Influence of Model Detail Level on the Prognosis Quality of the Perceived Sound of an Electrified Passenger Car Powertrain

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Abstract. Complex and resource intensive multi-physical models which integrate the domains of electrotechnical, structural dynamics and acoustics are needed to predict the noise, vibration and harshness (NVH) behavior of an electric passenger car drive train. Because of the highly limited resources in product development process of cars, engineers request efficient models with a good balance between accuracy and model creation as well as calculation effort. Knowing about which components and effects influence the prognosis is essential to adjust this balance between accuracy and effort. Therefore, in this paper a method is presented to determine the influence of the model fidelity level on the prognosis quality of the perceived drive train-related airborne sound under the use of hearing tests to consider the human noise perception. The work is based on a high fidelity multi-physical NVH of a small, series-produced electric vehicle drivetrain which is validated in structure- and air-borne-noise against test bench measurements. The influence of model detail level on the prognosis quality is analyzed using the aforementioned method taking into account four exemplary variant calculations of the proposed model: (1) Power electronics harmonics vs. ideal sine electric machine current, (2) electric machine with vs. without production deviations, (3) modal damping parameters derived from component measurements vs. modal damping taken from literature, and (4) numeric vs. analytical sound calculation method.

1. Introduction

Distinctive design and noise characteristics of vehicles are important, brand-specific differentiators in terms of aesthetic and emotional criteria. Hence, designing a sound that matches the vehicles' character and corresponds to customer expectations has always been a central task. In this process, simulation is an important tool. [1]

For the prognosis of an electric car drivetrain induced sound, typically multi-physical modelling approaches with a variety of model fidelity levels are used. This includes different methods for coupling the domains of electronics, structural dynamics and acoustics involved in the generation and transmission of noise, as well as different domain-specific models. The challenge is the efficient interdisciplinary combination of different, highly specialized models and computation methods that work in the time or frequency domain, as well as the definition of their interfaces [2].

The focus of past work regarding electrical machines, performed by electrical engineers, has often been the aspect of exciting forces [3], which includes field and force calculation and for more sophisticated approaches also a circuit simulation. However, state-of-the-art NVH simulation chains [4, 5] combine this aspect with the structural dynamic behavior. This can e.g. be achieved by methods of transfer path analysis as in [5], or by calculating excitation forces at the stator teeth and at the bearing points for a subsequent forced-response analysis as in [6]. All referenced approaches share the neglection of feedback effects. To include these, the electrotechnical and structural dynamics domain both have to be calculated in the time domain.

In structural dynamics domain in practice methods like torsion vibration [14], (elastic) multibody simulation (EMBS) [7, 8] or finite element method (FEM) models [9] are used. Mechanical engineers tend to focus on structural dynamics using precalculated electromagnetic force excitation spectra and neglect electric current feedback effects. [7, 8, 9]

The coupling between the domains of structural dynamics and acoustics is typically classified as weak [10]. This is due to the low reaction of the air on the drive train and, in principle, enables the structural dynamic and acoustic calculation to be done consecutively [11]. The surface velocities required for the acoustic calculation at each mesh node can be reconstructed by using the time-dependent modal velocity in combination with the recovery matrix, which establishes the connection between modal and nodal velocity [12]. However, the amount of data to be processed requires skillful handling, which is why occasionally either analytical radiation models are used [7, 8] or the system is often cut at the bearings. In this case, the bearing forces are calculated in time domain transformed into the frequency domain and the airborne noise is calculated using a finite element model of the drive train housing and boundary element model of the air envelope [14]. With this approach the interaction between the shaft system and housing [15] is neglected.

The frontloading effort for creating, parameterizing and calculating such Multiphysics models is high. Thus, models with an appropriate level of accuracy are required. However, today it is hard to judge the expediency of models, because the effect of different model fidelity levels on the predicted noise behaviour of a complete electric drivetrain has been investigated rarely in literature.

In [16] the influence of electrical machine stator modelling on the spatially averaged square of housing surface velocity of an electric drivetrain for the response Order 1 of the electric machine (EM) is analyzed. They found out that the transversely isotropic material model does not affect the general trend in the response but does show an increase in magnitude.

To what extent detailed modelling improves the prognosis quality of the perceived sound compared to simple modelling approaches is not investigated in literature. Hence, in this paper a method is presented to determine the influence of the model fidelity level on the prognosis quality of the perceived drive train-related noise with hearing tests considering the human noise perception. Therefore, a high fidelity multi-physical NVH of a small, series-produced electric vehicle drivetrain is presented which is validated in structure- and air-borne-noise. The influence of model detail level on the prognosis quality is analyzed using the method of four exemplary variant calculations of the proposed model.

