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Efficient Noise-Vibration-Harshness Modelling of Servo- and Traction Drives

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Abstract: This paper advances a system-simulation based universal modelling approach for NVH-simulation of electric drives. The main idea is to use commercial FE-tools for model parametrisation and implement generic reduced electrodynamic and acoustic models in a system-simulation environment. The NVH-calculation itself is done in a system-simulation framework, which can be easily coupled with control and machine models for electric drives. The proposed approach is worked out in detail. As a first example, the simulation procedure is performed for an outrunner traction drive of electrified foldable scooters.

Keywords: NVH, electric drives, servo drives, simulation, model order reduction, system simulation

1. INTRODUCTION

Noise emissions of electrical traction drives and the coupling of structure-borne sound to surrounding technical devices is increasingly becoming a key performance indicator (KPI) in the automotive industry and is also used as an indicator for condition monitoring e.g. of production machines. Thus, efficient modelling and reliable simulation techniques for NVH (Noise-Vibration-Harshness) of electrical power trains by coupled simulation tools is of high importance.

In this paper, we present a generic mathematical and system simulation based universal modelling approach for NVH calculation of E-drives, which allows taking into account influences of the control unit on NVH to ultimately simulate entire operating cycles. The work advances the existing acoustic modelling approaches for E-drives as presented in Boesing et al. (2015). An application example is given for an outrunner BLDC motor of a foldable electric scooter as introduced in Zirn et al. (2014). The key issues of the universal approach are separating physical quantities into design inherent and operation point dependent data. This is done by using a generalised mathematical representation and adequate model order reduction techniques for each physical domain. The reduced order models are connected to the current power train topology by integration into a system simulation environment. A modularised modelling structure also allows a flexible application to different E-drive topologies. Afterwards the NVH-simulation for entire operation cycles can be performed efficiently.

2. A UNIVERSAL MODELLING APPROACH (UMA) FOR NVH-SIMULATION OF ELECTRIC DRIVES

This chapter delivers a detailed elaboration of the universal NVH-modelling approach for E-drives. Besides a short review of the structural dynamic and electrodynamic models for an E-drive in section 2.1 and 2.2 as shown in Kotter et al. (2016), the presentation focusses on the electrodynamic modelling of E-drives, in particular of a direct-current outrunner motor in section 2.2.1, and on modelling of a permanent magnetic excited synchronous machine (PSM) with nonlinear electrodynamic characteristics in section 2.2.2. The structural dynamic and electrodynamic results are then merged by applying the NVH-synthesis process. This is presented in section 2.3. An efficient physical domain coupling using a generalised modal representation, which is indeed the most challenging step of the UMA, is displayed in section 2.4. In particular the connection of the structural dynamic and electrodynamic domain is displayed. Section 2.5 shows the practical application of the UMA. Finally in section 2.6 the benefits of the UMA in comparison to standard acoustic simulation procedures are worked out.

Section 3 then delivers the application of the universal modelling approach to an outrunner traction motor. Simulation results are presented and comparisons to simulations via standard commercial FE-calculations are drawn. Section 3 also shows first comparisons of the simulation to real measurements for the outrunner motor on a test-bench.

2.1 The structural dynamic model of an electric motor

The structural dynamic and the electrodynamic model of an E-motor can be deduced from a continuous formulation, i.e. a variational approach considering the whole energy of the system. The real physical state of the system is characterised by minimising the energy of the system.

To guarantee an efficient determination of all NVH-quantities, a linear structural dynamic system with small deformations is assumed. The mechanical properties are described by a symmetric, positive-definite Hooke-law and the classical Rayleigh damping with mass- and stiffness-proportional damping factors α and β. Due to harmonic force excitations in electric drives, harmonic displacements $\mathbf{u}$ and magnetic forces $\mathbf{f}_{\mathbf{mag}}$ in the equilibrium state, i.e. $\mathbf{u}(x,t) = \mathrm{Re}\{\boldsymbol{U}(x)\mathrm{e}^{\mathrm{i}\omega t}\}$ and $\mathbf{f}_{\mathbf{mag}}(x,t) = \mathrm{Re}\{\boldsymbol{F}_{\mathbf{mag}}(x)\,\mathrm{e}^{\mathrm{i}\omega t}\}$, are assumed. As worked out in the monographies on structural mechanics and partial differential equations by

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Ciarlet (2004) and Evans (2010) the displacement field $\boldsymbol{U}$ can be decomposed into a series of design-inherent, location dependent and mass-orthonormal structural eigenvectors (commonly known as mode shapes) $\boldsymbol{\varphi_m}$, $m \in \mathbb{N}$, with eigenfrequencies ω_m, as follows

$$\boldsymbol{U}(x,\omega) = \sum_{m\in\mathbb{N}} \lambda_m(\omega,\omega_m,\alpha,\beta)\cdot\boldsymbol{\varphi_m}(x). \qquad (1)$$

The modal coordinates λ_m do only depend on the working frequency ω, the eigenfrequency ω_m and the damping factors α and β. Based on the calculus of variations as presented in Ciarlet (2004) and Evans (2010) the authors have shown in Kotter et al. (2016) that the time-harmonic complex vibrational vector field $\boldsymbol{U}$ fulfils the variational equation

$$B(\boldsymbol{U},\boldsymbol{\varphi_m}) = F(\boldsymbol{\varphi_m}), \qquad (2)$$

$$B(\boldsymbol{U},\boldsymbol{\varphi_m}) = \int_\Omega \rho(\mathrm{i}\alpha\omega-\omega^2)\,\boldsymbol{U}\cdot\boldsymbol{\varphi_m}\,\mathrm{dx}$$

$$+\int_\Omega (1+\mathrm{i}\beta\omega)\,\boldsymbol{\sigma}\big(\boldsymbol{\varepsilon}(\boldsymbol{U})\big):\boldsymbol{\varepsilon}(\boldsymbol{\varphi_m})\,\mathrm{dx},$$

$$F\big(\boldsymbol{\varphi_m},\boldsymbol{F}_{\mathbf{mag}}\big) = \int_{\Gamma_N} \boldsymbol{F}_{\mathbf{mag}}\cdot\boldsymbol{\varphi_m}\,\mathrm{dS(x)}, \quad \text{for all } m\in\mathbb{N}.$$

