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4 September 2015 –Friday

09:00 – 10:00	**PLENARY SESSION III** LOCATION: ACEMP HALL CHAIR: Carmen Gerigan, Jan Vittek **KEYNOTE SPEECH** **Stator Flux Oriented Control for Traction Drives** Volker Staudt, Ruhr University Bochum, Germany **Systematic Evaluation and Improvement of Acoustic Behaviour of Electric Drive Trains** Kay Hamayer, RTWH Aachen University, Germany	
10:00-10:30	Coffee Break	
10:30 - 12:15	ORAL 6A Magnets and Materials (4) Room: Green I	ORAL 6B Fault Detection & Control (5) Room: Green II
12:15 - 13:30	Lunch	
13:30 – 15:30	POSTER SESSION 2 Electric Machines (21) Room: Lobby Tea and Coffee Service	ORAL 7B-Special session II Energy Management Strategies for Hybrid Electric Vehicle (4) Room: Green II
15:30 – 17:45	ORAL 8A Energy Conversion, Processing and Storage (7) Room: Green I	ORAL 8B Control of Electric Machines (7) Room: Green II
	Closing Ceremony	

Systematic Evaluation of Vibrational Behavior of Electric Drive Trains

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***Abstract*—The design and engineering of electrical drive trains is a multi disciplinary task. Usually several teams of different technical fields are involved in the development of new drive trains. Each team focuses on their own field of expertise. Even though the interactions of the described teams are well defined, acoustic irregularities are determined not before prototype stage frequently. This leads to the demand of systematic evaluation of the exciting sources and their transfer paths to the radiating surfaces. Once the sound radiating surfaces are identified, the main challenge is the decoupling of the excitation of different components of the drive train, such as electrical machine, gears, bearings etc. This step is crucial for the identification of design steps to improve the acoustic behavior. This paper presents a methodology to estimate structural transfer functions from the stator teeth of an electrical machine to the surface of its housing. The methodology is based on an operational transfer path approach and relies on a set of measurements where the force excitation is delivered by the machine itself. Since these forces are coupled a procedure for the decoupling of the transfer paths is presented. The whole model is in time domain and allow for the consideration of non linear structural behavior.**

I. Introduction

Acoustic radiation of electrical drive trains in general is an often discussed topic. The first relevant works have been presented in the early 20th century. In [1] the howling of electrical machines is described. At the beginning, empiric rules for the design of electrical machines were established, which were sensitive to the design size of the electrical machine. Jordan presented a structured analysis of the acoustic excitation of induction machines in 1950 [2]. On the basis of the temporal and ordinal decomposition of the exciting electromagnetic forces, the vibrational characteristics of electrical machines are evaluated. His work is still the basis for acoustic review of electrical machines today. Consequent developments of Jordan's method are exemplarily presented in [3] and [4]. A survey of the state of art of modeling the acoustic behavior of electrical machines is given in [5]. The mentioned publications point out the sensitivity of the acoustic behavior with respect to the operating conditions of electrical machines. But the focus of their works is the simulation of single operating points. Mostly sinusoidal stator currents are taken into account. In [6] the influence of current distortion including the effect of switching power electronics is presented. The evaluation of torque or speed dynamic operation is laborious, because the presented model is a frequency domain model. In [7] a time domain model of electrical machines is presented, taking into account the controller, electronics, nonlinear machine characteristics and the exact geometry of the machine. The evaluation of the electromagnetic forces is done in frequency domain. Based on this initial situation a transient drive train model was developed by the authors [8]. All the afore mentioned works lack in the sufficient modeling of the elastic structure.

The study of vibration characteristics of elastic structures is one important step for the evaluation of the acoustic behavior of a drive train. The work [9] presents one of the first structured analyses of eigenfrequencies and damping of elastic structures. Further development of mathematical methods like the fast Fourier transform [10] and improved measurement equipment led to the well known method of modal analysis [11]. Today a combination of experimental and numerical modal analysis is widely applied for the development of structural dynamic models. The drawback of this approach is the large effort for the development of reliable models. Especially, the commonly unknown or uncertain boundary conditions for the mount of the investigated component accounts for this effort. Since classic experimental modal analyses are not always applicable in installed situations, methods like the transfer path analysis (TPA), operational modal analysis (OMA) [12] and operational transfer path analysis (OPA) [13] are developed. An example for the experimental characterization of an automotive drive train is presented in [14].