2. Approach

For setting up the approach to determine the influence of the model fidelity level on the prognosis quality of the perceived drive train-related noise, a central question is, what base model should be chosen? Should it be a more realistic, but complex model which will simplified as part of the investigation? Or should be taken a more artificial, but simple one, which is increased further in complexity? To answer this question, one has to be aware of aspects of the interactions of component models and human perception of sound. In context of human perception of sound, one important aspect is masking. In simple terms, masking occurs when a tone can no longer be heard due to the level of other noise sources. Besides that, the interaction of model components describes the dependency of the behavior of one component model from the other. For example, in a gearbox model the complexity of a bearing model (linear vs. nonlinear) leads to a different meshing situation and thus, to a different noise spectrum. Being aware of these phenomena, a complex model with a high degree of realism and a noise spectrum as complete as possible is chosen as the base model.

Therefore, in the first step of the overall approach, a transient high-fidelity multi-physics simulation is built and validated. It's including most of the often-discussed components and effects which are relevant for the sound of electric drivetrains. For example, this includes power electronics and control, a fully coupled structural dynamics model between shafts and housing, as well as an accurate acoustic radiation model. With this, feedback in the current and the loads between the electrical and structural dynamics model and production deviation like geometric and magnetic eccentricity are taken into account. This model is the starting point for the analysis of several model simplifications and the analysis of their influence by means of a hearing test. (Figure 1)
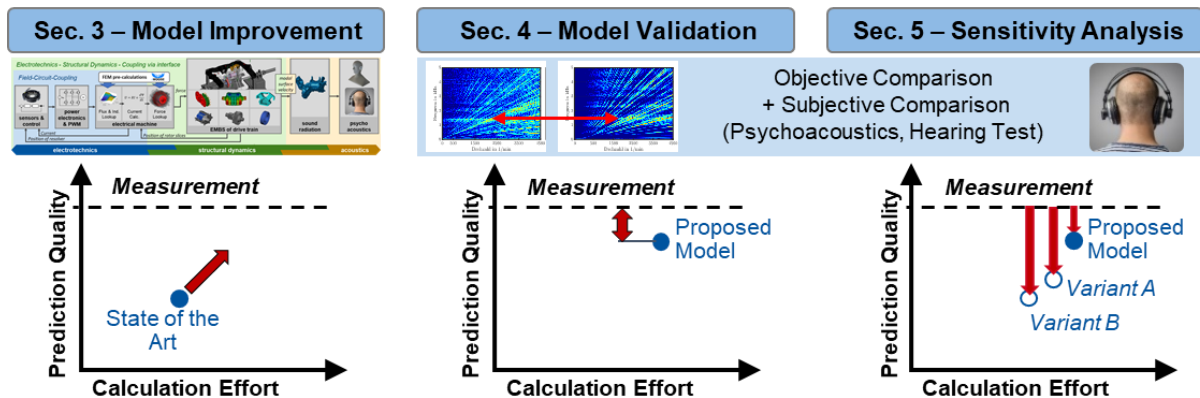
Figure 1. Approach to determine the influence of the model fidelity level on the prognosis quality of the perceived drive train-related noise with hearing tests considering the human noise perception.

3. Multi-Physical modelling approach

On the top level, the simulation chain consists of three parts according to the three domains: The electrotechnical domain, the structure dynamics domain, and the acoustics domain (Figure 2).
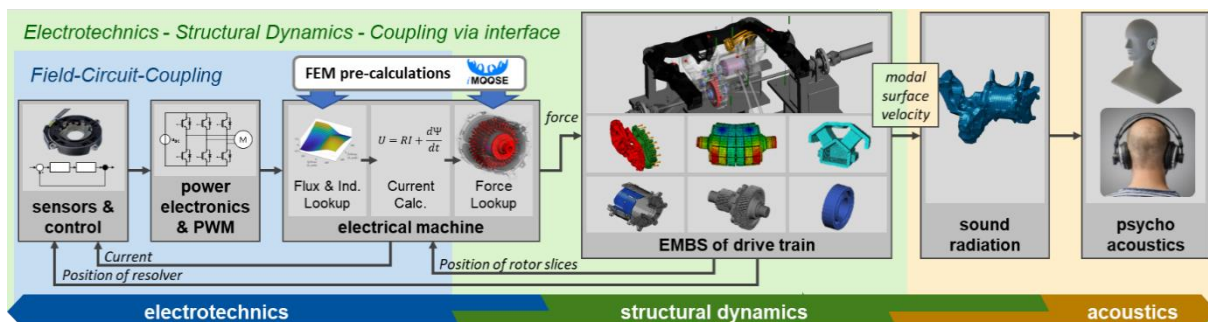
Figure 2. Overview of the simulation chain.