The expression $B(\boldsymbol{U},\boldsymbol{\varphi_m})$ is the structural dynamic bilinear form, considering the internal energy of the system, and $F\big(\boldsymbol{\varphi_m},\boldsymbol{F}_{\mathbf{mag}}\big)$ is the weak external work of the magnetic force field $\boldsymbol{F}_{\mathbf{mag}}$ in relation to a specific mode shape $\boldsymbol{\varphi_m}$.

Furthermore

- Ω is the considered domain (e.g. the geometry of the E-motor), Γ_N is the surface area, where the magnetic forces act on the structure Ω,
- $\boldsymbol{\sigma}$ is the stress tensor, related to the strain tensor $\boldsymbol{\varepsilon}$ by applying Hooke's law and finally
- ρ is the mass density.

The structural mode shapes are typically calculated with a commercial FE-tool as ANSYS. Figure 1 shows the CAD-geometry of a BLDC-outrunner motor which is denoted as the domain Ω in this section. In figure 2 typical bending mode shapes of the outer rotor and inner stator can be seen.

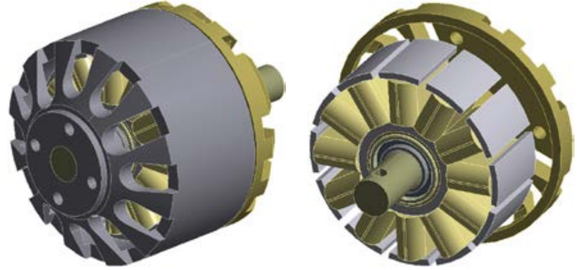

Fig. 1: CAD-geometry of a BLDC-outrunner

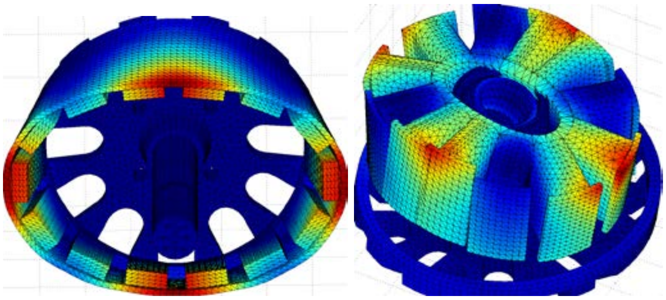

Fig. 2: Structural bending mode shape at 2315 Hz of a BLDC-outrunner.

2.2 *The electrodynamic model of an electric drive*

In this paper, our focus is a permanent-magnetic synchronous motor. Hence the electrodynamic model can be represented by a magneto-quasi-static problem in a time-harmonic formulation or a static problem. For details the authors refer to Kotter et al. (2016) and the dissertation Zaglmayer (2006). In analogy to the generalised modal representation of the structural vibrations according to equation (1) a mathematical analysis also yields a modal orthogonal decomposition of the magnetic forces into design-inherent force shapes $\boldsymbol{\psi_n}$ and working point dependent force amplitudes $f_n(t,I)$:

$$\boldsymbol{F}_{\mathbf{mag}}(t,x,I) = \sum_{n=1}^{N} f_n(t,I)\,\boldsymbol{\psi_n}(x). \qquad (3)$$

Here t, x, and I denote the time step, location in the air gap or on the stator teeth / magnets and the current working point. Due to the in general nonlinear magnetisation of permeable and magnetic material this expression is only locally valid in the current-operation range of an electric machine. The amplitudes $f_n(t,I)$ are described by a (generally unknown) nonlinear functional relation. How to deal with this problem is described in section 2.2.2.

2.2.1 *Linear electrodynamic modelling for a BLDC-outrunner traction motor*

The outrunner motor used in this work is a brushless three-phase direct current motor for a foldable electrified scooter, see figure 13. The magnetic forces can be considered as the dominant noise sources. As design-specific electrodynamic characteristics, the traction drive possesses 14 outer permanent magnets and 12 inner stator teeth. An ongoing discussion of the fractional slot, permanent magnet motor type can be found e.g. in Galea (2013).

Permanent-magnetic excitation of the BLDC Outrunner motor (here ~ 3000 A) is much higher than additional excitation of the current (here < 500 A). Thus, the magnetic operating point in a stator tooth is defined by the permanent magnet and can be linearised for small changes in the excitation of the motor currents. This results in a radial tooth force modulation ("jumping" tooth force differences), as shown in figure 4.

The difference $\Delta\,F_{\mathrm{mag}}$ in the static permanent magnetic attraction force between the stator and rotor depends approximately linearly on the motor current:

$$\Delta F_{\mathrm{mag}}(I) = K_r\cdot w\cdot c_M\cdot I, \qquad (4)$$

with

- ΔF_{mag}: static radial force difference,
- K_r: magnet height dependent radial force constant,
- c_M: length of the laminated core and magnets,
- w: winding number and
- I: motor current.

This observation is shown in figure 3.