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Addressing acoustic behavior of hybrid and electric vehicles

Using simulation to avoid noise, vibration and harshness issues

Executive summary

Current processes for designing electric drives primarily focus on energy efficiency. However, carmakers must be careful this does not divert their attention from addressing acoustic behavior. Whereas overall noise levels are expected to be lower than the ones produced by internal combustion engines (ICEs), some issues may arise, especially when structural resonances coincide. Performing vibro-acoustic simulation and analysis early in the design cycle is a must to prevent this from happening, and deliver high-quality products. Simcenter solutions help engineers front-load design decisions for structural resonances and accurately predict related noise, vibration and harshness (NVH) behavior.

Introduction

In response to legislative measures that aim to reduce carbon emissions on one hand [1], and changing customer preferences for efficient as well as ecological types of personal transportation on the other [2], an increasing number of drivetrains are being electrified. The market projections for hybrid and fully electrified vehicle sales, as shown in figure 1, strongly suggest the increasing use of this technology in the future automotive fleet [3].

Developing electric motors for hybrid and electrical vehicles is challenging. Replacing the traditional internal combustion engine with an electric motor obviously dramatically changes the vehicle drive. But it also affects the vehicle's noise, vibration and harshness. Although the overall noise levels produced by an electric motor are typically lower than those produced by an ICE, the harmonic content becomes tonal. As a result, the noise signature is often perceived as being annoying [4]. Additionally, having lower background noise increases the relative importance of secondary noise sources, such as road and wind noise, and noise generated by fans and electric auxiliaries.

The electric motor design community usually tackles NVH issues by exclusively focusing on reducing torque ripple (tangential forces) [5]. However, this paper also details the additional influence of radial forces on the noise signature. A detailed vibro-acoustic simulation approach in the early design stages allows electric motor/drive engineers to better understand all physical phenomena involved. In this way, they can minimize or even avoid excessive vibrations and negative noise perception.

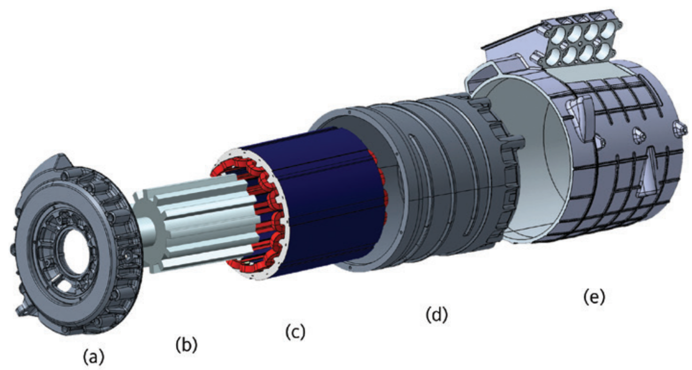

Figure 2: Main components of electric machines: (a) Cap; (b) rotor and shaft; (c) stator and windings; (d) cooling jacket and (e) housing.

