Psychoacoustics of electromagnetically-excited acoustic noise due to e-mobility electric motors

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Improving the sound quality analysis of electrified powertrains requires to evaluate the electromagnetically-excited acoustic noise and the resulting psychoacoustic metrics including parasitic aerodynamic and mechanical noise sources. This article presents how to couple MANATEE software, specialized in the fast assessment of electromagnetically-excited noise radiated by electrical machines, and LEA software, specialized in sound design and sound quality metrics. Experimental measurements of the sound radiated by an electric powertrain are carried and electromagnetic, aerodynamic, mechanical noise sources are separated. Some control and design parameters of the electric motor are changed and the overall noise is resynthesized to investigate their effect on sound quality.

1 Introduction

E-mobility device are increasingly present in our daily environment. Besides hybrid or full electric cars (HEV/EV), personal e-mobility transportation devices such as single-axis and self-balancing electric vehicles, electric scooters, Segways and e-bikes are also developing.

All these transportation devices include an electrified powertrain made of bearings, gears, cooling system, and an electric motor. This system can generate significant acoustic noise and this noise can be separated in terms of:

- Aerodynamic noise (e.g. wind, fans);
- Mechanical noise (e.g. tyre/road, bearings, gear mesh);
- Electromagnetic noise (e.g. magnet/slot interactions, Pulse Width Modulation [1][3]).

This noise can be unpleasant for passers-by or for drivers. In particular, electromagnetic noise can be responsible for strong tonalities and roughness. In some cases, the sound level of e-mobility device may also be considered as too low for safety reasons, and one may want to increase the noise level of the electric motor, or use this characteristic sound for audio branding. It is therefore important to be able to relate the psychoacoustic effect of electromagnetically-excited noise to the design parameters of the electrical motor and drive.

This work presents a study on a full electric traction chain for automotive application. First measurements are carried to capture the acoustic signature of an electrical drive during a run up. The different noise sources are separated and analysed in terms of psychoacoustic impact. Then it is demonstrated how to couple LEA and MANATEE software to study the sound quality of the electrical powertrain when varying some design parameters of the electric motor and of its control.

2 Acoustic measurements

2.1 Experimental set-up

Measurements are carried on a full electric car with maximum acceleration from 0 to 110 km/h (no Eco mode). Microphones are placed at driver's ear and 40 cm from electric motor under car hood. A 3D accelerometer is mounted on the motor housing. The electric motor is a wound rotor synchronous machine with Zs=48 stator slots and p=2 pole pairs.

The electric drivetrain includes a reducer and the motor is air-cooled so gear noise and aerodynamic noise are present inside measurements.

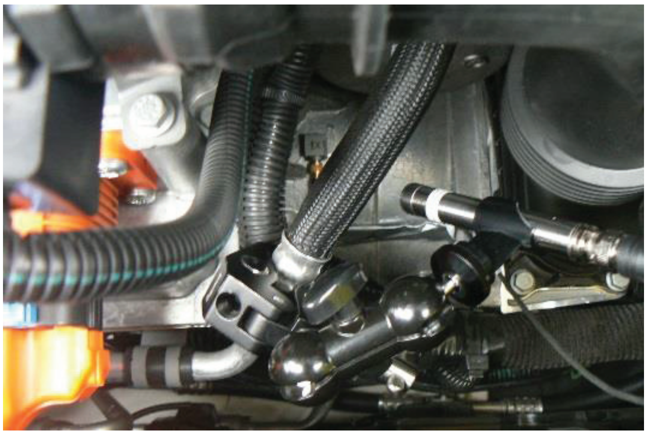

Figure 1: Experimental set-up.

2.2 Results and interpretations

Figure 2 shows the acoustic noise spectrogram measured during run-up. Aerodynamic and mechanical noise remain below 1000 Hz at max speed, while electromagnetic noise results in tonalities. One can distinguish two types of electromagnetic noise. The first one is due to excitations which are proportional to speed, they are due to interactions between pole field harmonics (rotor), stator slot harmonics, and armature field harmonics (stator). The second one creates excitations in "V-shape" centred around multiples of 10 kHz: these are created mainly by Pulse Width Modulation (PWM) current harmonics combined with fundamental rotor and stator fields.

