Noise-Vibration-Harshness-Modeling of a Disc Rotor Axial-Flux Electric Drive as Integrated Motor Generator in Hybrid Applications

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A system-simulation-based Noise-Vibration-Harshness-(NVH)-modeling for a disc rotor permanent-magnetic axial-flux synchronous motor is introduced. This E-machine type which is acoustically excited by magnetic forces requires a 3D-Finite-Element-based modeling for electrodynamics, structural dynamics and magnetomechanical coupling. Using orthogonal 3D-Fourier-based representations for structural mode shapes and for magnetic body forces an order-reduced, efficient and highly detailed model for coupling Electrodynamics to Structural Dynamics within a system simulation environment can be derived. By adopting modal force response superposition a time-based NVH-simulation for arbitrary operation cycles is possible. This work seems to be the first to derive a system-simulation-based acoustic analysis for electromagnetic devices physically described by 3D-FE-models, here by means of an axial flux E-machine. All relevant electromagnetic and structural mechanic noise contributions as well as correlations are derived. The full paper will finally show a validation of the numerical models with a good agreement to real world measurements.

***Index Terms*—Acoustic noise, drives, Fourier series, magnetic forces, vibrations.**

I. Introduction

An efficient system-simulation-based Noise-Vibration-Harshness-(NVH)-modeling approach for E-drives has been introduced in [1] and [2]. It is based on modal force response superposition for determining the NVH-characteristics of E-drives of arbitrary operation cycles. Acoustic run-up spectrograms and operational structural deflections at critical speeds are computed efficiently and are compared to measurements routinely. All relevant noise contributions are derived.

This work expands the given approach to E-machine types which require a 3D-Finite-Element-(FE)-modeling for all involved physical domains, including a magnetomechanical models for body vector fields like introduced in [6]. Due to working with 3D-models the mathematical necessities are far more challenging in comparison to [1] and [2]. By the authors' best knowledge this paper is the first to embed 3D-FE-based models for electromagnetic devices into a drive-simulation environment to analyze the real system-behavior.

The 3D-approach is exemplified by means of a permanent-magnetic disc rotor axial-flux machine (AFM). It can be observed in fig. 1 that the shown nodal magnetic forces on the stator teeth request a 3D-modeling technique. Standard 2D-models do not map the real physics sufficiently accurate. For adopting modal force response superposition as in [1] and [2] an orthogonal 3D-decomposition of physical vector fields via Fourier-methods is applied. Thus the computational costs of electrodynamic 3D-FE-models and its coupling to 3D-models for mechanics, as stated in [3], can be overcome as well as the limitation of analytical 3-D force models to simplified geometric structures as given in [4].

II. Fourier-Based Coupling of Electrodynamics and Structural Dynamics

An efficient and highly detailed 3D-FE-based magnetic force and domain-coupling model for NVH-simulation is developed. 3-D magnetic force effects due to complex winding schemes or

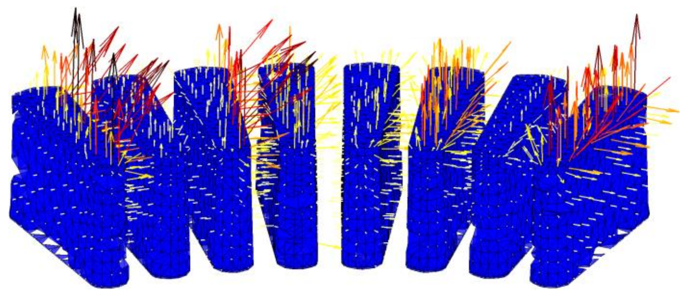

Fig. 1: Magnetic body forces arising on one stator of an axial flux EM. As visible the forces cannot be expressed by standard air-gap models for this complex geometry.