The electrotechnical model is a circuit simulation including an advanced representation of a PMSM. Via the interface described in section 3.2 it is physically, not numerically, strongly coupled to the structure dynamics domain, which is an EMBS. Output of the EMBS is the surface velocity, from which the radiated sound is calculated in the acoustics domain. This interface (section 3.4) is unidirectional, since the effect of the airborne sound on the structural dynamics is small and thus negligible.

3.1. Electrotechnical Domain

The electrotechnical approach is extensively described in [17], here a brief summary is given. According to Maxwell's stress tensor, magnetic forces are proportional to the square of the magnetic flux density. Its determining parameters, also considering the dominant non-idealities, are

1. The excitation from the current, whose calculation is described in section 3.1.
2. The excitation from the magnets. The scattering of the permanent magnet remanence is in the order of ±5 % according to the manufacturer's data sheet, which is supported by our own measurements. It is considered in the field calculation. Geometric deviations like magnet position are not addressed in this paper but can also easily be considered.
3. The magnetic conductance of the airgap as primary magnetic resistance. The dominant influence on the airgap is the eccentricity due to displacement or bending of the shaft. In various analytical [18, 19] and numerical [20] studies, dynamic eccentricity has been identified as the cause of sidebands and is therefore also modeled here.

3.1.1. Field- and Current Calculation

The field calculation and the circuit simulation including the power electronics are connected according to the approach from [5] and [21], hence decoupled due to the difference of the time constants. It is extended to the multi-slice method as shown in [22]. The field of the PMSM with buried magnets is calculated stationary, subsequently it is only dependent on the state variables rotor angle γ and current id and iq. The eccentricity extends the state space of the field calculation in 2D by the eccentricity radius r_{ecc} and eccentricity angle φ_{ecc}. The calculation is performed in advance in parallel using the FEM software iMOOSE from the Institute of Electrical Machines. The flux linkages Ψ_d, Ψ_d, Inductances L_d, L_q and tooth forces (see section 3.1.2) are stored in characteristic maps.

3D effects are approximated by means of the multi-slice method (see [22]). To reduce calculation effort the same LUTs can be used for all slices, in this case differences in production deviations between slices can be approximated by rotation angle offsets many times a pole pitch.

The symmetry of the PMSM reduces the number of field calculations required. To get forces at all teeth, which differ because of the eccentricity, a full 2D model is used. The stator geometry shows symmetry by the slot pitch, which has to be covered by the eccentricity angle dimension. If magnetization deviations are considered, the rotor has no symmetry making a full rotation necessary for the rotor angle dimension, otherwise a pole pitch is sufficient.

3.1.2. Tooth Forces and Eccentricity

The nodal forces from the FE calculation must be prepared for the modal representation of the EMBS with its limited number of force application points, and aliasing must be avoided. The order reduction from [23] summarizes the nodal forces on each tooth tip and transforms them into a tooth-specific coordinate system (tangential / radial / axial). The axial force is estimated for the continuously skewed machine from the skew angle and the assumption that the tan. force acts orthogonal on the tooth flank.

To remove aliasing problems while containing a good execution speed. the LUT of tooth forces has to be processed as illustrated in [17]. In short, the rotation dimension is Fourier-decomposed and high orders are neglected. Then it gets resampled, and finally some data is discarded to prevent redundant but mismatching forces which disturb the EMBS. The resulting tooth forces are illustrated in Figure 3.
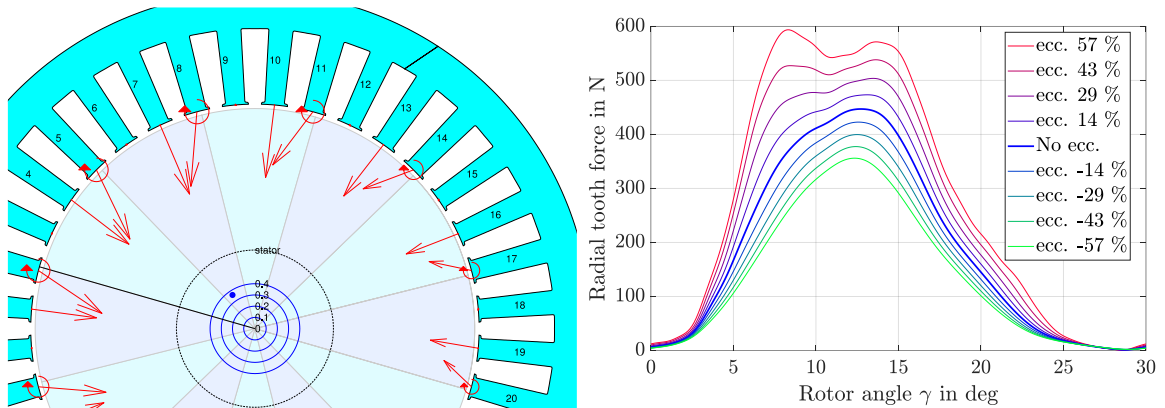
Figure 3. Tooth forces at 80 Nm; Left: All forces with radial, tangential and torque component at one rotational step which is at 0.37 mm (53 %) eccentricity to the top left; Right: Radial force at one tooth for different eccentricities (airgap widths) over one pole pitch.

