32nd Electric Vehicle Symposium (EVS32)
Lyon, France, May 19–22, 2019

Holistic approach to noise reduction in an in-wheel electric motor drive

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Summary

Compared to central electric traction motors, in-wheel motors are more sensitive to NVH characteristics. Therefore, focus on NVH design parameters is required in all phases of in-wheel powertrain development. This paper presents overall considerations and measures taken during motor design starting from initial optimization of the electromagnetic design, all the way to the activities required during mechanical design, including multi-physics optimization and evaluation. Furthermore, the paper also highlights the role of the traction inverter (motor controller) and its effect on the motor noise. Finally, the paper illustrates the system approach to NVH on the vehicle level from the perspective of in-wheel powertrain design.

Keywords: in-wheel motor, electric drive, noise, optimization, motor design, harmonics

1 Introduction

Electrification of vehicle powertrains is expected to bring notable reduction of vehicle noise emissions, and therefore increased passenger comfort. Electric motors are not inherently silent. They radiate noise up in the kHz range, and this noise is typically not appealing to humans in terms of psychoacoustics. Therefore, the aim of car manufacturers is to keep this noise levels as low as possible.

The current generation of electric vehicles (EVs) on the market often utilizes a central electric motor in addition to or as a replacement for the internal combustion engine (ICE), while the rest of the drivetrain including gears, transmission and differentials evolves only enough to support different operating regimes of the used central electric motors. This also affects noise isolation measures of such powertrains, where variations of standard approaches and solutions, such as using noise absorption and shielding materials, adopted to a different frequency scale are used [1]. This causes some challenges on the implementation side, however one of main difficulties in the vehicle NVH design can be argued to appear in the simulation phase, due to increased complexity of interacting subsystems and use of high-fidelity models that enable description of high frequency behaviour [2].

All variants of central motors are hidden under the bonnet and they can be noise-isolated from the surrounding environment. Screens for reducing airborne radiated noise, and large bushings for isolating structural vibrations are readily used in EVs in a similar fashion as on ICE vehicles. In case of in-wheel motors, none of this can be taken for granted and tuned in the same fashion.

When the electric motor is placed inside the wheels of a vehicle, this enables substantial reduction in complexity of the powertrain and opens up new possibilities for vehicle design. While this brings many advantages to the vehicle design process it also produces new challenges in terms of NVH.

In-wheel motors are placed inside the wheels of a vehicle as presented in Figure 1, and the airborne noise can be freely radiated into the surrounding environment. With respect to structure borne noise, the motors inside the wheel are rigidly attached within the corner components, and the vehicle suspension system assumes the added role of the sole motor vibration isolation system. In today's vehicles, a suspension system is primarily tuned to provide ride comfort in terms of low frequency vehicle resonances. While it also has a role in isolation of tyre-road vibrations, the transfer paths for high frequency vibrations are not so well explored.

Another difference stems from the direct-drive characteristics of Elaphe in-wheel motors, which exhibit extremely high torque, up to 1500 Nm. This means that even very small relative torque pulsations can cause significant vibration levels on the motor, particularly in combination with lightweight and slim mechanical design that is required from the in-wheel application. This brings the in-wheel motor developer into a position, where additional focus has to be placed on NVH at every stage of development process.