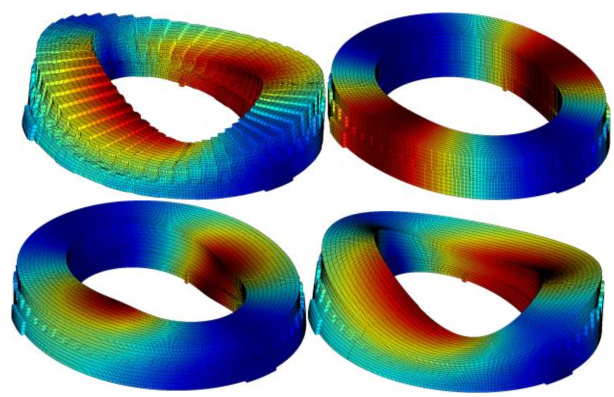

Fig. 2: in clockwise order, top to down:
a) (2,1)bending mode shape of a stator of an AFM
b) 3D-Fourier approximation up to $(n_r, n_\phi, n_z) = (0,2,0)$,
c) 3D-Fourier approximation up to $(n_r, n_\phi, n_z) = (2,2,2)$,
d) 3D-Fourier approximation up to $(n_r, n_\phi, n_z) = (3,4,3)$.
The modal displacement field has been mapped to a hexahedral grid via Lagrange-interpolation. This is needed for performing the Fourier-decomposition.

non-planar curved stator tooth geometries are taken into account. The nodal body force distribution over the entire three-dimensional stator teeth or rotor geometry is considered instead of the usual air gap force density as in [1]-[3]. Vector fields like magnetic forces and structural modal displacements for the stator core of the axial flux motor are represented by an orthogonal

3D-Fourier-approximation as derived in detail in [6]. The approach is exemplarily shown for structural mode shapes in fig. 2. This can be done analogously for nodal magnetic body forces via a 3D-Fourier decomposition on the stator core.

Conservative orthogonal Galerkin projection as shown in [5] is used to project the force field $\boldsymbol{F_D}$, defined on a JMAG electrodynamic FE-mesh $\mathcal{DM}(\Omega)$ and space $\mathcal{V}(\mathcal{DM}(\Omega), \mathbb{R}^3)$, to a hexahedral target mesh $\mathcal{TM}(\Omega)$ as in fig. 3 such that the force balance is preserved and the change in external work on the system due to interpolation is minimized. This finally enables the Fourier-approximation of magnetic body forces.

The target density field $\boldsymbol{F_T} \in \mathcal{V}(\mathcal{TM}(\Omega), \mathbb{R}^3)$ is derived by minimizing the L^2-distance of the field $\boldsymbol{F_D}$ to the target FE-space $\mathcal{V}(\mathcal{TM}(\Omega), \mathbb{R}^3)$ via an orthogonal projection. According to [5] this is equivalent to solving the linear equations

$$\boldsymbol{M_T} \cdot \boldsymbol{F_T} = \boldsymbol{M_{TD}} \cdot \boldsymbol{F_D}, \qquad (1)$$

with an invertible FE-"mass"-matrix $\boldsymbol{M_T}$ on the space $\mathcal{V}(\mathcal{TM}(\Omega), \mathbb{R}^3)$. The matrix $\boldsymbol{M_{TD}}$ is defined on a superordinate FE-space to $\mathcal{V}(\mathcal{TM}(\Omega), \mathbb{R}^3)$ and $\mathcal{V}(\mathcal{DM}(\Omega), \mathbb{R}^3)$. Thus numerically challenging algorithms need to be applied to create this space via a supermesh construction.

The domain coupling of Electrodynamics to Mechanics is performed analytically in the order-reduced orthogonal Fourier-framework. The L^2-scalar products for pairs of generic 3D-Fourier force shapes and modal displacements need to be determined as shown in fig. 4.

III. Efficient 3D-FE-Based NVH-Simulation

The NVH-simulation is performed within one simulation environment in connection with control and inverter topologies. As shown in fig. 5, spectrograms for the normal surface velocities are computed for a run-up of the E-drive. Operational deflections at critical speeds are highlighted in fig. 6 for the entire E-motor. The full paper will reveal a detailed NVH-analysis with an extraction of significant electrodynamic and structural noise contributions as well as a comparison to measurements.

