Hybrid NVH Simulation for Electrical Vehicles I - Force Excitation Model for Electrical Machines

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Introduction

The acoustical properties of electrical vehicles have become a main concern for automobile manufacturers during recent years. When compared to combustion engines, electrical drives induce a significantly lower absolute sound pressure level in the car cabin [1]. However, this comes at the price of increasing the dominance of formerly masked noise generated by other car components as well as electric drive components [2]. The FVA research project No. 682 provides a fast, modifiable simulation tool starting with a model for the electric drive train and resulting in a binaural auralization in the car cabin. The tool enables developers to freely change the properties of the electric drive components and listen to the resulting pure synthetic acoustics within a short time span.

In this contribution a force excitation model for permanent magnet synchronous machines (PMSM) is introduced. The locally calculated force densities on the stator tooth are used in the following simulation stages [3, 4] to calculate the acoustic emission into the car cabin. In figure 1 an overview of the complete model chain of the electric vehicle with focus on the electromagnetic force excitation model is shown. The simulation is performed across the entire operating area of the electrical machine. Depending on the adjustment of the accelerator pedal by the driver in a specific traffic situation, the operating point and thereby a corresponding behavior of the electrical machine is arranged. Different modeling approaches are considered to find a trade-off between simulation time and adequate simulation results. The preparation of the resulting data of the force excitation model and thereby the interface to the structural model is described in detail. The model is validated through measurements on test benches at the Institute of Electrical Machines (IEM). A test bench for the electrical machine and another for the entire drive train are introduced and the corresponding results are presented.

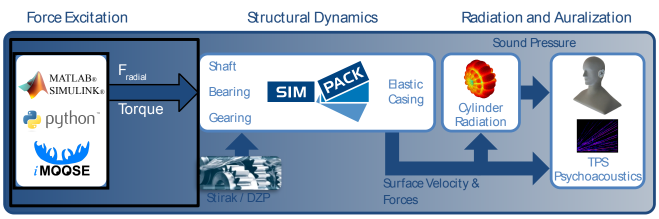

Figure 1: Block diagram of the presented model chain to describe the acoustic behavior of an electric vehicle. Focus on the first of three model parts: force excitation in the electrical machine.

Force excitation model

In this section the model to describe the force excitation in the electrical machine of the drive train is introduced. The model begins with the control of the driver and his adjusted operating behavior of the vehicle. In the control strategy of the converter system different operating points of the machine are determined, relating to the adjusted behavior of the vehicle. The operating points are described by the peak value of the phase current I and the control angle ψ. The resulting electromagnetic field distribution is evaluated in the air gap and basis for the force excitation in the machine. The produced tangential, radial and axial force components, excite vibrations on the tip of the stators teeth, which result in deformations at the stator yoke and the housing of the machine [5]. Due to negligible axial force components, a 2D model of the machine is applied. The force components are described as force densities to interpret the force behavior independently of the discretization of the model. The resulting force densities are applied to the stator teeth of a corresponding structure dynamic model, which is described in [3]. The output of the model consists of two data interface matrices with calculated radial force densities and torque distributions in the frequency domain.

Machine model

The electrical machine is a permanent magnet synchronous machine with buried NdFeB magnets. The number of pole pairs is $p = 6$ and the stator has $N = 36$ slots. To receive a detailed modeling of the shape of the rotor poles and stator teeth, a numerical approach for the simulation is considered. For the simulation of the electromagnetic force excitation a 2D model of the geometry with a model angle of $60°$ is used, based on the symmetry of the machine. The simulation is performed with 120 steps and a step angle of $0.5°$, to realize a sufficient resolution of the rotors movement for the evaluation of torque and force density. The machine has been chosen as typical reference for automotive drive train applications.