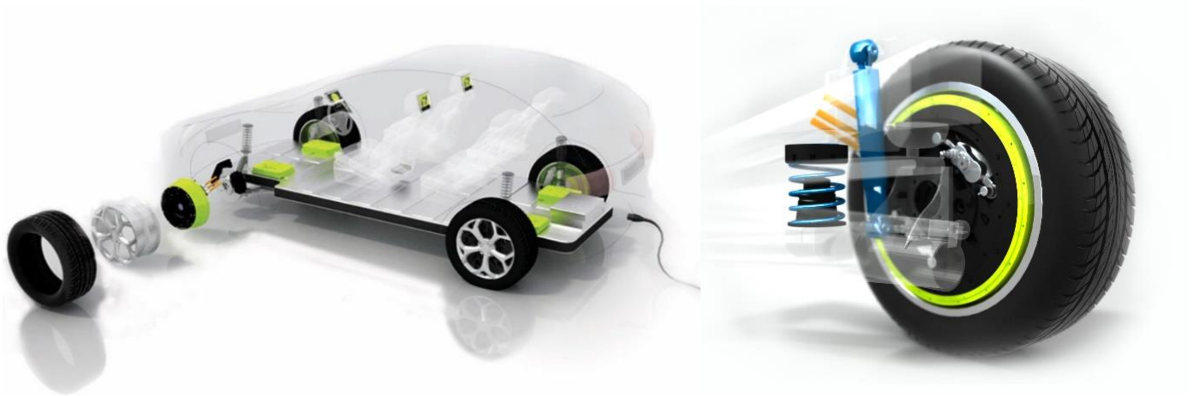

Figure 1: Elaphe 4-in-wheel drive architecture

2 Strategies for NVH reduction

Elaphe is committed to serving the market with the best in-wheel powertrains not only in terms of performance but also comfort, and many steps are executed during motor development to reduce the noise of the powertrain for a final application. In abstract terms, the motor development can be summarized in two main avenues of design considerations. The first is reduction of airborne noise through minimizing deflection of the motor structure, and the second is reduction of the structure-borne noise through reduction of torque pulsation. Especially for the latter it is very important that one does not consider the motor as an isolated system but the powertrain as a whole, considering actual motor current being fed to the motor by the inverter [3]. Finally, modifications can be made on vehicle level, that additionally help reduce noise propagation.

2.1 Motor coupled design optimization

Elaphe in-wheel motors electromagnetic (EM) part is only a few cm thick and fits into a small, constrained space inside a wheel rim, surrounding a standard brake assembly. While this design enables large torque generation with minimal motor mass and volume, it is prone to deflections arising from oscillations of electromagnetic forces within the motor.

In the initial phase of motor design, multi-objective optimization of motor electromagnetic parts is performed, with NVH being one of primary optimization goals in addition to fulfilment of performance and integration requirements. Next to cogging torque and torque ripple, the focus is also given to radiated acoustic emissions at both low and high loads, over the whole speed range of the powertrain.

The optimization process is implemented through a genetic algorithm, where concurrent evaluations of motor EM design run in parallel within each generation of the algorithm. Several thousands of parametric variations of a given design are evaluated within such optimization cycle. An acoustic map (shown in Figure 2) is created for the most promising design candidates in order to inspect for any additional artefacts that could result in undesired levels of acoustic noise.

Since details of a motor's structural design are not known at this stage of development, a generalized motor model is used, taking into account that the main structural properties affecting noise radiation originate from geometry of the motor EM part. Due to the large number of required evaluations of EM designs, the evaluation process is highly optimized. Therefore, analytical acoustic models, fed by electromagnetic fields from EM FEM are used, instead of acoustical FEM. The use of even the most simplified acoustic FEM was dismissed as an option, as it would substantially lengthen the optimization process, even with the use of high-performance computing (HPC).