The proposed methodology to estimate the mechanical transfer paths is based on the idea of the operational transfer path analysis. The exciting forces are thereby calculated by means of a transient machine model. With the presented approach a systematic evaluation and classification of possible excitation sources is possible.

II. Simulation of nodal forces and structural analysis

For the accurate characterization of vibrations, the local distribution of the electromagnetic forces has to be simulated. Theoretical backgrounds of the numeric computation of local electromagnetic forces have been proposed over 20 years ago by Bossavit in [15] and [16]. His publications did not lead to the application of the presented method for the computation of forces in a wide range. This may originate from the fact, that vector analysis, which is common in electromagnetic field computation, is not sufficient to explore the underlying concepts. Instead, differential geometry is required. The proposed energy based concepts are picked up and considered in detail in [17]. Results can be transformed from the differential geometry back to vector analysis and give the fundamental result, that the connection between electromagnetics and mechanics can be described by the work of Maxwell's stress tensor σ_{em} on the gradient of a virtual velocity field $\mathbf{v}$:

$$\int_{\Omega} \sigma_{em} : \nabla \mathbf{v} \, \mathrm{d}\Omega = -\int_{\Omega} \rho^{\mathbf{f}}_{em} \cdot \mathbf{v} \, \mathrm{d}\Omega + \int_{\partial\Omega} \mathbf{n} \cdot \sigma_{em} \cdot \mathbf{v} \, \mathrm{d}\partial\Omega \quad (1)$$

where Ω describes the considered domain and $\rho^{\mathbf{f}}_{em}$ is the electromagnetic force density. $\mathbf{a} : \mathbf{b} = a_{i.j} b_{i,j}$ is the tensor product and $\mathbf{n}$ is the normal vector on the surface of Ω. If electric fields and magnetostriction are neglected, the Maxwell stress tensor is given by

$$\sigma_{em} = \mathbf{b} \ \mathbf{h} - \{\mathbf{h} \cdot \mathbf{b} - \rho^{\Psi}(\mathbf{b})\}\mathbf{I} \quad (2)$$

where $\mathbf{h}$ describes the magnetic field strength, $\rho^{\Psi}(\mathbf{b})$ is the energy density in function of the magnetic flux density $\mathbf{b}$ and $\mathbf{I}$ is the identity matrix. For a rigid body Y with motion described by the velocity field $\mathbf{v} = \mathbf{v_0} + \mathbf{w_0} \times \mathbf{r}$ with constant $\mathbf{v_0}$ and $\mathbf{w_0}$, the classic approach for the computation of global forces $\mathbf{F}$ and $\mathbf{T}$ by surface integration on ∂Y is described by:

$$\mathbf{F}_Y = \int_{\partial Y} \mathbf{n} \cdot \sigma_{em} \ \mathrm{d}\partial Y, \quad (3)$$

$$\mathbf{T}_Y = \int_{\partial Y} \mathbf{r} \times (\mathbf{n} \cdot \sigma_{em}) \ \mathrm{d}\partial Y. \quad (4)$$

The considered domain Y can be chosen larger than the rigid body as long as the additional domain is contained in force-free regions. Applied to electrical machines, the surface integration can be evaluated at an arbitrary position in the air gap. The disadvantage of this approach is the influence of the discretization on the surface integration. Especially for computation of local forces this approach is not suitable due to the strong dependency of the resulting forces on the integration surface and its underlying discretization. An alternative to improve the force computation by additional analytic methods is presented in [18]. The magnetic flux density in the air gap is represented by an analytic formulation after the numerical computation to avoid the decrease of the convergence order by the derivative from the vector potential. In practice another approach is favorable where the considered domain Ω is chosen larger than the rigid body Y. The velocity field is set to $\mathbf{v} = (\mathbf{v_0} + \mathbf{w_0}) \times \mathbf{r}_{\xi}$, where ξ is a continuous scalar function, with a value of one on Y and zero on $\partial\Omega$. Application of this velocity field results in the eggshell method and the force $\mathbf{F}$ is computed by volume integration:

$$\mathbf{F}_Y = -\int_{S} \nabla\xi \cdot \sigma_{em} \ \mathrm{d}S. \quad (5)$$