Calculation of force density on stator teeth

The simulation is performed with Finite Element Analysis (FEA) and the local forces at the surface of the stator teeth are calculated with the eggshell approach [6]. This approach offers a small sensitivity for local discretization in contrast to classical calculation methods with surface integration of maxwell stress tensor [7]. Based on the air gap flux density distribution, the local forces are cal-

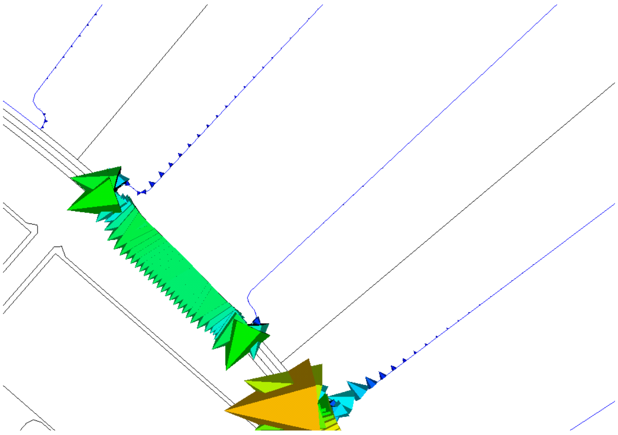

Figure 2: Force distribution on stator teeth. Time and spatial dependency. Operating point with peak value of phase current $I = 300\,\text{A}$ (nominal current) and control angle $\psi = 10°$.

culated for each node of the simulation mesh, which is situated at the boundary of the stator teeth with the air gap and slots of the machine. The local forces are converted into force densities to introduce a quantity independent of the size of discretization elements. The force densities are represented as time and spatial dependent vectors (see figure 2).

2D Fast Fourier Transformation (FFT) of radial force density

The resulting time and spatial dependent radial force density vectors are collected in a 2D matrix and transferred by 2D Fast Fourier Transformation (FFT) into the frequency domain. The calculated complex Fourier coefficients are used for further interpretation (figure 3). In figure 3 the relevant constellations for time and spatial dependent radial force density coefficients are shown in a colored grid and the colors represent the amplitude of the coefficients. The radial force density is an indicator for the strain amplitude at the yoke and housing of the machine and thereby for the surface velocity, which is basis for the acoustic emission of the machine. The same constellations of radial force density orders, printed in figure 3, are relevant for the acoustic emission. Although, the amplitude of the radial force density on its own is not sufficient for the interpretation of the acoustic behavior. Harmonics of the force density are transformed differently depending on their frequency and the behavior of the structure. For example order 0 in the time axis of the force density shows a high amplitude for the orders 0 and 36 in spatial axis, but for the surface velocity the harmonics for frequency 0 Hz can be neglected. In the presented machine design with number of pole pairs $p = 6$ and number of slots $N = 36$ a dominant constellation of surface velocity orders is spatial order 0 and time order 36, due to the first slot harmonic at time order 36, which can not be evaluated with the force density in figure 3. The structural deformation depends on various reasons, for example the temperature of the cooling system or the interaction between machine and gear, which are concerned in a structural model [3]. Also the acoustic emission and a psychoacoustic interpretation at the human ear are considered in an acoustic model [4].

Evaluation in d-q-diagram

The torque and force density distribution are analyzed for different operating points in the d-q-diagram. The simulation is performed in 10 A steps for the peak value of phase current I between 0 and 300 A and in 5° steps for the control angle ψ between 0 and 90°. Operating points in between are described after interpolating the results. The skewing of the stator is considered by the multi-slice method [8]. In figure 4 the results for the radial force density in the constellation (time order 36, spatial order 0) are shown. In operating point P3 with $I = 300\,\text{A}$ and $\psi_{\text{opt}} = 10°$ the maximum torque is pro-

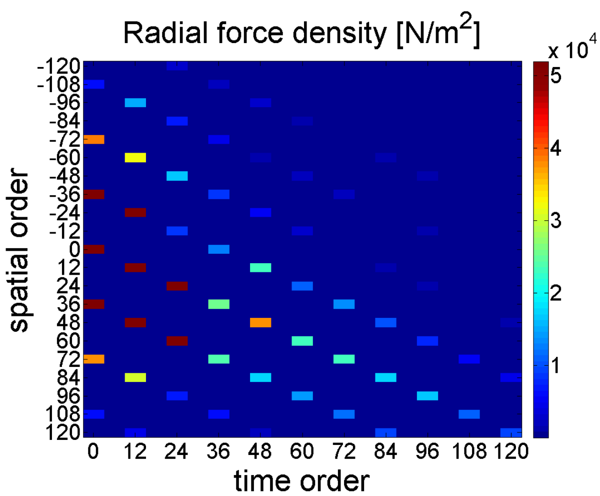

Figure 3: Radial force density [N/m^2]. 2D Fast Fourier Transformation (FFT) for time and spatial behavior. Operating point with peak value of phase current $I = 300\,\text{A}$ and control angle $\psi = 10°$.