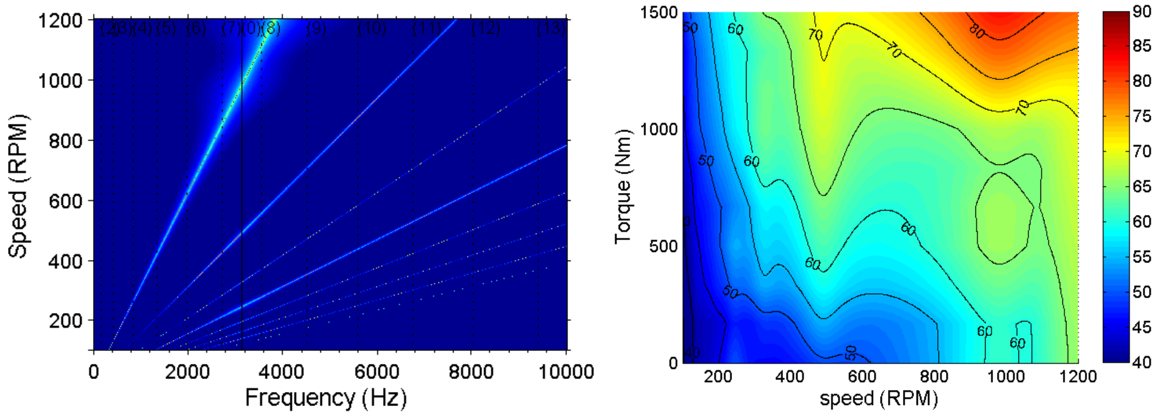

Figure 2: Analytical evaluation of harmonic spectrum for different motor speeds at fixed torque (left) and map of motor sound power in dB(A) over whole speed-torque range of motor (right).

When external dimensions of EM parts are determined, structural optimization of a motor housing can be performed. In outer rotor motor configurations, in contrast to most inner rotor electric motors, the rotor is the less rigid part and is also the main source of airborne noise. Therefore, in terms of acoustics, the main focus is on rotor optimization. This optimization can take place at the same time as EM optimization, since the most problematic structural modes can be predicted in advance, based on experience from previous designs. For this part, topology and topography optimizations are carried out to obtain a rotor shape with maximal stiffness and minimal deflections with respect to the most pronounced structural modes. Design space is very limited in the radial direction, while the axial space allows more room for optimization. Naturally, the constraints of structural load requirements and production technology capabilities have to be respected at all times. The process is graphically depicted in Figure 3, for Elaphe L1500 in-wheel motor rotor housing.

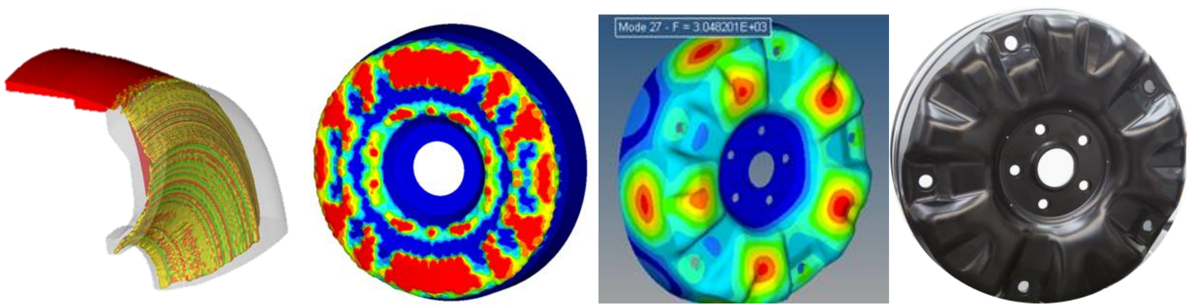

Figure 3: (a) Design space for rotor structural optimization. (b) Effective radiated power of a motor design under evaluation. (c) Rotor housing geometry, optimized for noise excitation with one of the main eigenmodes. (d) Physical prototype.

In both of the above described optimizations, electromagnetic and structural, the boundary conditions for a given optimization from the counterpart optimization are not known in all detail in advance. Thus, several most promising solutions are selected for further evaluation.

In the last step of motor design optimization, fully coupled electromagnetic and acoustic FEM is performed for the different combinations of promising designs to determine the best combination of EM and structural design. Since several design evaluations have to be carried out, for some of the main excitation harmonics over the whole motor operating range, the entire coupled analysis process is computationally optimized, and a fully automated multi-physics workflow, as presented in Figure 4, has been developed for efficient and repetitive evaluation of radiated noise.