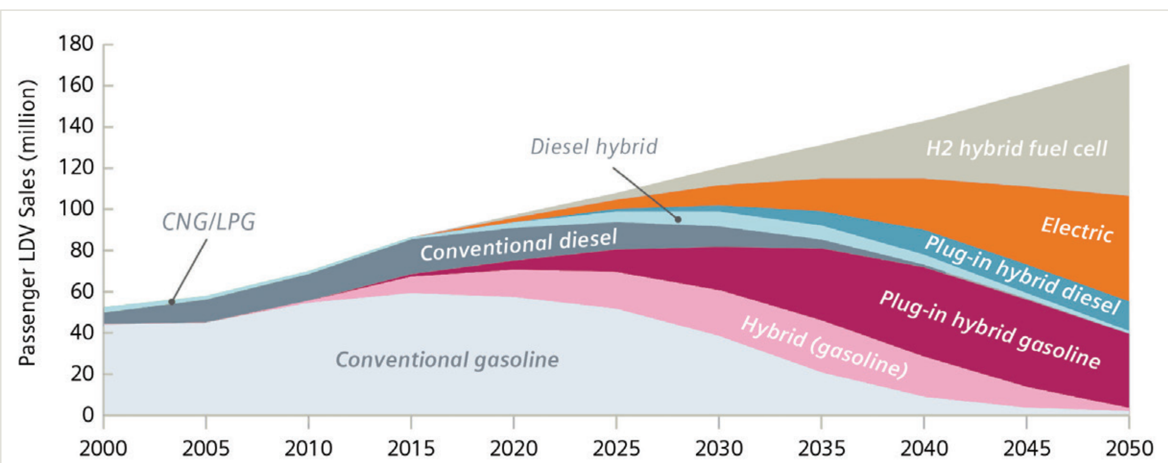

Figure 1: Annual sales of light-duty vehicles, BLUE Map scenario, 2000-2050 (Source IEA [3]).

Structural resonances account for most noise

Electric motors have a number of components in common, as illustrated in figure 2. These components along with others can contribute one way or another to noise. Some common sources are: electromagnetic (EM) excitation of the structure, aerodynamics (from the relative motion between rotor and stator), bearings (mostly associated with bearing defects and poor design), misalignment and imbalance (due to assemblage). Noise issues generated by EM excitation of the structure need to be addressed in the design stage.

A literature study shows that focusing on reducing torque ripple to decrease electric motor noise radiation is common industry practice [5, 6, 7, 8 and 9]. This unilateral approach is applied to different electric motor types, including brushless permanent-magnet motors (PMM) [4], permanent-magnet synchronous motors (PMSM) [6], brushless DC motors [7] and switched reluctance motors (SRM) [9]. These studies show that to a large extent, torque ripple causes fluctuation in the tangential forces applied to the rotor. So it plays a crucial role in evaluating the motor's operational performance. But torque ripple is not the only root cause of NVH issues. This white paper shows that structural resonances, particularly radially-excited planar modes, are crucial aspects to take into consideration when studying electric motor noise. Unfortunately, they cannot easily and directly be related to torque ripple. Yet this study intends to provide a deeper understanding of the noise-generating mechanism, enabling designers and engineers to better address NVH issues during the early stages of the design process.

Acoustic and structural responses related to rotating machinery are usually evaluated in a run-up test. Resulting physical magnitudes can be plotted as a function of the linearly increasing rotational speed; for example, in a waterfall diagram. Figure 3 shows an example of such a test for a SRM.

Two dominant phenomena can be observed in this figure (highlighted in the bottom image of picture 3 as yellow gradient lines and a red vertical line):

- The gradient lines are motor order lines. At any stationary rotational speed, any response spectrum will show discrete peaks at fundamental frequencies, corresponding to the harmonics and sub-harmonics of the motor's operation. As these peak frequencies shift linearly with changing rotational speed, they can be observed as straight gradient lines in the waterfall display. Figure 3 shows that the fundamental (or lowest) order for this particular motor is order 6. That corresponds exactly to the number of electric poles