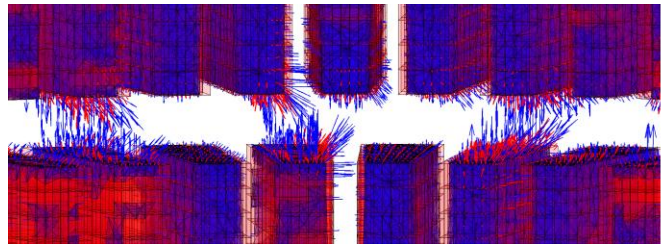

Fig. 3. The forces $\boldsymbol{F_T}$ (red) are calculated according to (1). A quite similar spatial course of $\boldsymbol{F_T}$ and $\boldsymbol{F_D}$ (blue) and, as expected, different amplitudes due to unequal volumes of donor and target mesh and number of nodes can be observed. However the volume integrals of the density fields, i.e. the total forces, and total external work are quite the same.

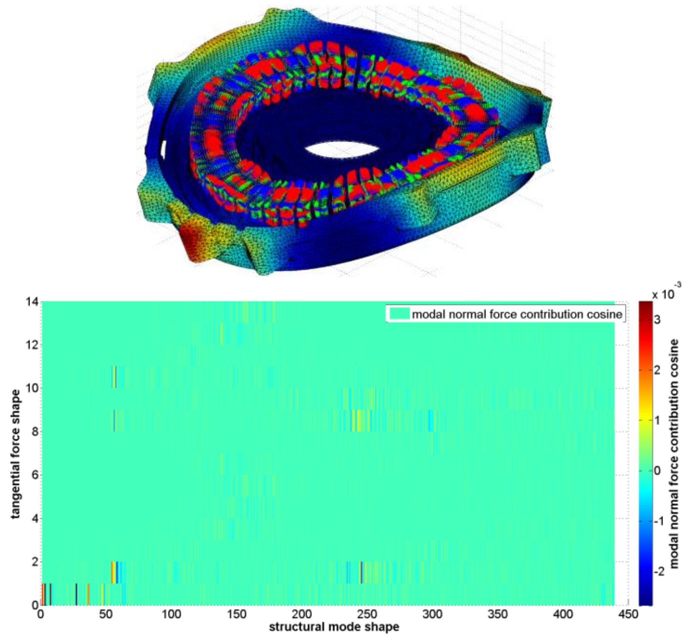

Fig. 4. Up: Applying harmonic force shapes to structural model.
Down: Excerpt of the modal coupling matrix. Decomposed force and modal displacement fields are L^2-integrated and deliver the physical contributions of both domains to the structural behavior. Excited structural mode shapes for each tangential force shape n_ϕ in axial coordinate direction are displayed.

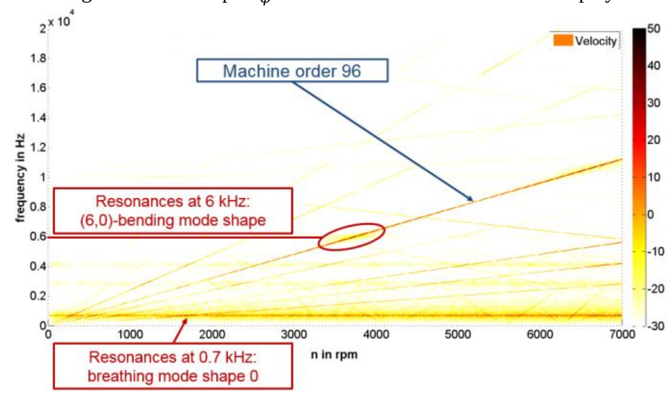

Fig. 5. Acoustic numerical run-up spectrogram for the axial flux motor.

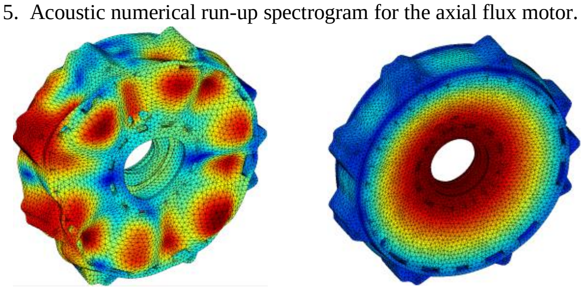

Fig. 6. Circumferential wave behavior of the structural deflections due to wave behavior of magnetic forces for resonances highlighted in fig. 5.

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