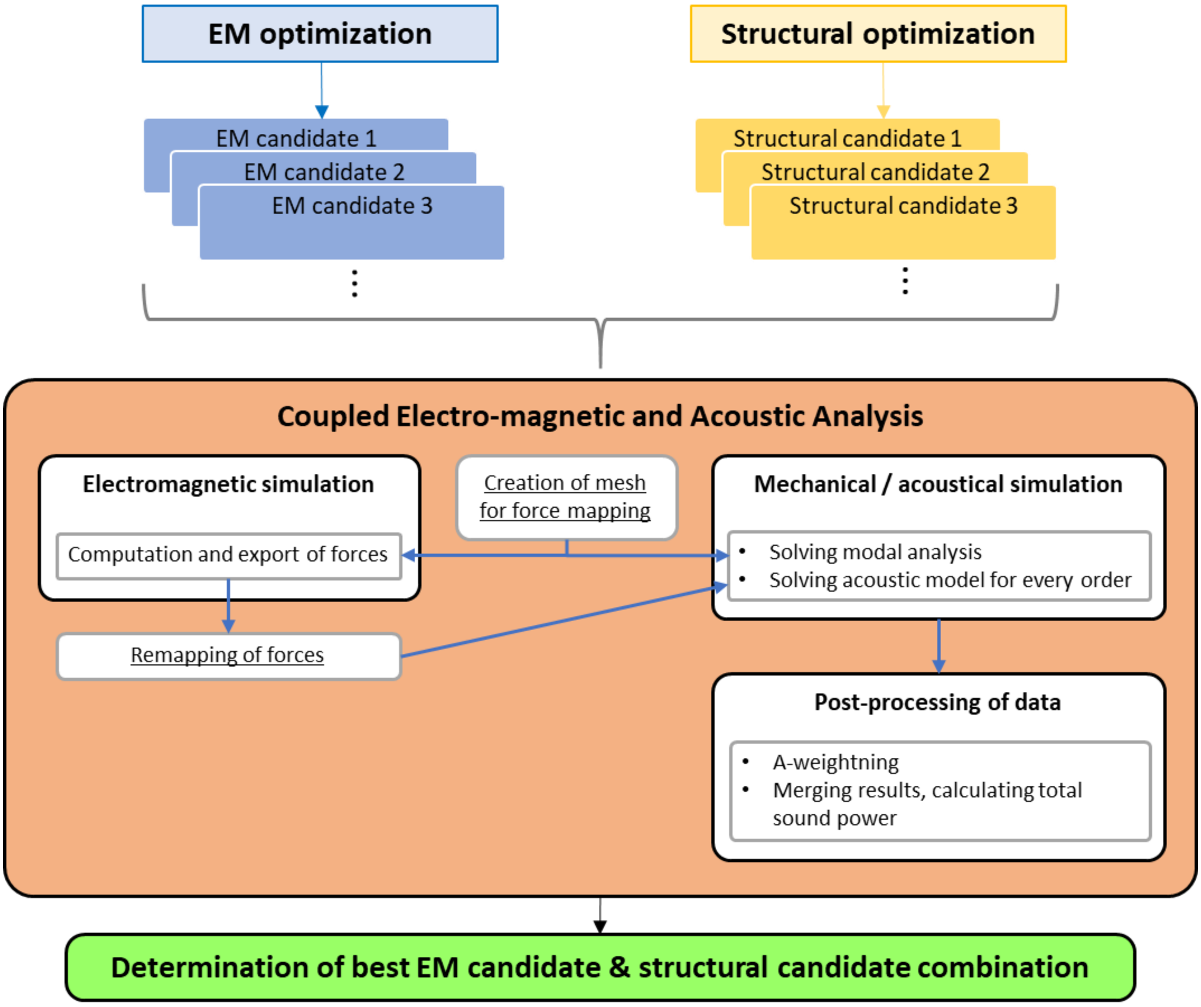

Figure 4: Motor design optimization workflow consists of three parts. Electro-magnetic optimization, structural optimization and fully-coupled electro-magnetic and acoustic analysis.

