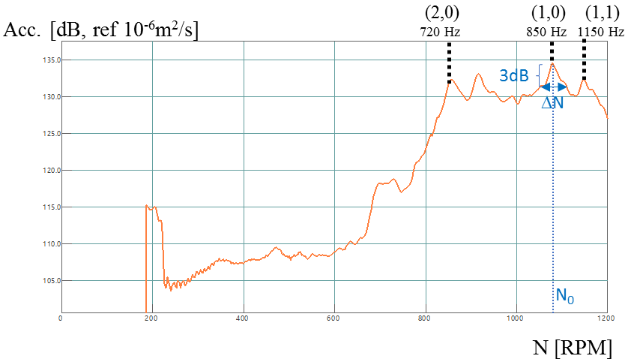

Figure 5: Order Tracking Analysis of order 50 from acceleration spectrogram

- ODS: Vibrations are measured using 6 roving accelerometers and 1 reference accelerometer located on the outer yoke of the stator. The 6 roving accelerometers are moved 16 times to map the 96 nodes of the whole geometry (from Figure 4 (right)). With this setup, the ODS can capture radial modes with circumferential wavenumbers up to 12 and axial wavenumbers up to 2 according to Shannon theorem (24 nodes per circumference plane and 4 nodes per axial plane). The forced response of the SPMSM stator is investigated at 550 RPM where no resonance is noticed on the acceleration spectrogram. Deflections due to the forced stress harmonics $2f_s$, $4f_s$, $10f_s$ are illustrated in Figure 6. There are rotating waves of respective wavenumber -2, -4 and 2. The rotation direction is captured with the wavenumber sign (positive or negative). $(2f_s, -2)$ and $(4f_s, -4)$ rotates in the opposite direction compared to $(10f_s, 2)$. The ODS accounts for another excitation at $(2f_s + f_R, -1)$ which typically highlights a dynamic eccentricity (refer to 4.2).

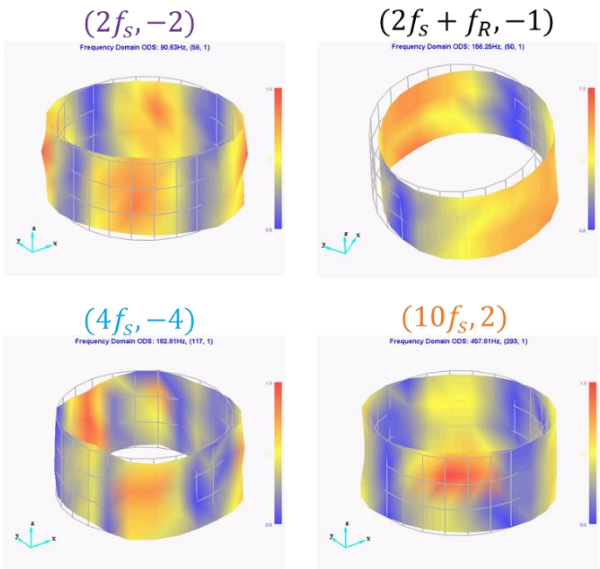

Figure 6: Rotating deflections of the stator yoke at 850RPM due to forced excitations at $(2f_s, -2)$, $(4f_s, -4)$, $(10f_s, 2)$ and $(2f_s + f_R, -1)$

- Spatiograms: the testbench is equipped with 20 accelerometers evenly distributed along the yoke circumference to study the contribution of each wavenumber up to a maximum wavenumber $r = 10$ according to Shannon theorem. A run-up is performed and averaged spectrogram is filtered by wavenumber from -9 to +10. Spatiograms at -2, 2, -4 and -1 are given in Figure 7.