3.2. Interface between Electrotechnical and Structural Dynamics Domain

The electrotechnical domain structural dynamics domain both run simulations in the time domain with variable step-size solvers to account for nonlinearities. The circuit simulation is implemented in MATLAB Simulink (MathWorks). The EMBS is implemented in Multi-Body Simulation framework called SIMPACK, which features an interface to Simulink. It works by a fixed rate data transmission, which, as compromise between execution speed and frequency resolution, is set to 60 kHz in the investigations shown in this paper. To avoid aliasing in the interface, it is necessary to lowpass the high frequency current, but with little phase lag. A second-order Butterworth-filter (corner 20 kHz) is chosen as a compromise.

In each time step the circuit simulation provides the machine current i_d and i_q to the EMBS, which in return feeds back the rotor angle γ of each rotor slice. The force Lookup is performed in the EMBS, which has the advantage of the EMBS being able to run with an ideal current and therefore without the circuit simulation, effectively modeling a perfect controller. For the force look-up, via symmetries the machine state is reduced to a state which is mapped in the LUT [17].

3.3. Structural Dynamics Domain

The structural dynamics NVH model includes the drivetrain components electric machine with coolant, gearbox with differential, side shafts, support arms, subframe and coolant supply (Figure 2).
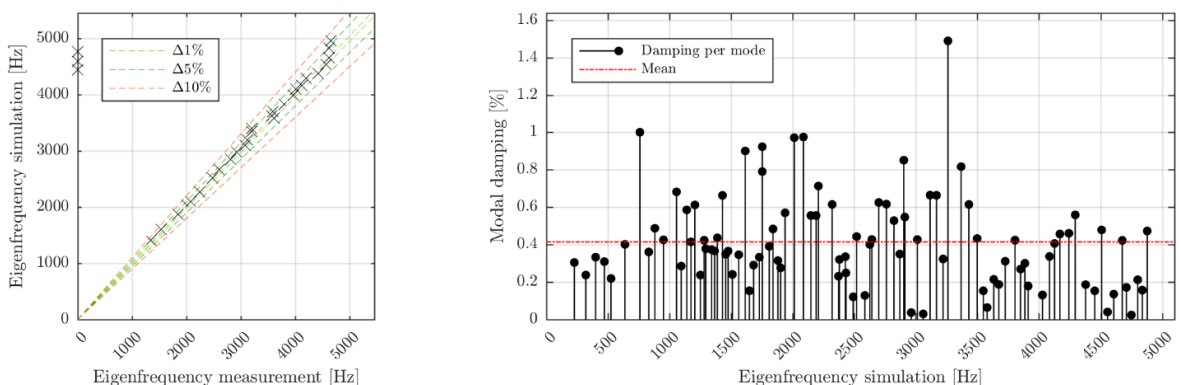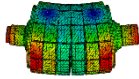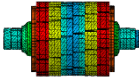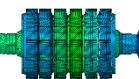

Figure 4. Left: Eigenfrequencies for the gearbox housing assembly by measurement and simulation; Right: Modal damping of the drivetrain housing assembly.

The components are idealized with elastic bodies and coupling elements (force elements and joints). The structural dynamic properties of rotor and stator, which are characterized by a layered structure, are modeled with the help of material models with direction-dependent properties and

parameterized using methods of multi-scale modeling (representative volume element - RVE) and measurements. In addition, the load-dependent, non-linear stiffnesses of the deep groove and tapered roller bearings as well as the excitation behavior of the gear are integrated in this environment. Joints are used to model the kinematic behavior of tripod and constant velocity joints of the side shafts.

Elastic component models have been extensively validated with modal analysis and impedance measurements. The results for housings (Figure 4) and rotor (Table 1) are presented here as an example.

Table 1. Mode shapes and eigenfrequencies of the rotor by measurement and simulation.

| Mode		Measurement		Simulation		Deviation
#	Type	Shape	Frequency	Shape	Frequency	
1./2.	Bending		3741 Hz		3753 Hz	0,32 %
3.	Torsion		4022 Hz		3919 Hz	-2,56 %
4.	Axial		5500 Hz		5601 Hz	1,84 %

Furthermore, the imbalance condition of the rotor is measured in the bearing planes and considered in the modally reduced EMBS model of the rotor. The investigated rotor fulfils the requirements of balance quality 2.5 as the usual balance quality for high-speed electrical machines.