The obtained result is NVH-optimized motor design, with a detailed acoustical signature of the motor, before commissioning any physical prototypes. The simulated spectrum in Figure 5 is similar to the one in Figure 2, however one can observe more realistic sound power levels with a lot more details, especially in resonant behaviour. In absence of any noise isolation and considering uniform noise reflection from the vehicle, we can estimate the pass-by noise (according to ECE R51.03) of such a machine to be around 22 dB less than the calculated noise power.

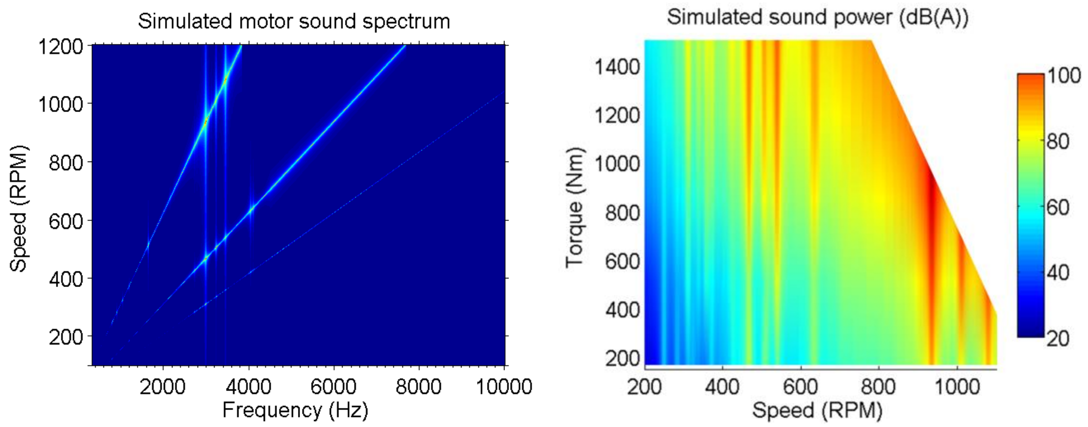

Figure 5: FEM simulated radiated acoustic noise for Elaphe L1500 motor. LEFT: waterfall diagram of sound power spectrum with the main harmonics. RIGHT: sound power over the whole motor operating range. SPL level from the motor at pass-by test is estimated to be 22 dB lower than calculated sound power, evaluated around 400 RPM and low torque.

2.2 Inverter induced ripple reduction

During the initial motor design phase, it is hard to perform a detailed evaluation of all aspects of the NVH characteristic, especially for those that are connected to the motor-inverter interaction. While the designed motor cogging is negligible, determined mostly by production tolerances, and the torque ripple is kept below 0.5% of full torque for every motor working point (shown in Figure 6), significant vibrations can still occur on the motor.

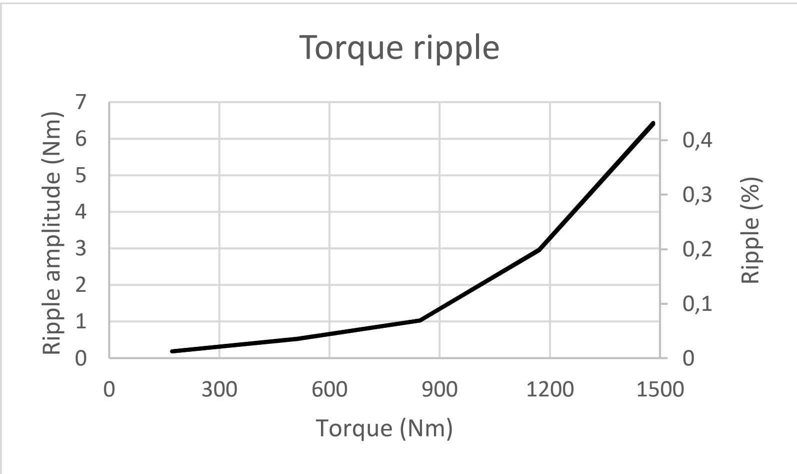

Figure 6: Torque ripple of Elaphe in-wheel L1500 motor

Thus, next to intrinsic ripple optimization, additional measures are required on the motor control level. While the choice of PWM frequency does not have a direct large impact in the case of low-speed direct-drive motors with relatively high PWM frequencies (>10kHz), there are several low frequency harmonics that appear due to the imperfect sinusoidal currents, being fed by thy inverter into the motor windings [3]. This ripple can be higher than the ripple obtained in motor design, considering sinusoidal current input, and can contribute a major part to structure-borne vibrations. Various algorithms can be implemented in motor control in order to compensate this effect.