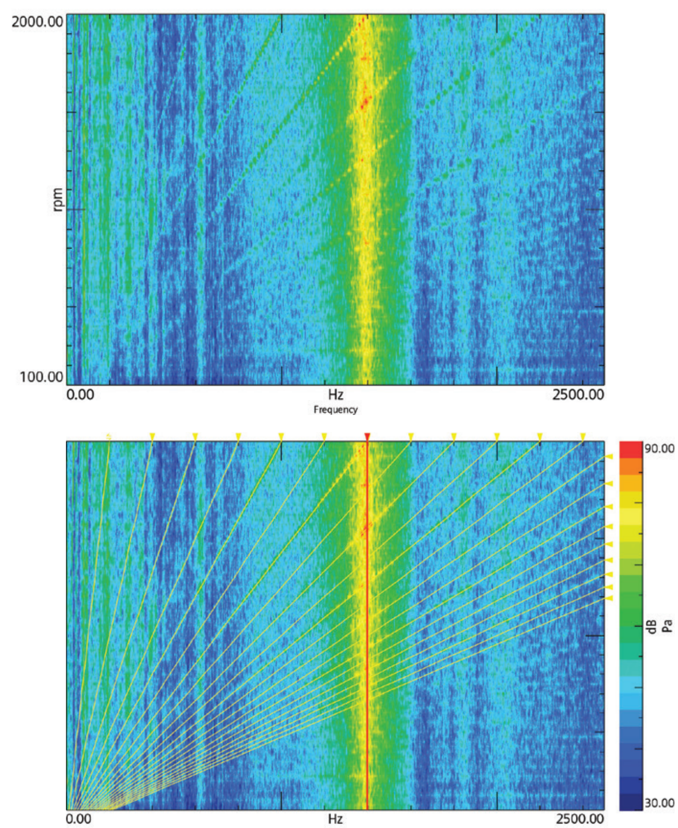

Figure 3: Measurement of a SRM motor noise signature.

- The vertical lines are independent from the rotational speed and correspond to structural resonances. These can be investigated using modal analysis. Testing this specific motor structure showed an ovalization mode around 1,390 hertz (Hz), which perfectly matches the frequency of the vertical line in figure 3

Acoustic responses are highest for combinations in which both phenomena coincide. This is where order lines and resonance lines intersect. In these cases the energy, which is introduced by the harmonic electromagnetic force, is reinforced largely because of the low mechanical impedance of the structure at these frequencies. In other words, both source and energy transfers are maximal. Accurately predicting this interaction requires multi-physical simulation. A simulation strategy that captures the behavior of the entire system helps explain how the noise signature measurements look like.

Noise sources in electric motors or drives

Electromagnetic forces are generated when rotor and stator are unaligned. These have a radial and tangential component, as illustrated in figure 4. For operational purposes, the tangential component is the most interesting one, as it produces the power. The radial component is absorbed in the rotor and the stator, and transformed in an elastic deformation.

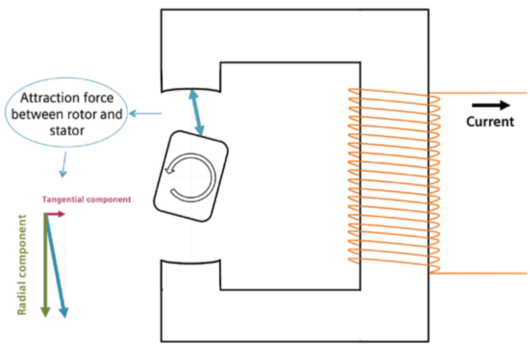

Figure 4: Electromagnetic forces as generated in a SRM.

As shown in figure 4, the attraction force on one of the stator teeth can be split into a tangential component (red) and a radial component (green). Plotting these as a function of mechanical angles for a motor that has a single pole symmetry shows that radial forces have much higher amplitudes than tangential forces (figure 5). Consequenty, they have the potential to be the main sources of vibration and related noise.

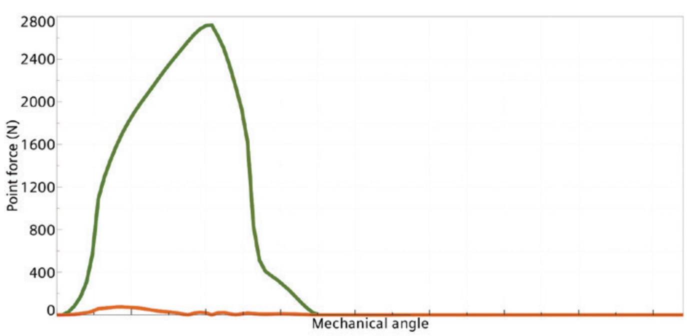

Figure 5: Evolution of radial and tangential forces on a stator tooth for a motor with a single pole symmetry.