Theory shows that the first type of excitations occurs in open circuit (very light torque level) at multiples of the stator slot number (H48, H96 etc – H noting the mechanical orders, not the electrical orders), while it occurs at multiples of H24 (H24, H48, H72 etc) at partial load. These electromagnetic excitations are pulsating, which means they excite in phase all the stator teeth, both in radial and tangential directions. It is known the vibroacoustic behaviour of most electric motors used in automotive traction is dominated by driven by pulsating forces [6]. In this case one can deduce from the spectrogram that the breathing mode of the lamination has a natural frequency lying in the 4900 – 5200 Hz range.

One can also show that the main PWM excitations are actually pulsating [2]. The excitation frequencies are given by harmonic orders f_{swi}+/-3f_s, f_{swi} +/-5f_s etc and 2f_{swi}, 2f_{swi}+/-2f_s, f_{swi} +/-4f_s etc. One can see that these excitations do not meet any structural resonance. The main PWM lines are far from the breathing mode of the stator close to 5kHz, so PWM noise comes from a forced excitation of the motor.

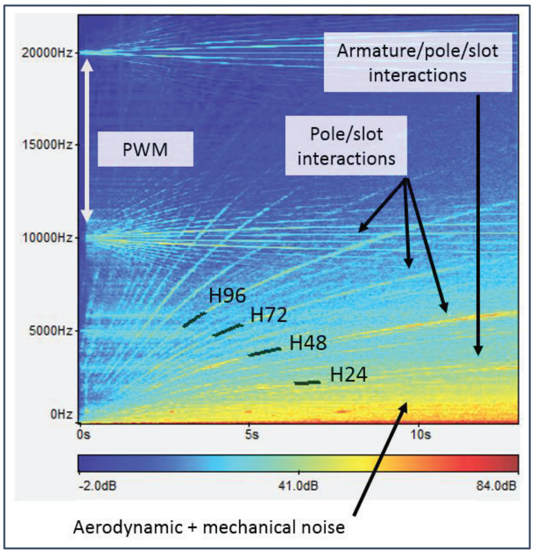

Figure 2: Sound Pressure Level (SPL) spectrogram measured close to electric motor at max torque during run-up.

3 Simulation workflow

3.1 MANATEE software

MANATEE [5] is the first simulation software specialized in the assessment of noise and vibrations in electrical machines. It combines semi analytical electromagnetic, structural and acoustic models to speed up the evaluation of electromagnetically-excited noise and vibrations during pre-sizing of electric motors. It can also be coupled to third party electromagnetic and structural finite element software during detailed design phase.

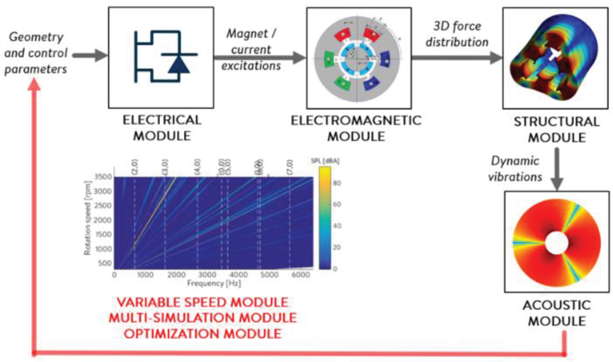

Figure 3: MANATEE simulation workflow.

MANATEE has been validated with several industrial cases [7] and it can be used to synthesize the calculated electromagnetic noise. The acoustic calculations include A-weighting sound power and pressure level, but do not include the evaluation of psychoacoustic metrics, so the generated sound file must be imported in other software for sound quality analysis.

3.2 LEA software

LEA is the premier software solution for sound simulation, analysis, perceived quality and playback. Users can identify the components of the sound and investigate their influence on human perception, individually and as a whole. Based on acoustics recordings, LEA makes it possible to determine acceptability thresholds and build indicators of quality, based on psychoacoustics metrics.

3.3 Principle

If some software such as MANATEE allows to calculate and synthesize the electromagnetic acoustic noise, the evaluation of the sound quality of the electric motor requires to combine all sources of noise (electromagnetic, aerodynamic and mechanics), in particular to correctly account for masking effects. However, electromagnetic sources can be uncoupled from aerodynamic (fan noise) and mechanical (bearing) sources. It is therefore possible to modify the electromagnetic excitations using MANATEE and resynthesize acoustic signature within LEA for psychoacoustic analysis.