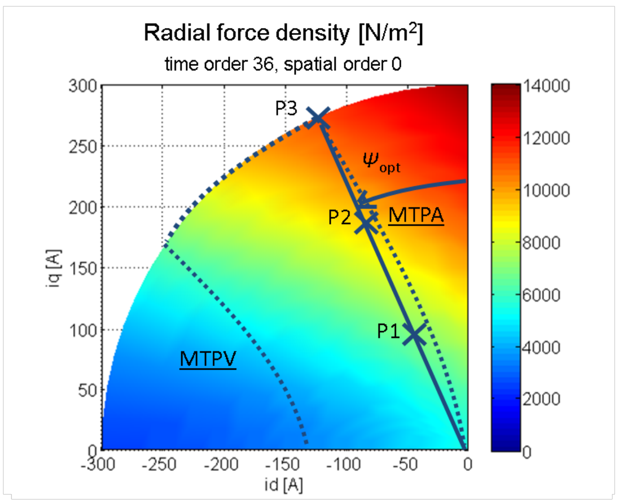

Figure 4: i_d-i_q-plane for radial force density at the stator teeth of the PMSM. P1, P2 and P3 are three referenced measuring operating points with peak value of phase current $I = 100\,\text{A}$, 200 A and 300 A and control angle $\psi = 10°$.

vided (nominal operation), but the radial force density in the presented order constellation maximizes for the control angle $\psi = 0$. Therefore, the operating point is an important design parameter for radial force density evaluation and is included in the interface to the structural model.

Interface to structure dynamic model

To connect the electromagnetic force excitation model of the machine with the entire structure dynamic model of the drive train, an interface is defined. The radial force density and the torque are submitted in two data matrices, including the operating point and the complex coefficients in the frequency domain. Therefore, the matrix for radial force density has four dimensions:

1. Peak value of phase current I
2. Control angle ψ
3. time orders of 2D-FFT
4. spatial orders of 2D-FFT

The interface matrix for the torque has three dimensions:

1. Peak value of phase current I
2. Control angle ψ
3. time orders of FFT

The calculation time for the simulation is approximately one day and depends on the number of operating points which are considered. The acoustic emission is based on the radial force density excitation on the surface of the stator teeth and a rotational vibration described by the torque. The electromagnetic force excitation is modeled in 2D but the structural model of the drive train in 3D. The 2D model is adapted to the 3D model under consideration of the skewing of the stator. Therefore, the multi-slice method [8] is used. The machine is axially divided in slices, which are shifted due to the mechanical offset resulting of the skewing. The offset requires a transformation of the operating point for each slice.

Validation

The validation process of the model chain starts with model parts, in this case with the electrical machine. It ends with the measurement of the electric vehicle. For the presented force excitation model two different test cases are considered. Therefore, the measurement was performed for two test benches at the Institute of Electrical Machines (IEM).

Test benches

The validation process of the force excitation model is performed in two steps:

1. Measurement of electrical machine independent from the drive train, to validate electromagnetic force excitation model part (figure 5).
2. Measurement of electrical machine in context of the entire drive train, to analyze structural behavior and interaction between both model parts (figure 6).

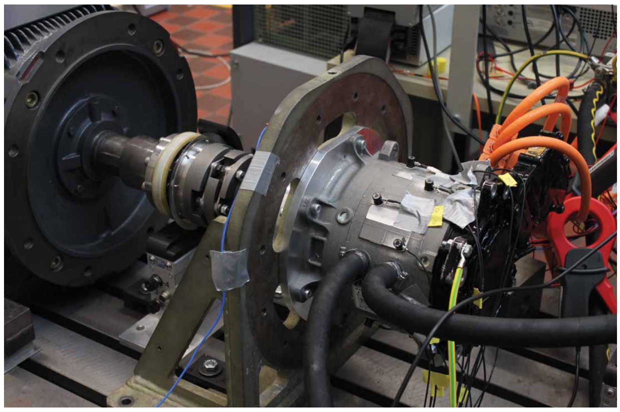

Figure 5: Test bench at the Institute of Electrical Machines (IEM) for the electrical machine. From the left to the right: Load machine with speed up to 5000 rpm. Torquemeter. Coupling. Sample machine for testing. Acceleration on the housing of the machine: Two axially shifted rings with each seven sensors (tangentially shifted to each other).