The domain $S = \Omega - Y$ can be defined automatically to contain one slice of elements around the rigid body Y. The function ξ is set to the sum of all shape functions of the nodes which have contact to the rigid body Y. This approach is also suggested in [19]. It can be shown, that this method is equivalent to [20] for linear materials properties and corresponds to [21] for non-linear material properties. Implementation in an FE environment is a trivial task because the required volume integration and the gradient of the shape function is usually already available. A more detailed description of the topic is presented in [17].

For the consideration of the electromagnetic forces acting on the stator of an electrical machine in a transient drive train model, the number of locally distributed forces have to be reduced to a manageable number with respect to computational effort and the setup specific measurement options. The forces are directly averaged per stator tooth in time domain. Therefore, the stator is divided into N_1 parts, whereby the division is applied in the exact middle of each slot. The local forces at the nodes n of the FE model are decomposed in radial and tangential component and are afterwards averaged to three forces, the radial component, a tangential component which describes the local distribution of the radial forces and the torque generating tangential component, acting on one point of sum-force. The radial forces per tooth can be calculated for each required current and rotor position. The general approach for the averaging of the local forces is illustrated in Fig. 1. When defining Ω to be the numeric domain and ∂Y_q the sub region of the stator tooth q, the edges on the surface on this sub region are called $e \in \partial Y_q$ and the nodes on these edges are called $n \in e$. Then each radial component of the force $F(n)$ is summed up. For the radial component of the local force $F_{rad,avg}$ it holds

$$F_{rad,avg} = \sum_{n \in e} F_{rad}(n). \quad (6)$$

After only applying (6) one will sacrifice the information of the force distribution on the inner stator surface. But the effect of the local radial force distribution can be modeled by an additional tangential force component on the stator teeth, assuming that the forces acting on one stator tooth only results in a non plastic deformation and the second eigenfrequency of the tooth is considerably higher than the investigated frequencies. The distribution of the local forces are transformed to a torque with respect to a virtual center of rotation d. This torque is then transformed to a tangential force component acting on p. In this case the calculation is expressed by:

$$F_{tan,avg} = \left(\sum_{n \in e} F_{tan}(n) \cdot l_{lever,n} \right) \cdot \frac{1}{l_{tooth}}. \quad (7)$$

In a second step the tangential forces are considered and are averaged per stator tooth as well (same procedure like in (6)). Therefore, three force components can be distinguished: The radial forces on each stator tooth, the tangential force component derived from the local distribution of the radial forces on each stator tooth and the torque providing tangential force components on each stator tooth.

III. IDENTIFICATION OF THE STRUCTURAL TRANSFER FUNCTION

The structural dynamic simulation of a single machine is presented in manifold publications. In [22], Roivainen analyses the vibro-acoustic behavior of induction machines. The parameterization of the simulation model is laborious. A structural dynamic analysis based on simulated unity-force-responses is performed. But still only the motor itself is modeled. In the target application a lot of additional measurements are performed, because no complete drive train model can be applied.

In [23] an application of the unity-force-response is discussed based on measurements. The discussed mechanical transfer function is an OPA approach. In comparison to the OPA, the exciting forces are simulated instead of measured directly or are approximated based on accelerometer signals.