4 Psychoacoustics investigations

4.1 Characterization of the different noise sources

In this part LEA is first used to separate the following noise sources: A. mechanical & aerodynamic noise, B. Electromagnetic noise due to pole/slot or armature/pole/slot interactions under sinusoidal supply, C. Electromagnetic noise due to PWM (see Figure 4).

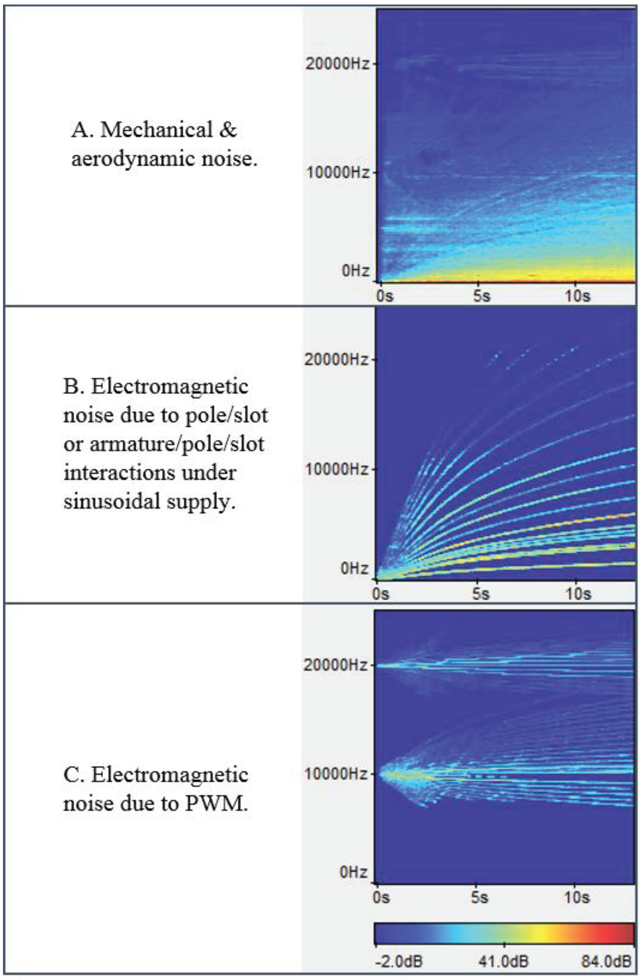

Figure 4: Separation of sound sources in LEA.

Using order extraction feature of LEA and without the need of a tachometric measurement, both armature/pole/slot interaction and PWM noise are isolated from aerodynamic & mechanical noise.

This first step makes it possible to preliminary identify the acoustical impact of each noise component by listening to each of them independently, before going more into details on psychoacoustics' metrics calculation.

4.2 Effect of the switching frequency

In this part the effect of the switching frequency is studied using LEA and MANATEE. The choice of the switching frequency is mainly a compromise between acoustic noise reduction (high switching frequency) and losses reduction (low switching frequency).

As the PWM noise comes from a forced excitation of the stator, it can be potentially transposed in the frequency domain to study the effect of a variation of the switching frequency. In theory, PWM noise is affected by the mechanical response of the system (if the switching frequency is set to 5 kHz, a stronger response should be observed due to the resonance of the "breathing mode" of the stator) but also because the magnitude of current harmonics and resulting electromagnetic excitations vary with the switching frequency. One can show that the force magnitude of the PWM excitation in this type of electric motor is inversely proportional to the switching frequency [8]:

$$L_p = 20log_{10}(\frac{f_{swi2}}{f_{swi1}}). \quad (1)$$

This means that the following gain adjustment has to be carried when transposing the PWM noise pattern:

Table 1: Applicable gain when changing switching frequency

Frequency [kHz]	10	9	8	7	6	5
Gain [dB]	0	0.92	1.94	3.01	4.44	6.02

The value of this gain is here obtained analytically and can be confirmed using MANATEE simulations under PWM supply.

To study the effect of the switching frequency on human perception, the following steps are performed under LEA:

i. Removal of PWM noise to create a reference spectrogram without PWM.
ii. Transpositions of PWM pattern around different switching frequencies.
iii. Synthesis of the new sounds with new switching frequencies.
   Figure 6 illustrates these 3 steps, with the switching frequency transposed to 7kHz.
iv. Calculation of psychoacoustics metrics.

Six switching frequencies are studies: 5kHz, 6kHz, 7kHz, 8kHz, 9kHz and 10kHz (being the original one). Table 1 gains were applied to PWM pattern for each new sound synthesis.