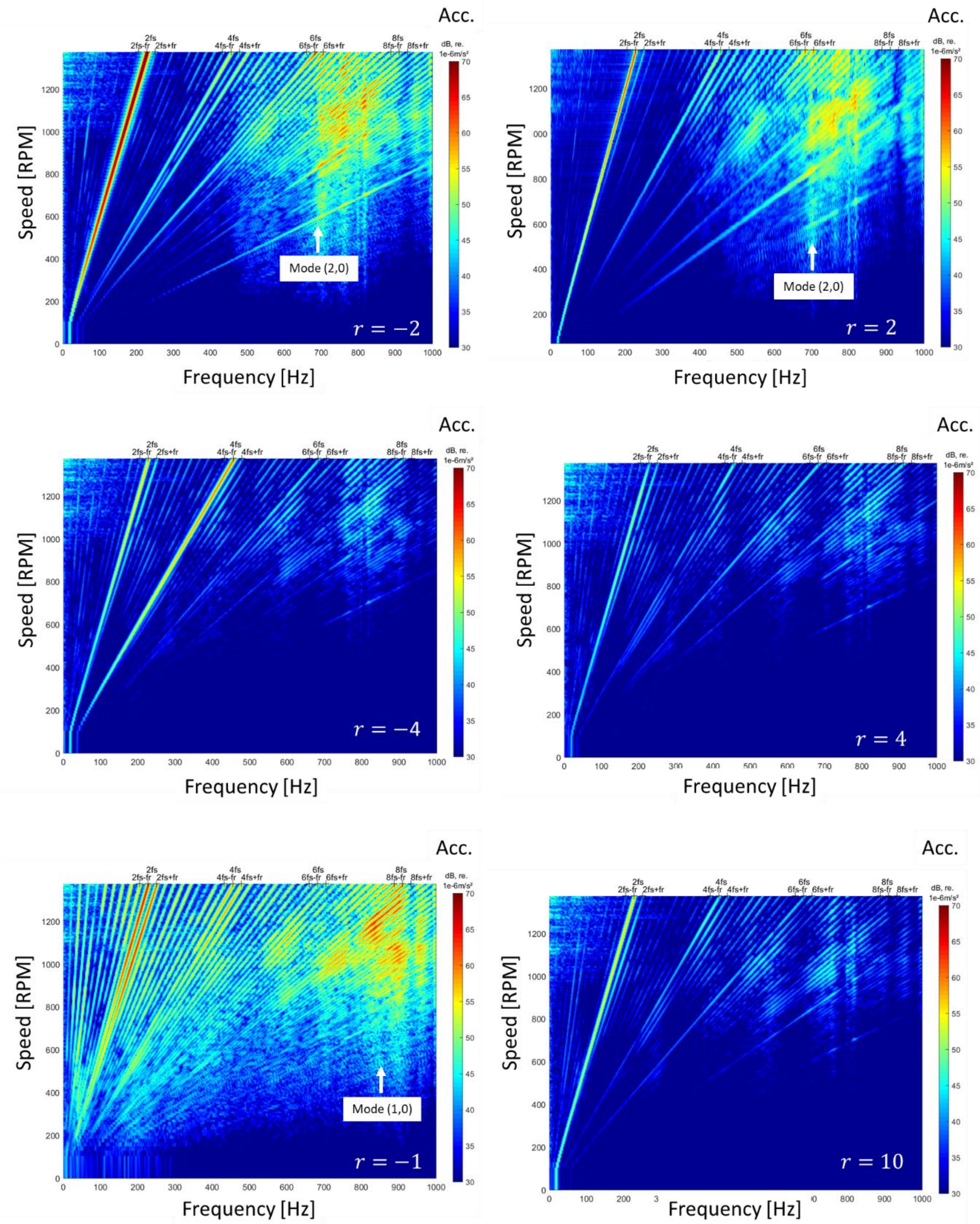

Figure 7: Spatiograms at wavenumber -2, 2, -4, 4, -1 and 10

The largest contributor to a given excitation can be identified comparing all spatiograms. Significantly higher acceleration levels are noticed on the straight line at $2f_S$ for $r = -2$, meaning excitation at $2f_S$ actually mostly comes from r=-2. Similarly higher accelerations levels are noticed on the straight lines at $2f_S + f_R$ for r = -1 and at $4f_S$ for r=-4 meaning excitation at $2f_S + f_R$ mostly comes from r=-1, and excitation at $4f_S$ mostly comes from r=-4. No specific excitation occurs at wavenumber r = 10.