The general idea is to model the structure of a drive train by transfer functions, whereby one single transfer function in frequency domain is defined by

$$A(\omega) = H(\omega) \cdot F(\omega). \tag{8}$$

In this equation, a describes the measured signal, H the transfer function and f the exciting force, which is usually measured. To determine the frequency dependent transfer function of a system, the excitation with a well defined excitation force, covering the frequency range of interest, is essential. While operating an electrical drive, forces acting on the stator teeth are a source of vibration. It is mostly not possible to externally excite the stator teeth in assembled condition. Therefore, the electromagnetic forces excited by the machine itself are to be utilized. In this case these forces acting on the stator teeth cannot be measured. Therefore, simulated force excitations are used (compare II) to determine the transfer functions. This approach is strongly influenced by the quality of the simulated forces. The afore described method to compute the local forces is applied to simulate the forces in adequate accuracy. The validation of this method to compute local forces is for example presented in [24] and [25]. Furthermore, the exact operating conditions have to be considered for the local force simulation. For the identification of the transfer function, the excitation has to be applied to the magnetization

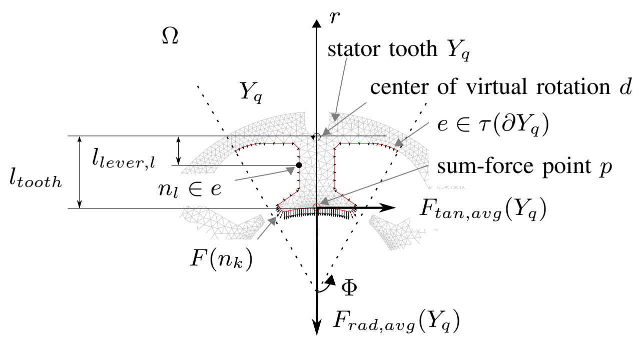


Fig. 1: Averaging of the local forces for one tooth.

axis (d-axis) of the machine. It is important, that the machine is not rotating and no torque is generated in order to avoid disturbances, which may for example be unbalance forces, bearing excitations or the influence of torsional vibrations.

But the excited forces are electrically and magnetically coupled. Hence, an excitation of a single force acting solely on one stator tooth is not possible. Therefore, the transfer functions have to be decoupled. This leads to a system of equations described in matrix form. In case of an electrical machine, the relation of a signal $v_{s,m}(\omega)$ at sensor location s for the measurement m, to the forces $f_{q,m}(\omega)$ acting on the tooth q for the measurement m is described by the transfer function $h_{s,q}(\omega)$:

$$\begin{pmatrix} a_{1,1}(\omega) & \dots & a_{1,m}(\omega) \\ \vdots & & \vdots \\ a_{q,1}(\omega) & \dots & a_{q,m}(\omega) \end{pmatrix} = \begin{pmatrix} h_{1,1}(\omega) & \dots & h_{1,q}(\omega) \\ \vdots & & \vdots \\ h_{s,1}(\omega) & \dots & h_{s,q}(\omega) \end{pmatrix} \cdot \begin{pmatrix} f_{1,1}(\omega) & \dots & f_{1,m}(\omega) \\ \vdots & & \vdots \\ f_{q,1}(\omega) & \dots & f_{q,m}(\omega) \end{pmatrix}. \tag{9}$$

Solving (9) leads to the unknown transfer function $h_{s,q}(\omega)$ as

$$\mathbf{H}(\omega) = \mathbf{F}^{+}(\omega) \cdot \mathbf{A}(\omega) \tag{10}$$

where $\mathbf{F}^{+}(\omega)$ is the pseudo inverse the of matrix $\mathbf{F}(\omega)$.

Possible excitation currents are step functions, pure sinusoidal excitations at different frequencies or sweeps. The step function has the advantage of simple handling and fast results. Measurements can easily be averaged for the suppression of noise. The post processing is done in the frequency domain. But in real application no ideal step function is excited and a poor resolution for higher frequencies is obtained. Applying (10) one observes, that the inverse force matrix has to be calculated for each frequency. Furthermore, nonlinearities in the mechanical structure are hard to detect.