On top of that, engineers can investigate how the structure dynamically responds to that force input. By considering the contribution of each individual force component to accelerations on the outer surface, they can calculate the corresponding transfer functions. Figure 6 shows that planar modes dominate the structural response, and that the radial force components play the most important role in exciting such modes.

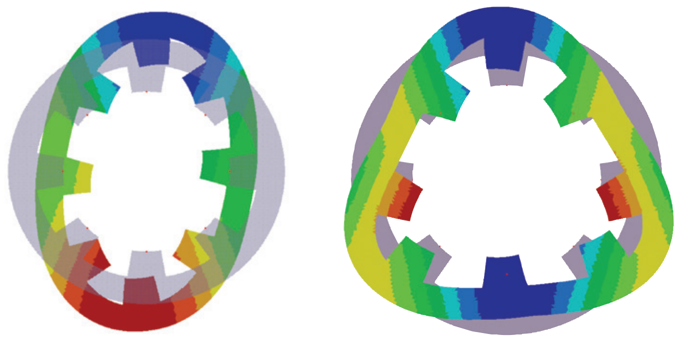

Figure 6a: Ovalization and triangular mode shapes.

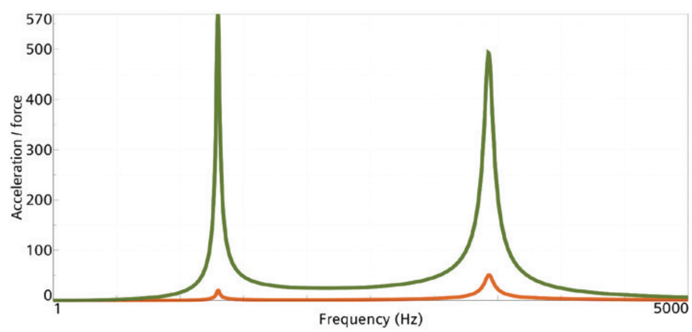

Figure 6b: Transfer function between the tangential (red) and radial (green) force component and an outer surface acceleration.

Combining these two observations, one can conclude that the noise signature of an electric motor will be primarily defined by the fluctuation of radial forces rather than tangential forces. When addressing NVH issues in electrified systems, engineers have to consider this without discarding the possible effect of tangential forces and torque ripple as they can cause rattle noise in the transmission.

The vibro-acoustic simulation process

By definition, noise produced by electric motors involves multi-physical simulation, as harmonic electromagnetic forces excite structural vibrations, which then result in noise radiated from the outer surface. In such cases, the challenge is usually to numerically describe the coupling between the different domains. In case of strong coupling, for example, various domains need to be solved simultaneously, as they interact. However, this specific case demonstrates a weak coupling between all domains. It cannot be expected that stator deformations influence the electromagnetic forces too much, or that the acoustic pressures influence the surface vibrations [10]. As such, a simple cascaded simulation procedure can be applied, in which the result of one domain can be simply transferred to the next one as a boundary condition.

The NVH analysis begins with electromagnetic calculations to find the forces on the stator. These forces are calculated as shown in the lower part of figure 7. The resulting forces are transferred onto a structural finite element (FE) model. In this case, Simcenter 3D™ software was used. The vibrating modes of the stator are calculated, followed by a modal-based forced response simulation of the structure as specified in the upper part of figure 7. Next, the resulting displacement of the stator is mapped to an acoustic mesh and is used as a boundary condition for the vibro-acoustic radiation problem.