From inverter-motor interaction three main sources of vibrations can be identified.

The first effect is connected to the dead time of transistor bridges in the inverter [4], which can significantly distort the waveform current that is being fed to the motor, as shown in Figure 7. This effect is most noticeable at low speeds and is especially expressed in motors with low phase inductivity. If it is not compensated, it can be a source of large vibration of the whole powertrain.

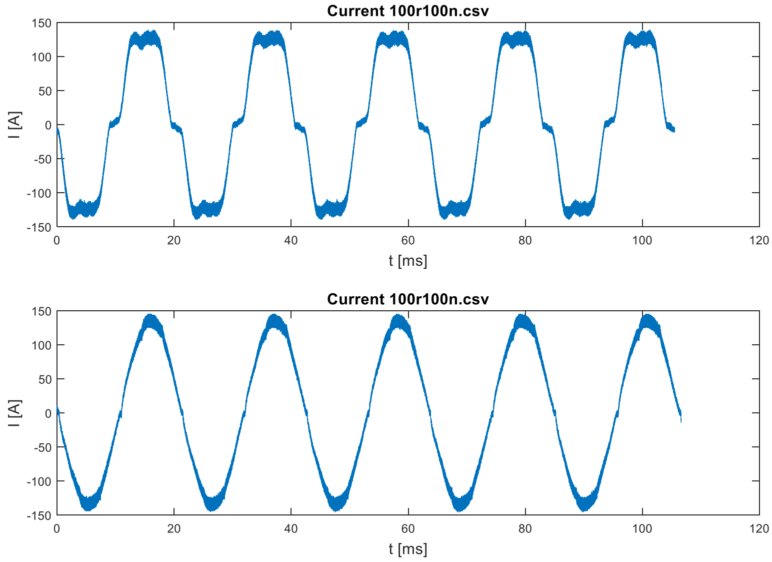

Figure 7: Current that is fed to the motor. TOP: current before compensation BOTTOM: current after compensation.

The second important effect is the current sensing inaccuracy [5] due to production tolerances of current sensors. One can expect up to 2 % offset and nonlinearity in these sensors, and on a 1500 Nm torque range, this can cause significant vibration levels, if not managed properly.

The third effect is position sensing inaccuracy [6], which is pronounced in motors with a high number of pole pairs, such as direct-drive in-wheel motors. This occurs since the electrical angle inaccuracy is proportional to mechanical and position sensor tolerances multiplied by number of pole pairs. Figure 8 demonstrates the nonlinearity of position sensing before and after compensation. The compensation of such inaccuracies affects the vibration levels over the whole operating range, but is most pronounced at high speeds.

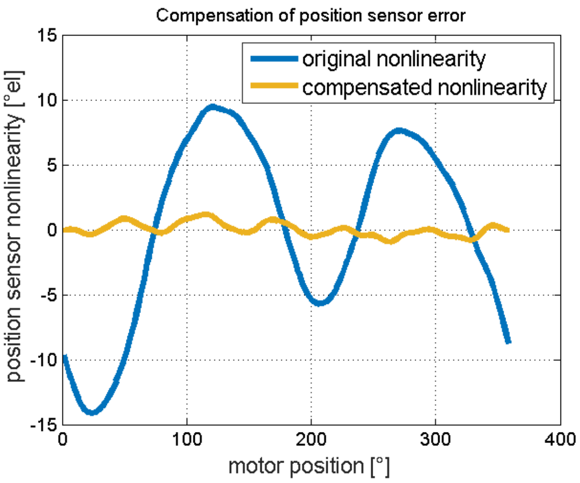

Figure 8: Extreme case of position sensor nonlinearity before and after compensation.