Pure sinusoidal excitations deliver a higher quality of measurement signals and averaging is also efficient. With this approach even signals with low signal to noise ratio can be characterized. The post processing is again done in frequency domain, but nonlinearities are easily detectable. The disadvantage is high effort for the measurements in a large frequency range, because with higher frequencies the mode density increases. Therefore, frequency increment per measurement may have to be reduced at higher frequencies.

In order to reduce the measurement effort, sine sweeps can be utilized. When evaluating these signals in frequency domain one has to deal with very accurate windowing and leakage correction. The post processing is the same compared to the excitation with pure sinusoidal excitation.

But it is also possible to determine transfer functions in time domain. For a single-input single-output (SISO) system it holds

$$a(t) = h(t) * f(t) \tag{11}$$

whereby the operator $*$ describes a convolution in time domain.

In order to calculate $h(t)$ one has to determine an inverse time function $f^{-1}(t)$ for $f(t)$, which satisfies the condition $f(t) * f^{-1}(t) = \delta(t)$, whereby $\delta(t)$ is considered to be the Dirac function in time domain. The transfer function $h(t)$ can then be calculated by

$$h(t) = a(t) * f^{-1}(t). \tag{12}$$

The complexity is to find the inverse function of the exciting force $f^{-1}(t)$. For an exponential sine sweep this is for example described in [26], [27] and [28]. When applying this to an electrical machine with N_1 stator teeth this approach has to be extended for multiple-input multiple-output (MIMO) systems. As described afore, the electromagnetic forces are coupled. When considering that the excitation of electromagnetic forces is in the linear working region of the soft magnetic material and that the deformation of the air-gap due to these forces is small in comparison to its width, then all forces acting on the stator teeth are in linear relationship. Furthermore, for a permanent magnet synchronous machine an excitation of a sinusoidal current in the d-axis of the machine leads to sinusoidal forces on the stator teeth with the same frequency and only small harmonic content. This means

$$\mathbf{F}(t) = \begin{pmatrix} f_1(t) \\ \vdots \\ f_q(t) \end{pmatrix} = f_{unity}(t) \cdot \begin{pmatrix} c_1 \\ \vdots \\ c_q \end{pmatrix} \tag{13}$$

whereby q represents the respective the stator tooth and c_q the linear force factor. The symmetric forces are the crucial conditions for the extension of the model. In the case of an electrical machine the number of excitation inputs is equal to the number of stator teeth N_1. This leads to the requirement of at least N_1 measurement points in order to solve the given system of equations. In sum N_1^2 transfer functions, from each stator tooth to each measurement point, have to be determined. The system of equations can be described as

$$\mathbf{a}(t) = \mathbf{h}(t) * (\mathbf{C} \cdot f_{unity}(t)) \tag{14}$$

which leads with 9 to

$$\mathbf{h}(t) = \mathbf{C}^{-1} \cdot \left(\mathbf{a}(t) * f_{unity}^{-1}(t)\right), \tag{15}$$

i.e.

$$h_{s,q}(t) = \sum_q c_{q,m}^{-1} \cdot \left(a_{q,m}(t) * f_{unity}^{-1}(t)\right) \tag{16}$$

whereby $\mathbf{C}$ is the linear force scaling matrix, $c_{q,m}^{-1}$ the q,m-th entry of the inverse force scaling matrix $\mathbf{C}^{-1}$, $f_{unity}(t)$ the unity amplitude force sweep with exponential frequency increase and $f_{unity}^{-1}(t)$ its inverse time function. This approach turns out to be robust for slight deviations of the afore mentioned conditions. The OPA approach relies on low cross coupling between inputs, the consideration of all relevant paths and a low coherence of the input forces. In case of the electrical machine the exciting forces acting on the stator teeth are correlated, which may lead to an ill conditioned problem. From experience, the number of indicator responses should exceed the number of forces. As a rule of thumb, a typical factor lager then two is recommended [29]. The experience of the authors has shown, that many measurements have to be performed to get reliable results. A larger number of measurements lead to a better condition of the force matrix $\mathbf{C}$. Further on, an exact consideration of asymmetries, such as eccentricities, deviations in the magnetization of permanent magnets and anisotropic soft magnetic material behavior, in the electrical machine drastically reduce the condition of the force matrix. The total harmonic distortion of the exciting forces shall be below 10 % [30].