3.4. Interface between Structural Dynamics and Acoustics Domain

The calculation of the sound radiation by means of a state-of-the-art Boundary-Element-Method-simulation (BEM) requires (spatially and temporally) high-resolution export of the surface velocities on the drive train which leads to a practically unmanageable amount of data in this case. Therefore, a minimum data representation under the use of the ATV (Acoustic Transfer Vector) Method [12] is applied. The ATV between the housing velocities and the resulting sound pressures at selected receiver points represent the transfer properties of the air volume taking into account the radiating housing geometry [24]. Once the ATV matrices have been determined for all frequencies, the calculation of the resulting sound pressures for any load case is performed as a simple vector product of the velocity distribution on the surface mesh and the calculated transfer vectors. The transient surface velocities required for each node of the acoustic model are calculated per time window, transformed into the frequency domain, and then multiplied with the ATV-Matrices. After corresponding calculation for all time windows of a simulated run-up, inverse transformation and superposition in the time domain are performed. Detailed description can be found in [25].

3.5. Acoustics Domain

A BEM model considering all partial elements of the entire drive train geometry as radiating enveloping surface is used to calculate the ATV-Matrices (Figure 5). The mesh with nearly 100000 nodes is suitable for the calculation of air borne sound up to a frequency of 16 kHz.
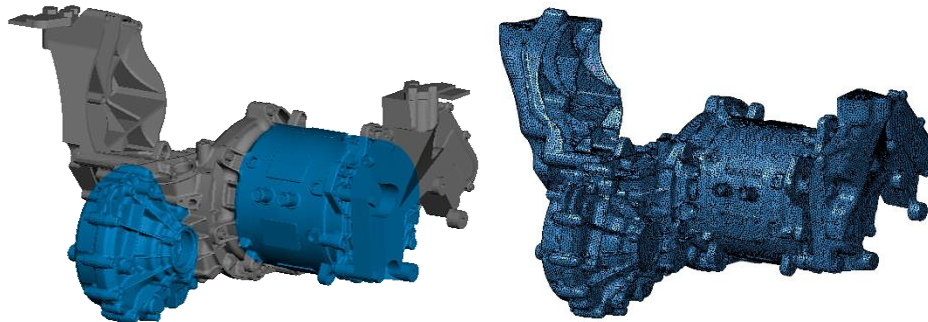
Figure 5. Left: Approximation of gearbox and stator housing by means of replacement cylinders; Right: Boundary element housing model (mesh) in LMS Virtual.Lab.

4. Validation

Simulation results for the electric machine current show good accordance to the measurement and represent the machine harmonics (-5, +7, -11, +13, etc.) good as well as the harmonics from the pulse width modulation (PWM) of the inverter (Figure 6). However, the PWM harmonics amplitude is too low due to the neglected nonlinear behavior of the machine inductance which decreases at higher frequencies. This effect requires some kind of hysteresis in the time domain and therefore is difficult to implement.
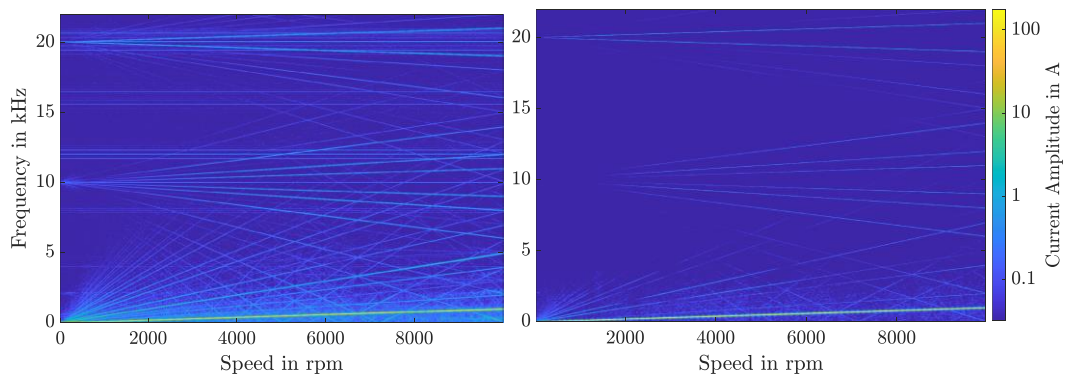
Figure 6. Comparison between the measured current (left) and the simulated current (right).