To observe the impact of the switching frequency more significantly, only the first second of the sounds is studied. Following psychoacoustics metrics are investigated: Loudness ISO532B, sharpness, roughness.

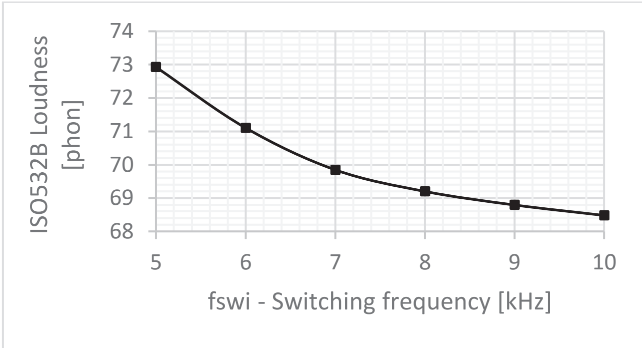

Figure 5: ISO532B Loudness according to fswi.

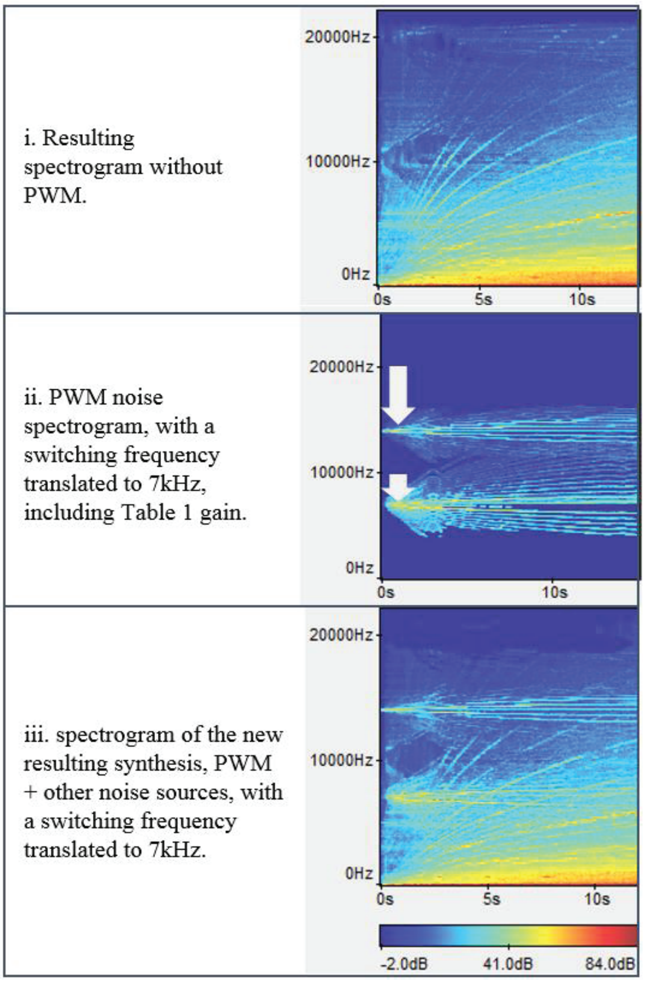

Figure 6. Steps to transpose the switching frequency.

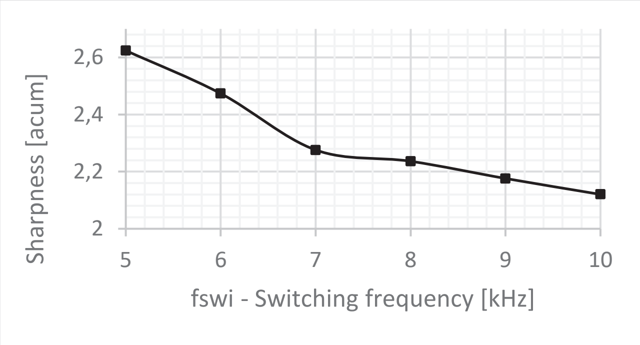

Figure 7: Sharpness according to fswi.