Tab. I: Major data of the analyzed machine.

Description	Symbol	Value	Unit
Machine type	—	PMSM	—
Rated speed	n_N	1500	min^{-1}
Rated torque	T_N	1.35	Nm
Rated current	i_N	2.3	A
Rated power	P_N	215	W
No. of poles	$2p$	8	—
No. of phases	m	3	—
No. of slots	N	6	—
Circuit	—	Y	—

IV. Examination of the Proposed Approach

A. Device under test and test bench

The device under test (DUT) is a small power permanent magnet synchronous machine (PMSM). In Tab. I the major data of the analyzed machine is given. The test bench consists of the DUT above with an incremental position sensor, a torque transducer, and a powder break, Fig. 2. The machine is supplied by a linear amplifier with a maximum line-to-line voltage of 500 V. To measure the vibrational characteristics of the machine six accelerometers are mounted around its circumference.

B. Determination of the transfer functions

The transfer functions from the forces acting on the stator teeth to accelerometers are determined based on exponential sweep measurements. In total $N_1^2 = 36$ transfer functions $h_{s,q}$ are determined in the frequency range up to 6 kHz. This

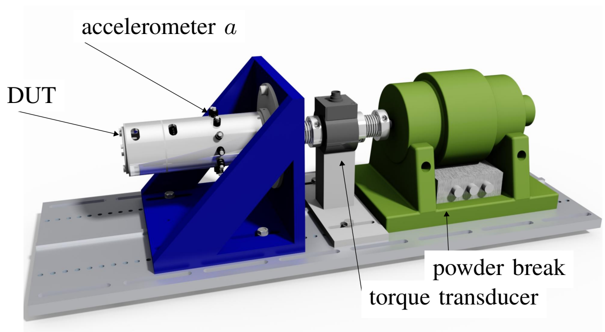


Fig. 2: Device under test and test bench setup.

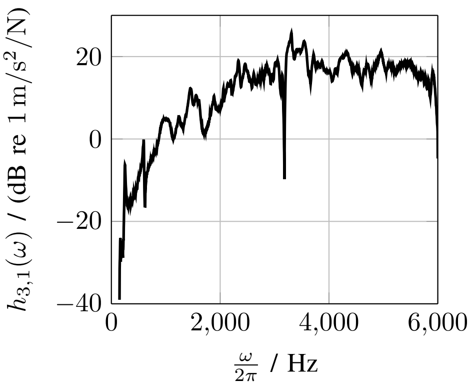


Fig. 3: Measured transfer function from stator tooth 1 to sensor 3.

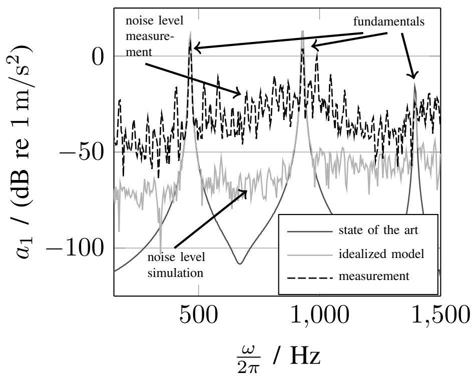


Fig. 4: Comparison of the measured and simulated sensor signal a_1 for the state of the art model the and idealized model.

frequency range is chosen in order to model forces, which are excited up to the 13th current harmonic at the maximum speed or pwm. The transfer function $h_{3,1}$ from stator teeth 1 to sensor 3 is presented in Fig. 3 in frequency domain exemplary. For the estimation of the 36 transfer functions measurements at 64 randomly chosen rotor positions have been done, in order to archive a sufficient condition value the matric $\mathbf{C}$.

