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 \((n_r, n_\theta, n_z) = (0,2,0)\).
c) 3D-Fourier approximation up to \((n_r, n_\theta, n_z) = (2,2,2)\).
d) 3D-Fourier approximation up to \((n_r, n_\theta, n_z) = (3,4,3)\).

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 $\mathbf{F}_D$, defined on a J MAG electrodynamic FE-mesh $\mathcal{D} \mathcal{M}(\Omega)$ and space $\mathcal{V}(\mathcal{D} \mathcal{M}(\Omega), \mathbb{R}^3)$, to a hexahedral target mesh $\mathcal{T} \mathcal{M}(\Omega)$ 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 $\mathbf{F}_T \in \mathcal{V}(\mathcal{T} \mathcal{M}(\Omega), \mathbb{R}^3)$ is derived by minimizing the $L^2$-distance of the field $\mathbf{F}_D$ to the target FE-space $\mathcal{V}(\mathcal{T} \mathcal{M}(\Omega), \mathbb{R}^3)$ via an orthogonal projection. According to [5] this is equivalent to solving the linear equations

$$\mathbf{M}_T \cdot \mathbf{F}_T = \mathbf{M}_{TD} \cdot \mathbf{F}_D,$$  \hspace{1cm} (1)

with an invertible FE-"mass"-matrix $\mathbf{M}_T$ on the space $\mathcal{V}(\mathcal{T} \mathcal{M}(\Omega), \mathbb{R}^3)$. The matrix $\mathbf{M}_{TD}$ is defined on a superordinate FE-space to $\mathcal{V}(\mathcal{T} \mathcal{M}(\Omega), \mathbb{R}^3)$ and $\mathcal{V}(\mathcal{D} \mathcal{M}(\Omega), \mathbb{R}^3)$. 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.

REFERENCES