2.2.1 Injection of higher current harmonics

The compensation of sensing inaccuracy is also vital for the implementation of any active torque ripple reduction by current modulation, since the error angle is multiplied for higher harmonics of base electrical frequency. This method enables substantial removal of structural vibrations, but becomes less effective for higher harmonics and higher speeds, as the PWM frequency limits the maximum bandwidth up to which the higher harmonics can be compensated. Such modulation is successfully utilized in Elaphe in-wheel motors for removal of the primary 6 current harmonics, as shown in Figure 9.

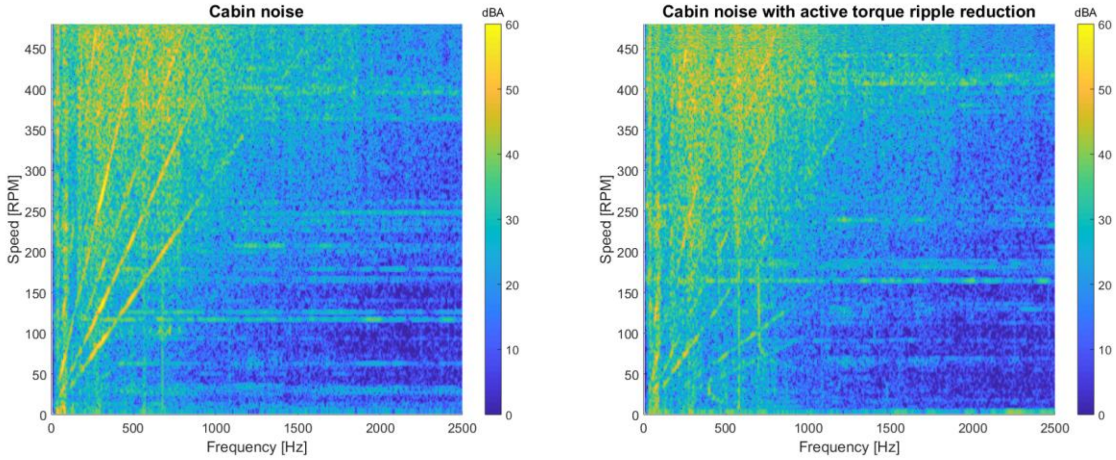

Figure 9: Waterfall diagram of cabin noise without (left) and with active torque ripple reduction (right).

2.3 System level approach by vehicle design

To address cabin noise by vehicle design, transfer paths have to be clearly understood. Measurements reveal that a vehicle suspension is able to effectively isolate all high frequency vibrations, as shown in Figure 10, where we see that none of motor vibrations above 500 Hz result in cabin noise. The presented case study implements standard torsion beam suspension, which is not tuned in any way towards vibration insulation from in-wheel motors, and additional work in this direction is expected to further improve the isolation characteristics. This result is also important from the point of applicability of active current modulation, as the bandwidth enabled by the PWM should already enable torque pulsation removal in this limited frequency range. For higher class vehicles, additional active cabin noise reduction can be effective in the concerned frequency range for total elimination of powertrain noise.