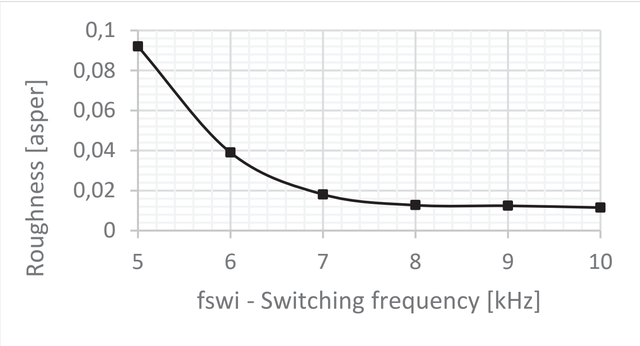

Figure 8: Roughness according to fswi.

As one can hear thanks to the sound synthesis made by LEA, psychoacoustics metrics confirm that the switching frequency has an impact on human sound perception (see Figure 5, 7 and 8). Thanks to psychoacoustics metrics, an objective acceptability threshold can be built to determine to which extent the sound of the electric engine could be rough, sharp, or loud. Further investigations and jury tests are needed to set such thresholds.

By conducting studies combining MANATEE and LEA, a lower switching frequency could be potentially set, allowing to optimize the compromise between the noise reduction and the losses reduction.

More precise studies can also be conducted to investigate human sound perception, either by investigating tonality metrics (PR and TNR from ISO7779, DIN45681, ISO1996-2 annex C, Aures model, available in LEA), or by studying sound perception according to time or RPM in LEA, as shown in Figure 9 for the Loudness.

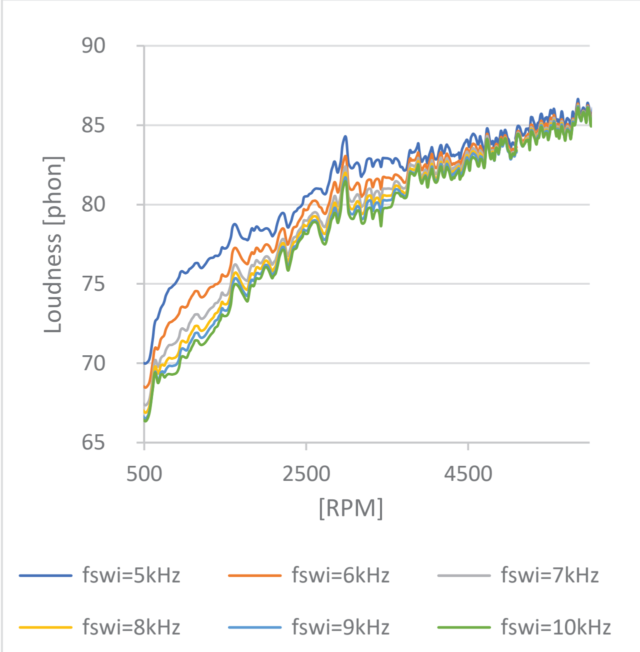

Figure 9: ISO532B Time-varying Loudness according to the RPM - Switching frequency study

4.3 Effect of the electric motor design

In this part some parameters of the electrical machine itself are chosen and varied in MANATEE so to see their impact on noise and vibration harmonics. The following parameters are chosen:

- pole width W1r;
- pole radius R1r;
- stator slot opening W0s.

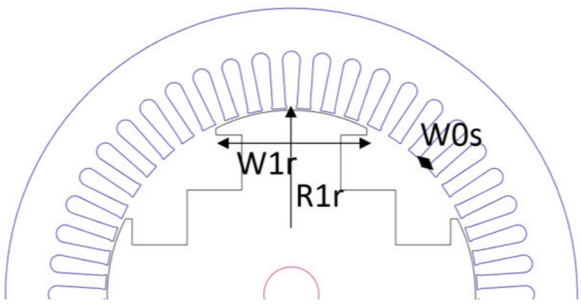

Figure 10: Illustration of the varying parameters of the electrical machine

Due to harmonic interference phenomena the dimensions of the magnetic circuit have a strongly non-monotonic effect on radial and tangential magnetic force harmonics. As an example, Figure 11 illustrates the effect of the pole width on different noise harmonics.