C. Evaluation of the determined transfer functions

Based on the transfer functions described, different operating scenarios can be studied. As a first example, a constant operation point at $n = 3500$ min^{-1} and a load of $T = 1$ Nm is evaluated and for validation purpose compared to measurements. In order to show the influence of different levels of detailing the following models for the force computation are applied for the validation:

- Perfectly sinusoidal phase currents and a machine model without deviations in geometry and magnetization (state of the art),
- controlled phase currents with distortion and a machine model without deviations in geometry and magnetization (idealized model),
- controlled phase currents with distortion and machine model with static rotor eccentricity of $0.1\mathrm{mm}$ and a 3% mean deviation of the magnetization of each magnet (proposed model).

All simulations are performed using a transient model which is presented in [8] and [31].

For the evaluation, the signal of accelerometer a_1 is chosen exemplary. The measured and simulated sensor signals are evaluated in frequency domain. The results are presented in Fig. 4 and Fig. 5.

The fundamental frequency component is $f_0 = 466.67$ Hz. When only comparing the fundamental frequency and its multiplies, all models deliver sufficient accuracy. The force model with perfectly sinusoidal currents only models these fundamental excitations. When adding a current controller and model for the measurement of the rotor position and stator currents, the overall noise level is increased. The influence of the current distortion (its odd harmonics $5, 7, 11, 13$) are included in the model.

Each manufactured electrical machine has deviations in geometry and material properties. Due to these production variances, additional field harmonics are present. Since these properties are not known exactly, the previous given deviations are assumed. The authors recommend performing a stochastic tolerance value analysis to determine meaningful parameters for the simulation. For the studied machine subharmonics with ordinal number $k \cdot 0.25,\ k \in \mathbb{N}$ is excited when a combination of static rotor eccentricity and magnetization deviations is present. The comparison to the measurements reveals, that these subharmonics are also present. For the modeling of the vibrational characteristics of a drive train it is crucial to take into account the machine with estimated deviations, the control, rotor position and current sensors.

Further more a start-up is studied. The conditions for the start-up are defined in Tab. II.

The transfer functions show dominant resonances around $f_1 = 180$ Hz and $f_2 = 600$ Hz, compare Fig. 3. This is also obtained from the start-up spectra. Fig. 6a the

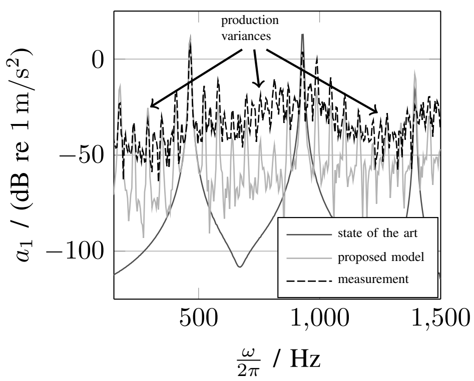
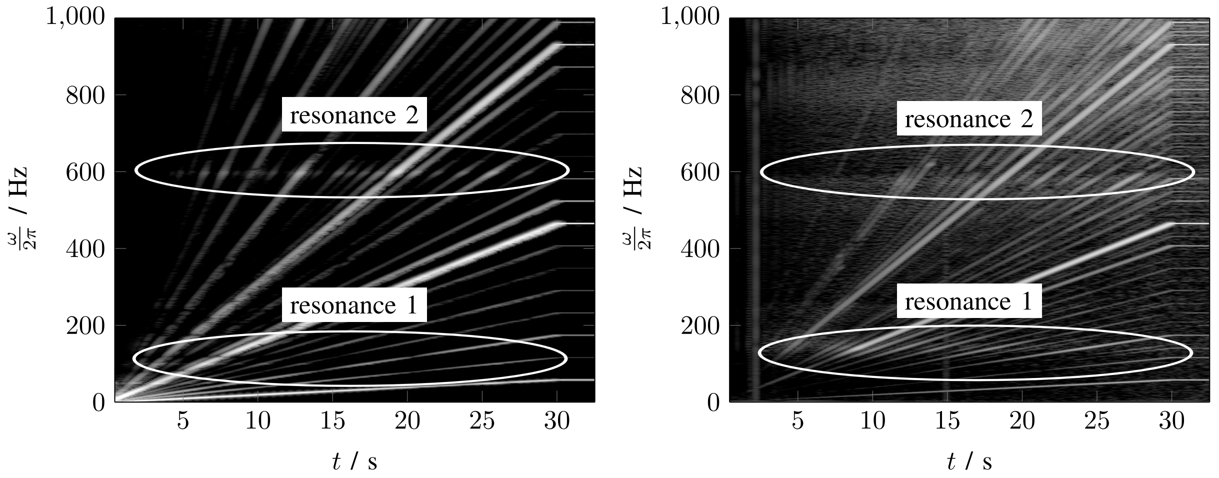