Figure 6: Test bench at the Institute of Electrical Machines (IEM) for drive train of electrical vehicle. Two load machines. Subframe of the vehicle with sub-construction for test bench: Electrical machine, gear and differential, fixed with three bearings in the subframe. Side shaft and wheel bearing with adaption to load machines on each side. Water cooling system for electrical machine and converter.

Measurement

To analyze the excitation of force at the surface of the electrical machine, acceleration sensors are placed on the housing. The measurement sequence is performed as run-up of speed with steps. Each step is operated for about

Table 1: Measuring plan for machine test bench

symbol	value	unit	comment
n	0-5000	rpm	100 steps at 50 rpm
M	0-140	Nm	
I	0-300	A	nominal current 300 A
U_Z	400	V	
$\theta_{winding}$	20-150	°C	

10 seconds to ensure a stationary operating point of the machine. Measured quantities are current, speed, torque, temperature and acceleration on the surface of the machine. The measuring plan for the machine test bench is described in table 1. The limit of speed of the load machine is 5000 rpm, the nominal torque of the sample machine is around 130-140 Nm, nominal peak value of phase current is $I = 300\,\mathrm{A}$. The intermediate circuit voltage U_Z is set to 400 V. The limit for winding temperature θ_{winding} is 150°C. In the drive train test bench a similar measuring plan is performed. Due to the gear transmission ratio of 10 the load machines have to generate up to 700 Nm each, while the maximum speed at the wheel is 700 rpm. In this case the testing is performed for three operating points with peak value of phase current $I = 100\,\mathrm{A}$, 200 A, 300 A and control angle $\psi = 10°$.

Comparison of torque distribution between simulation and measurement

To validate the presented model, the simulated torque distribution is compared to the results of the measurement, which is shown in figure 7. The results are presented for a 60° rotation of the rotor and therefore the cogging torque of six stator teeth are dominant in the behavior. For the measurement an additional harmonic is superposed, which is not considered in the simulation. This is caused by eccentricity and other construction variabilities, which are not considered in the model.

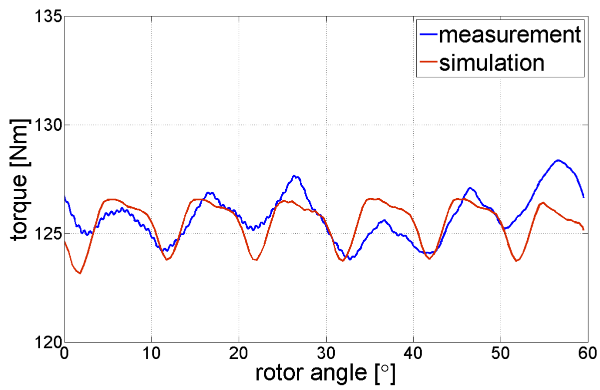

Figure 7: Distribution of torque in the PMSM for rotation of 60°. Comparison of measurement on test bench for electrical machine and simulation. Operating point with peak value of phase current $I = 300\,\mathrm{A}$ and control angle $\psi = 10°$ (nominal torque).

Conclusions

In this work a force excitation model for the electrical machine of an electric vehicle is presented. The model is the first part of a model chain to describe the acoustic behavior of electric vehicles, consisting of a force excitation model, a structural model and an acoustic model. Starting with the drivers adjustment of the acceleration pedal in a traffic situation and ending with a binaural auralization in the car cabin, the model chain describes the relevant processes inside the electric vehicle. The analyzed machine is a permanent magnet synchronous machine (PMSM) with buried magnets. The force excitation is locally calculated at the surface of the stator teeth with a 2D Finite Element Analysis (FEA) simulation. The adaptation to the 3D structural model with consideration of skewing and rotational vibrations is presented. The simulation is performed for the entire operating area of the electrical machine. The validation of the model and the interface to the structural model is achieved by two different test benches for the electrical machine and for the drive train, integrated in the subframe of the vehicle. The simulations are in good accordance with the measurements.

Acknowledgment

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