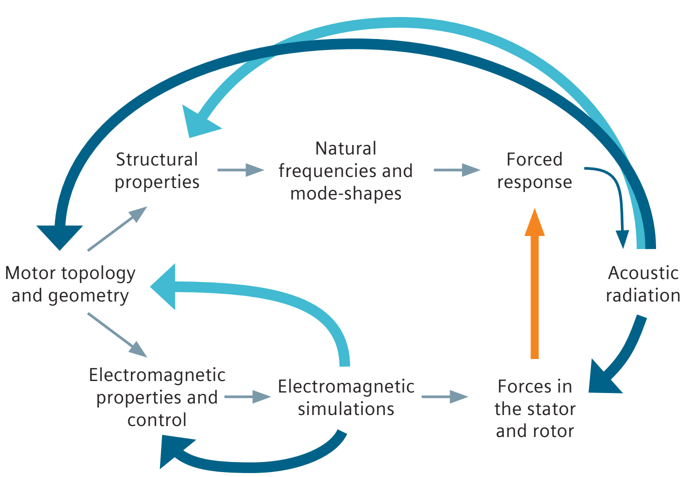

Figure 7: Design diagram for a complete multi-physical NVH analysis of electric motors.

Figure 7 shows the different steps or iterations a particular design follows when addressing both electromagnetic and NVH problems. When issues with the final electromagnetic design arise, they can be addressed by either altering the EM properties (selection of different materials, different control strategy, etc.) or by redefining/changing the geometry and topology of the motor. Additionally, NVH performance can be improved by comparing the final simulated acoustic signature with specific targets, and applying corrections to the structural properties and motor geometry, or by reshaping the force profiles applied to the structure.

Essential to this process is having powerful simulation tools for electromagnetic and vibro-acoustic predictions, such as JMAG® simulation software and Simcenter 3D. For vibroacoustic analysis, Simcenter 3D software provides abundant prediction capabilities, and can be seamlessly integrated within a multi-physical process. Using Simcenter 3D software to realize a strong correlation between simulation and experimental tests is described in the paper, "Multiphysics NVH Modeling: Simulation of a Switched Reluctance Motor for an Electric Vehicle, IEEE Transactions on Industrial Electronics" [10].

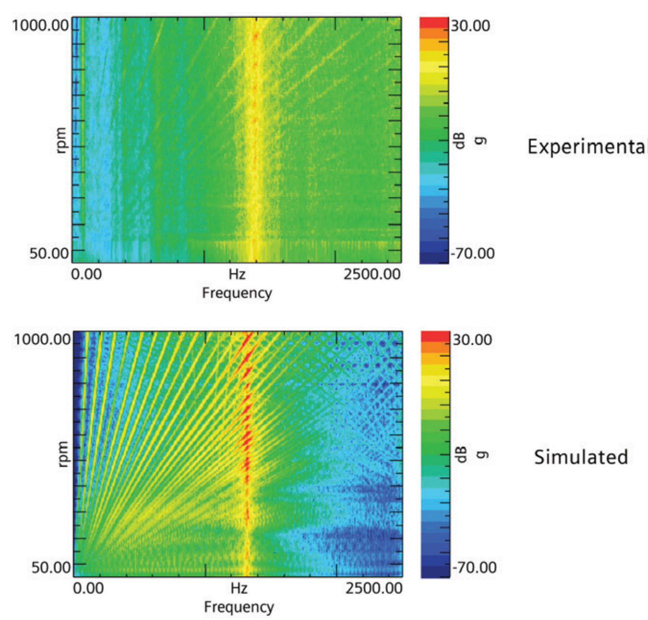

Figure 8: Run-up experimental and simulation from 0 to 1,000 rotations per minute.

Conclusion

This white paper demonstrates the value of taking a new approach to electric motor design. In order to successfully address any acoustic issues in electric drives and comply with customer demand for high quality, motor designers have to include advanced and comprehensive NVH analysis in the early design stages of vehicle development. This white paper recommends a shift in attention, as the radial component contributes substantially more to electric motor noise than torque ripple. To fully capture the mechanisms and major contributors of the acoustic signature of an electric motor, an advanced vibro-acoustic analysis is advised.

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