Fig. 5: Comparison of the measured and simulated sensor signal a_1 for the state of the art model and the proposed model.



(a) simulation (b) measurement

Fig. 6: Acceleration at sensor a_1 at start-up operation (identically scaled).

Tab. II: Conditions of the start-up operation.

Description	Symbol	Value	Unit
Acceleration rate		116.67	$\frac{\text{min}^{-1}}{s}$
Maximum speed	n_{max}	3500	min^{-1}
Load torque	T_{load}	1.0	Nm

simulated measured spectrum and Fig. 6b shows the one. Comparing the levels shows, that the difference is comparable to the differences present in Fig. 5. It can be stated that the dominant excitations are present in the simulation and the that the amplitudes of these excitations match the measurements sufficiently.

In general, the proposed method leads to transfer functions which model the mechanical structure very accurately. Additional studies with different machines are planed, because of the effective measurement effort for the determination of the transfer functions and the successful result obtained. In the simulation of the electromagnetic forces the influence of eddy currents is not taken into account yet. This does not limit the method for the studied PMSM. But when increasing the frequency range of interest strongly or analyzing induction machines the influence of eddy currents on the electromagnetic forces may not be neglected.

V. Conclusion

In this paper a model for the simulation and analysis of vibrational characteristic of an electrical drive train is presented. Basis for the study of the structural dynamic behavior of the mechanical structure are transfer functions, which are obtained in operational setup based on measurements. The approach is comparable to an OPA, whereby a comprehensive model for the local force estimation is applied. A time domain approach for the estimation of transfer functions especially designed for electrical machines is developed. The presented approach utilizes the coupling of the forces acting on the stator teeth simultaneously. A decoupling of the transfer functions is then performed. As an example, a PMSM with six stator teeth is studied. A transient drive train model is used, taking into account the digital control, position and current sensors, the mechanics, and a nonlinear model of the electrical machine with consideration of manufacturing deviations. The transfer functions are qualified by means of comparison to measurements. These transfer functions proved themselves to be reliable, robust and fast to estimate (comparably low measurement effort). The time domain approach allows for the consideration of non linearities of the mechanical structure, which leads to a realistic approximation of the vibrational characteristics. The authors strongly recommend further development of the presented approach.

Based on the proposed model, the influence of different types of models for the calculation of electromagnetic forces are compared. As the state of the art, a model driven with ideal sinusoidal phase currents is applied. It is shown, that the fundamental excitations and its multiples are well modeled. When comparing to measurements, significant excitations are missing. This can be improved by introducing the control and position and current sensors to the model. The overall level of the simulation becomes closer to the measurements, but still not all obtained excitations are modeled. Introducing estimated deviations to the magnetization of the permanent magnets and a rotor eccentricity, leads to the excitation of subharmonics as they are obtained in the measurements. In addition, a simulation of a start-up is presented. With the proposed model it is possible to study speed and torque dynamic operation scenarios.

The authors would like to corroborate the important steps for the study of the vibrational characteristic of electrical drive trains:

- A valid model of the structural dynamic behavior of the drive train is essential,
- many important electromagnetic excitations are due to deviations in material properties and in geometry,
- therefore, a simulation with meaningful parameters obtained by stochastic tolerance value analysis is recommended and
- a drive train model as described in [8] containing the important components and their interaction leads to more realistic vibrational prediction.

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