The rotation direction is captured with the wavenumber sign (positive or negative).

In addition, structural modes that are excited by electromagnetic forces can also be captured on a spatiogram. Modes of deflection shape (1,0) (and respectively(2,0)) actually appears as straight lines on spatiograms at r = 1, -1 (and respectively r = 2, -2).

4.2 Simulation analysis

Some electromagnetic and vibroacoustic numerical calculations are run within MANATEE e-NVH simulation environment at variable speed and at specific speeds [3]. Magnetic excitation forces are given as output from the simulation and are expressed as stress harmonics applied at the interface between the airgap and the external stator structure. Main stress harmonics calculated for the testbench PMSM are represented in Figure 8 as a function of electrical order k and wavenumber r.

Table1: Main air gap stress harmonics of testbench PMSM machine and their main origins

Stress harmonic σ_i	σ_1	σ_2	σ_3	σ_4
(kf_s, r)	$(2f_s, 10)$	$(2f_s, -2)$	$(4f_s, -4)$	$(10f_s, 2)$

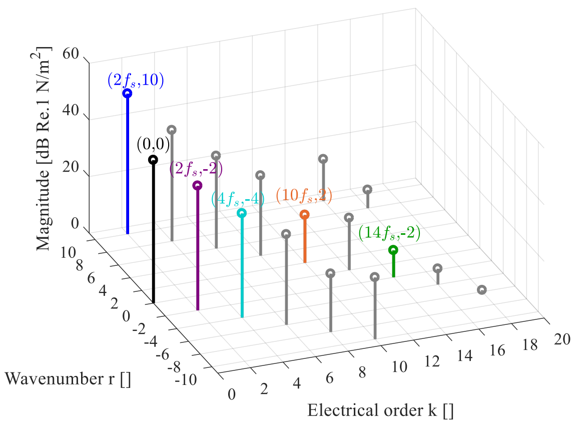

Figure 8: Main air gap stress harmonics of testbench PMSM machine

An additional stress harmonic appears $(2f_s + f_R, -1)$ when dynamic excentricity is considered.

Simulation results are favourably compared to experimental results for $(2f_s, -2)$, $(4f_s, -4)$, $(10f_s, 2)$, and $(2f_s + f_R, -1)$.

However, the deflection due to the fundamental stress $(2f_s, 10)$ is not visually noticeable experimentally at $2f_s$. This is explained by the stiffness of the stator structure which filters the main stress harmonic of wavenumber $r = 10$, and by the fact that this stress harmonic of wavenumber $r = 10$ is modulated by the 12 stator teeth due to spatial aliasing and folded back to wavenumber -2.

5 Conclusion

Some advanced NVH post processing techniques are proposed to fully analyse the origin of electromagnetic noise and vibrations present in electrified powertrains. Unlike standard NVH techniques, they allow to efficiently discriminate the wavenumbers (spatial orders) of the magnetic excitation waves and to quantify their respective contribution, speeding up the diagnosis and the choice of noise mitigation strategies to be implemented. Other post processing based on tooth flux sensor and normalization with excitation magnitude can be used to improve numerical simulation models and quantify operational asymmetries of the e-machine.

References

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Authors

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Jean Le Besnerais currently works in EOMYS ENGINEERING as an R&D engineer on the analysis and reduction of acoustic noise and vibrations in electrical systems. Following a M.Sc. specialized in Applied Mathematics (Ecole Centrale Paris, France) in 2005, he made an industrial PhD thesis in Electrical Engineering at the L2EP laboratory (France). He worked from 2008 to 2013 as an R&D engineer in railway and wind industries (ALSTOM, SIEMENS Wind Power, NENUPHAR Wind). In 2013, he founded EOMYS ENGINEERING.