In the following sound pressure level (SPL) (Figure 8) and acceleration at an exemplary point orthogonal on the electrical machine surface (Figure 7) are investigated.
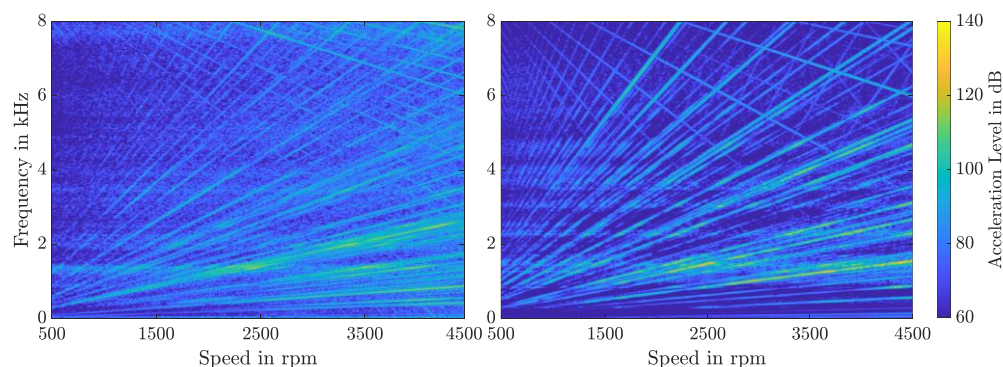
Figure 7. Surface acceleration radial on the housing of the electrical machine; Left: Measurement. Right: Simulation. Runup at 80 Nm.

A good agreement is achieved, especially regarding the main harmonics. Peaks in acceleration level resulting from natural frequencies, especially in the lower frequency range up to 5 kHz, are well represented in the simulation. The allocation of the harmonics to their origin reveals that the gearbox

of the examined drive train dominates the NVH behavior compared to the acoustically unobtrusive PMSM. Furthermore, in the simulation the rotor of the electric machine has a very low dynamic eccentricity. Therefore, sidebands do arise solely from the 'magnetic' eccentricity.

Deviations between measurement and simulation can be observed: E.g., PWM harmonics are missing, probably due to the three parallel paths of the winding on 120º of the motor circumference each, which allow for minor equalizing currents. In addition to that, underrepresented grinding noises in simulation could be caused by the missing excitation of the side shaft models. Furthermore, the gearbox oil filling and therefore the mass and damping influence is ignored. And in the context of acoustic radiation calculation surrounding passive components are neglected. Nevertheless, the reference model far exceeds the state of the art and is rated suitable for valuable variant simulations.
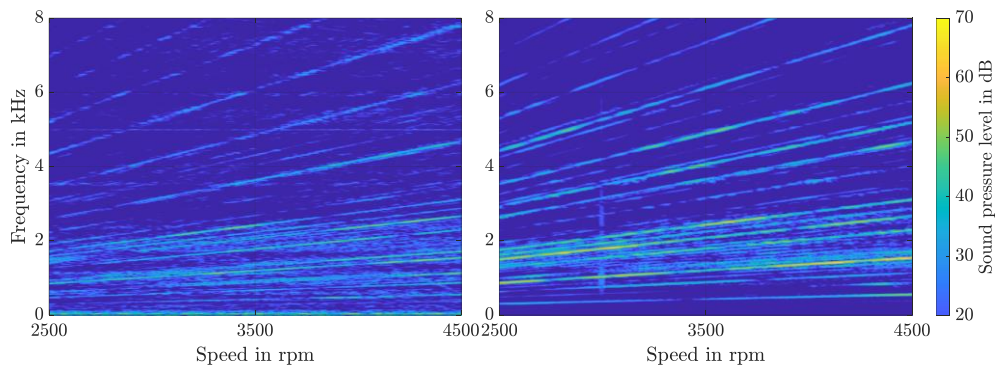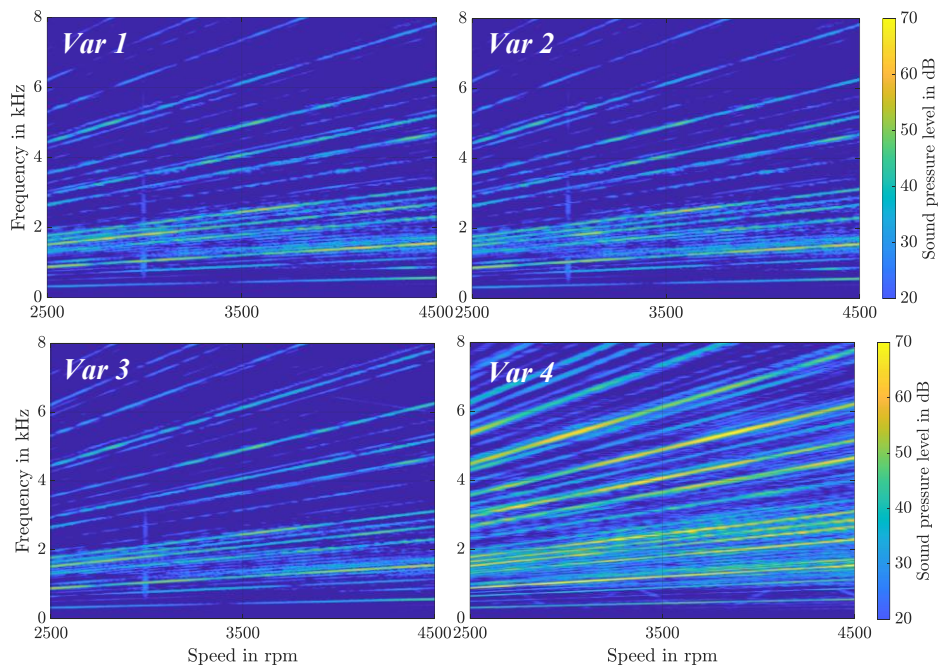