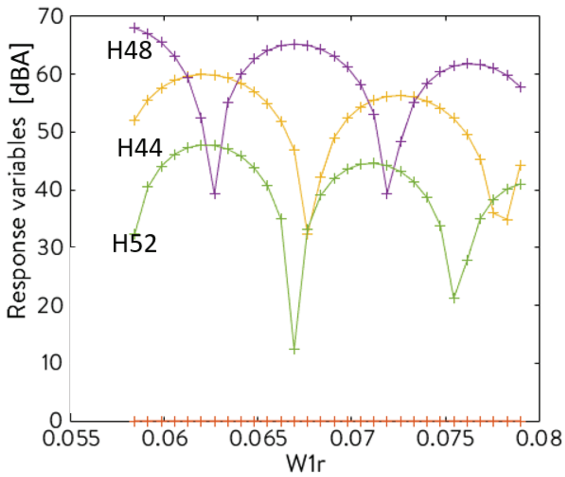

Figure 11: Effect of pole width on noise and vibrations obtained with MANATEE software

Order / Gain [dB]	H28	H44	H48	H52	H88	H96
W1r +/-10%	+6.7 +0.6	**+13.6** **+5.5**	**-9.7** **-2.3**	**+7.0** **-26.8**	+3.1 +3.6	+0.5 -2.2
R1r +/-10%	+0 +10.6	-5.5 +1.4	**-13.4** **+13.9**	**-8.7** **+9.1**	-5.2 -4.3	**-11.8** **+9.2**
W0s +/-10%	+0 +0	+1.1 -3.0	-0.8 +0.6	+0.3 -1.2	+3.3 -5.2	+2.4 -4.3

The variation of the electrical machine design parameters includes the effect of radial and tangential force harmonics on the vibration response of the stator.

As the design variation evaluated in MANATEE software are independent of the speed, the gain to be applied on the experimental harmonics is also independent from speed. The sound of the modified electric powertrain can therefore be resynthesized within LEA for psychoacoustic studies as done in the switching frequency study.

5 Conclusions

MANATEE software from EOMYS and LEA software from GENESIS can be advantageously combined to analyze and optimize the sound quality of electric powertrains after manufacturing or at design stage. It is demonstrated how the psychoacoustic behavior of electric drives can be both influenced by electrical machine design parameters (pole width) and control parameters (switching frequency).

As expected, the higher is the switching frequency, and the lower is the loudness and roughness. More importantly, the combination of LEA and MANATEE allows to virtually resynthesize the combination of aerodynamic, mechanical and electromagnetic noise of the electrical drivetrain. It is therefore possible to optimize the control and the design of electrical machines with respect to sound quality metrics in a fully virtual environment.

References

[1] J. Le Besnerais, P. Pellerey, V. Lanfranchi et autres, 10 nov. 2013, "Bruit acoustique d'origine magnétique dans les machines synchrones" in "Machines électriques tournantes : conception, construction et commande", [en ligne], Editions T.I. [Paris, France], 2016, d3581

[2] J. Le Besnerais, V. Lanfranchi, M. Hecquet and P. Brochet, "Characterization and Reduction of Audible Magnetic Noise Due to PWM Supply in Induction Machines," in *IEEE Transactions on Industrial Electronics*, vol. 57, no. 4, pp. 1288-1295, April 2010.

[3] J. Le Besnerais, V. Lanfranchi, et M. Hecquet, et autres, 10 mai 2013, "Bruit audible d'origine magnétique dans les machines asynchrones" in "Machines électriques tournantes : conception, construction et commande", [en ligne], Editions T.I. [Paris, France], 2016, d3580

[4] J. Le Besnerais, "Reduction of magnetic noise in PWM-supplied induction machines − low-noise design rules and multi-objective optimisation," Ph.D. dissertation, Ecole Centrale de Lille, France, Nov. 2008

[5] MANATEE software, Magnetic Acoustic Noise Analysis Tool for Electrical Engineering. Version 1.05, http://www.eomys.com, EOMYS ENGINEERING, 2016

[6] Hofmann, A., Qi, F., Lange, T., De Doncker, R. W., Doncker, R. W. De, & De Doncker, R. W. (2015). The breathing mode-shape 0: Is it the main acoustic issue in the PMSMs of today's electric vehicles? 2014 17th International Conference on Electrical Machines and Systems, ICEMS 2014, 3067–3073.

[7] J. Le Besnerais, "Fast prediction of variable-speed acoustic noise due to magnetic forces in electrical machines," 2016 XXII International Conference on Electrical Machines (ICEM), Lausanne, 2016, pp. 2259-2265.

[8] Liang, W., Luk, P. C. K., & Fei, W. (2017). Analytical Investigation of Sideband Electromagnetic Vibration in Integral-Slot PMSM Drive with SVPWM Technique. IEEE Transactions on Power Electronics, 32(6), 4785–4795.