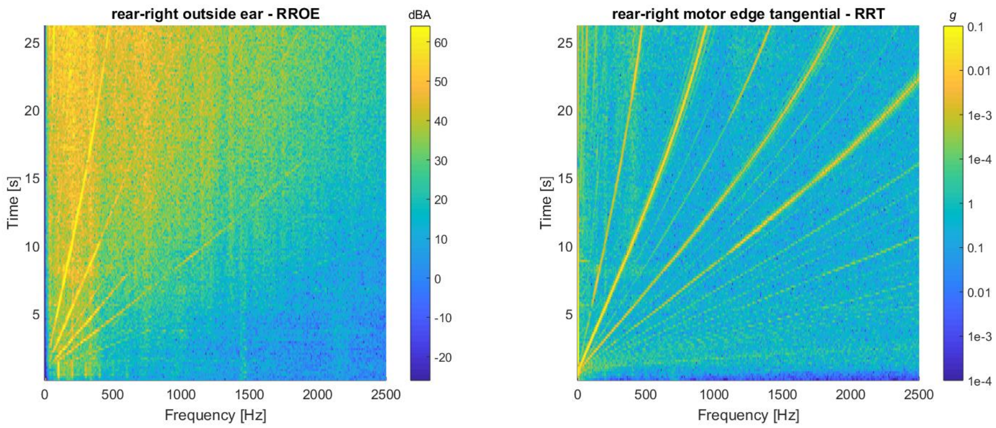

Figure 10: Waterfall diagram of cabin noise (left), and vibrations on the in-wheel motor (right) during maximum vehicle acceleration, without any compensation.

Another aspect that can be addressed on a vehicle level is the vehicle's pass-by noise. Even without any additional actions, the noise can be successfully managed in most applications. By minimally changing the vehicle design, modified rims and bumpers, which reflect airborne noise towards the vehicle and absorb most of it, can be considered, so that the noise does not propagate from the vehicle. The tests were performed with a closed rim in semi-anechoic environment, and the results reveal that a substantial reduction in noise emitted from the motor (and vehicle wheel) can be achieved. The sound pressure levels from the microphone positioned 0.7 m axially away from the motor in Figure 11 show that when rim openings were reduced to below 15% of the rim surface, the average noise level dropped by nearly 10 dB in comparison with a standard (mostly opened) rim. An additional drop of similar amplitude was recorded when the rim was fully closed. At least partially closed rims pose no problem for thermal aspects of brakes and motors already in current production vehicles. If directed air-cooling channels from the vehicle side can be implemented, also fully closed rims could become a reality.

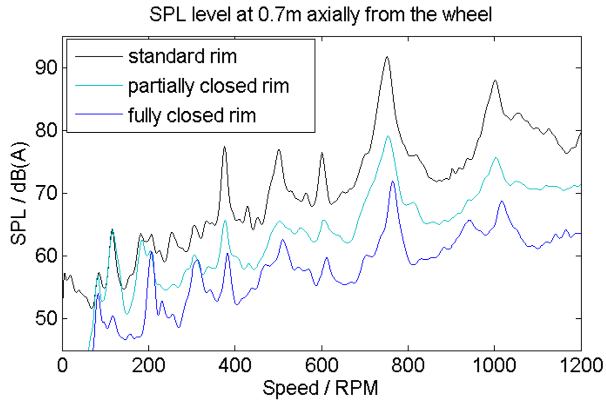

Figure 11: Reduction of radiation noise due to rim design, near the wheel.

3 Conclusions

This paper describes a holistic approach to NVH management, including several methods that have already been implemented in Elaphe-designed in-wheel electric powertrains. As demonstrated in this paper, each method on its own has a substantial influence on the noise and vibration behaviour of a vehicle. The result of combining these approaches in the new generation of Elaphe motors, which will remain unrivalled in the performance level of in-wheel motors, will feature a refined experience of the smooth and quiet powertrain for the user.

Several of the methods presented show the current state of development with standard inverter hardware components, and can be further improved, approaching and achieving operation without any noticeable harmonic components in the cabin. In the subjective overall evaluation, the least refined feature sets the threshold for the comfort level, and therefore none of the above aspects should be neglected in the development of the powertrain.

For in-wheel powertrain development it is even more critical, that the NVH aspects are considered already in the heart of motor development process, as due to specifics of available integration space and high torques and forces within the direct drive motor, less options for corrective actions remain during integration, compared to motors mounted centrally under the hood. As in-wheel motors become one of the mainstream choices in the mobility industry, vehicle-level solutions will play an important factor in the overall comfort experience, including tuning of suspension components for damping in the audible frequency range and active damping techniques for the most demanding applications.

Future cooperation with partners will therefore converge into a holistic vehicle NVH design, adjusted for in-wheel technology.

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