Figure 8. Sound pressure level 1 m above the center of the drive train; Left: Measurement; Right: Simulation.

5. Sensitivity analysis

5.1. Variant models and objective results

Within this section the variant models of validated simulation chain are presented and compared against the reference simulation in terms of SPL (Figure 9).

Figure 9. Sound pressure level 1 m above the drive train center, runup at 80 Nm; Top left: Variant 1, ideal current; Top right: Variant 2, ideal electric motor; Bottom left: Variant 3, 2 % modal damping; Bottom right: Variant 4, analytical sound radiation model.

5.1.1. Variant 1: Ideal Current

The first variant assumes an ideal controller which keeps the current perfectly constant at any time. This is done by feeding the force lookup with a fixed current combination. As expected, the PWM harmonics are missing in this variant. The motor current harmonics are also not present, but even in the reference simulation they are so small that they cannot be separated from other excitation orders.

5.1.2. Variant 2: No Production Deviations in Electric Machine

Variant two assumes an ideal electrical machine to determine the influence of its production deviations. Within this model, the rotor eccentricity has no effect on the electromagnetic force calculation and all magnets properties are set equal. As expected, a small difference to the reference simulation can be seen (Figure 12). As stated above, the drive trains NVH behavior is dominated by the two transmission stages, the PMSM is fairly quiet even with its production deviations. To some extend the PWM harmonics are reduced in this variant.

5.1.3. Variant 3: Damping from Literature

The third variant tunes all modal damping ratios of the housing group in the EMBS to 2 %, a value from a standard range given in literature [26]. The result shows that the sensitivity of the surface acceleration for the modal damping is rather low. The measured values of the housing group scatter between 0.02…1.5 % with a mean of 0.43 %, thus with a 2 % value the mean surface acceleration level is slightly reduced.

5.1.4. Variant 4: Analytical Sound Radiation Model

The existing velocity data is sampled on the housing parts (stator and gear housing), which are approximated as cylinder bodies, both in axial and in circumferential direction (Figure 6 left). According to the underlying theory, only those modes on cylindrical bodies contribute to the radiated airborne sound whose wavelength is greater than or equal to the considered airborne sound wavelength [27]. Since at least two interpolation points per wavelength are necessary for the correct description of these modes, the maximum interpolation point distance required for an upper cut-off frequency of 16 kHz is about 1.1 cm. On the ends of the cylinder bodies, which are regarded as ideal piston radiators, the velocity is scanned at the same spatial distance. The detailed mathematical derivation of the formulas used in the analytical approach can be found in [7].

5.1.5. Psychoacoustic Evaluation

For the test bench measurement, the reference simulation and the four selected model variants, the single values of the following psychoacoustic parameters, averaged over the entire signal duration, are listed in Table 2: Loudness (DIN 45631/A1), Sharpness (DIN 45631/A1; DIN 45692), Roughness (Hearing Model Sottek), Tonality (Hearing Model Sottek) and Psychoacoustic Annoyance (after Fastl & Zwicker).

**Table 2**. Time-averaged single values of the psychoacoustic parameters

	Loudness	Sharpness	Roughness	Tonality	Annoyance
Measurement	28,1	2,1	0,045	1,67	32,1
Reference model	29,3	1,85	0,029	2,48	30,6
Ideal current	29,3	1,85	0,029	2,48	30,6
Ideal E-Machine	28,7	1,87	0,032	2,42	30,2
Literature damping	26,0	1,94	0,027	2,29	28,0
Analytical radiation	66,2	2,35	0,035	4,63	84,9

Overall, it can be stated that the loudness and sharpness level is basically well met by the simulations. Practically indistinguishable from the reference simulation is the variant "ideal current".

The variant "ideal electric machine" shows very small deviations in the order of 2 % (loudness) or 1 % (sharpness) compared to the reference simulation. Slightly larger deviations of about 12% (loudness) or just under 5 % (sharpness), which are just about in the order of magnitude of the just noticeable differences (JNDs) reported in literature, result for the variant "literature damping".

5.2. Hearing test

In order to investigate the dependence between the prediction quality of the noise behavior and the model detailing as well as the general prediction quality of the system model considering the human auditory perception, a "Multi-Stimulus Test with Hidden Reference and Anchor" (MUSHRA) test with 30 participants was performed. In this test, different noise stimuli are evaluated by the test participants in relation to a reference on a continuous scale from 0 (completely dissimilar) to 100 (absolutely identical). Also presented are the so-called hidden reference (an unlabeled duplicate of the reference signal) and an anchor signal in order to promote the best possible utilization of the scale range and/or disqualify unreliable or unqualified listeners. In the present case, the reference stimulus, a noise measurement on the powertrain test bench, was compared with the reference simulation and the four abstracted model variants. As can be seen from the averaged similarity value of 98.5, all test persons assigned by far the highest similarity value to the hidden copy, as expected. While 4 of the 5 tested model detail levels with scores between 50.1 and 56.0 are perceived as very similar, only the variant with the analytical radiation approach with an average value of 26.9 deviates significantly from this, which according to the participant survey was due in particular to the substantially different loudness of the radiation model variant implemented here. On the one hand, a comparatively large variance in the evaluations can be seen, which means that the absolute similarity of individual simulations to the test bench measurement is assessed differently by the test persons individually. The slightly different mean value and the somewhat larger variance indicate that the model variant literature attenuation of the 4 very similar noises could have been perceived differently at least by some subjects. However, a post-hoc Tukey multiple comparison test could show that there are no significant differences between the groups 'reference model, 'ideal current', 'ideal electric machine' and 'literature damping', whereas the group averages of 'measurement', 'radiation model' and 'anchor signal' differ significantly from all other six groups. (Figure 10)
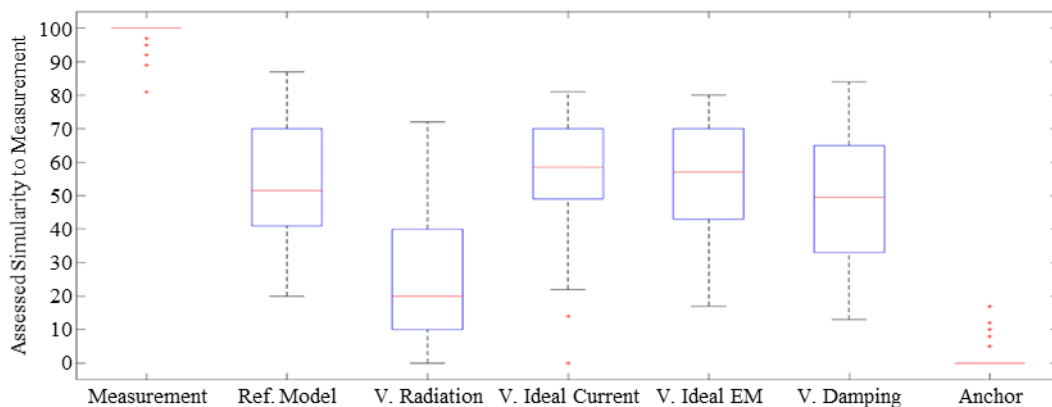
Figure 10. Boxplot of the similarity evaluations of all test persons in the listening test.

6. Conclusion and Outlook

In this paper a method to analyze the sensitivity of the NVH behavior of an electrical drive train is proposed, implemented and exemplarily applied. It was developed in a joint 2.5-year project of the three contributing institutes.

Central part of this method is a combined implementation of state-of-the-art simulation techniques and modelling approaches from other researchers to an extensive, multi-domain simulation chain with the goal to model as many possibly relevant effects as feasible in the project. To achieve this, efficient

interfaces between the electrotechnical and structural dynamics domain, as well as between the structural dynamics and the acoustics domain were developed. The simulation chain includes active and retroactive effects between the electrotechnical and structural dynamics domain, various production deviations and a sophisticated sound radiation calculation. The validation of this simulation chain versus the measurement shows a good agreement, but also some remaining discrepancies which leave scope for improvement.

This NVH simulation chain is used to exemplarily evaluate four variants and their influence: The current harmonics from the controlled electrical machine, its production deviations, the modal damping of the housing group, and the sound calculation method. The results are compared objectively via Campbell diagrams as well as via the MUSHRA hearing test to evaluate the perception of the NVH behavior by the subjects. For variant one, two and three a low sensitivity is determined which partly can be attributed to the NVH behavior being dominated by the transmission, while the analytical sound radiation calculation of variant 4 shows a high sensitivity and is deemed unsuitable.

The method can be used to further analyze the sensitivity of the NVH behavior on this drive train and can be applied to other electrical drive trains. Improvements are possible regarding the frequency range, friction excitations, PWM harmonics and by further reducing the calculation effort, especially by a more efficient sound radiation calculation.

7. Acknowledgement

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