Received: 16 June 2020 | Accepted: 24 November 2020

DOI: 10.1002/pamm.202000080

A simulation of an electric machine considering the coupling of rotor- and electrodynamics

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In this paper, a method is presented to determine the vibrational behavior of an electric motor and the associated structure. Therefore, a holistic simulation approach is used, which takes into account the mutual influence of structural mechanics and electrodynamics. For this purpose, a multi body simulation (MBS) is extended so that electromagnetic loads can be considered, which are calculated by using the finite element method (FEM). In electric machines an undisturbed and constant magnetic field is of great importance. Even small variations of the air gap lead to changes in the magnetic field compared to the ideal geometry, which cause a change in the resulting torque and vibration excitation. Especially local and global asymmetric air gap changes due to load- and operation-dependent deformations of the stator and rotor are problematic. Such deformations result on the one hand from the electromagnetically excited structural vibrations and on the other hand from the rotordynamic loads. For these reasons, it is necessary to consider the electro- and structural-dynamic effects together. The developed method is presented on a simple generic motor to show the influence of the coupling.

1 Introduction

The vibration behavior has a clear influence on the operational lifetime, the sound radiation and the comfort. For this reason, the numerical analysis of an electric engine must be able to predict also the vibration behavior at an early stage of the product development process. It should be noted that smallest variations in the air gap of the motor can change the electromagnetic fields and the resulting forces and moments. An eccentric rotor creates a strong force in the direction of the smallest air gap between rotor and stator [1]. This force is called unbalanced magnetic pull (UMP) and influences the vibration behavior of the structure [2], which influences the air gap as well. These days, the interactions between mechanical structure and electromagnetic components are usually not taken into account. In contrast, a coupled approach including the feedback of the interactions of structural vibrations and electrodynamics is presented in this paper. Especially, in the context of rotor dynamic analysis the coupling of electrodynamics and multi body systems is novel. The need for such a holistic simulation approach that considers these interactions arised in a previous study of an electric wheel hub motor [3].

2 Coupling of multi body systems and electrodynamics

MBS are used to describe the dynamic behavior of bodies under the influence of loads. The interactions between bodies determine the dynamical behaviour of the overall system. The equation of motion of the multi body system can be derived using the linear momentum and angular momentum for rigid bodies or using a mechanical principle (e.g. Hamilton's principle) for the description of elastic bodies [4]

$$\underline{\underline{M}}_{\text{MBS}}(\underline{q},\underline{\dot{q}})\,\underline{\ddot{y}} + \underline{h}_{\omega}(\underline{\omega},\underline{q},\underline{\dot{q}}) + \underline{h}_{\text{el}}(\underline{q},\underline{\dot{q}}) = h_{\text{o}}(\underline{x},\underline{\dot{x}},\underline{\varphi},\underline{\omega},\underline{q},\underline{\dot{q}},t) \quad . \tag{1}$$

For calculation of the kinematic quantities position $\underline{x}$, orientation $\underline{\varphi}$ and elastic deformations $\underline{q}$ as well as their time derivatives, the inertia terms, which are represented by the mass matrix $\underline{\underline{M}}_{\text{MBS}}$ and the acceleration vector $\underline{\ddot{y}} = [\underline{\ddot{x}}\ \underline{\dot{\omega}}\ \underline{\ddot{q}}]^T$, the vector of centrifugal-, Coriolis- and gyroscopic forces $\underline{h}_{\omega}$, the elastic characteristics represented by the vector of elastic forces $\underline{h}_{\text{el}}$ and the acting forces have to be considered. The differential equation can be solved with standardized solvers.

The electrodynamic forces acting on the mechanical system are determined by an electrodynamic FEM simulation of the engine. The solution of the electrodynamic problem is done in every time step. The resulting forces are functions of the kinematic quantities such as shaft displacements $\underline{x}$, the corresponding velocities $\underline{\dot{x}}$, the rotational speed ω_z and the angle of rotation φ_z. The FEM formulation of electromagnetic phenomena is described in detail in various literature [5]. The following system of equations is used in the paper at hand

$$\underline{\underline{K}}\,\underline{A} = \underline{J} + \underline{B}_0, \tag{2}$$

using the permeability matrix $\underline{\underline{K}}$, the magnetic vector potential $\underline{A}$, the current density $\underline{J}$ and the magnetization $\underline{B}_0$. From the magnetic vector potential $\underline{A}$, the magnetic flux density $\underline{B}$ and the magnetic field intensity $\underline{H}$ can be determined using the magnetic permeability μ and the rotation rot

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$$\underline{B} = rot(\underline{A}) \quad , \quad \underline{H} = \frac{1}{\mu}\underline{B} \quad . \tag{3}$$

With the magnetic field intensity $\underline{H}$ the electrodynamic forces $\underline{h}_{\text{o,elec}}$ can be calculated and applied as a part of the outer loads $\underline{h}_{\text{o}} = \underline{h}_{\text{o,mech}} + \underline{h}_{\text{o,elec}}$ to the mechanical field problem (MBS procedure). The electrodynamic forces $\underline{h}_{\text{o,elec}}$ are obtained using the Maxwell's stress tensor by an integration along the edges Γ of the element

$$d\underline{h}_{\text{o,elec}} = -\frac{\mu_0}{2}\underline{H}^2 d\Gamma + \mu_0(\underline{H} \cdot d\Gamma)\underline{H} \quad , \tag{4}$$

therein μ_0 is the magnetic permeability.

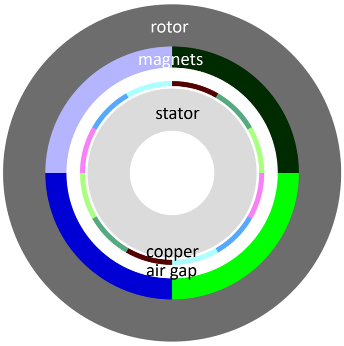

Fig. 1: Electrodynamic model of the motor.

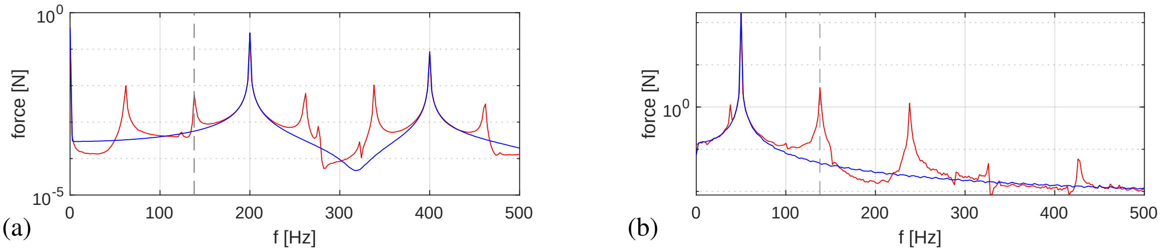

Fig. 2: Frequency spectrum of the electrodynamic forces of one node at (a) the stator, (b) the rotor. The blue curve shows the motor in a central position (rigid bearing) and the red curves takes into account the influence of an elastic bearing with constant spring stiffness.

3 Influence of the coupling on the vibration behavior of an exemplary motor

The influence of the interaction between structural vibrations and electrdynamic forces is shown using an exemplary motor (see Fig. 1) with rigid or elastic bearings. The motor rotates with a constant rotational speed of 50 $1/\text{s}$. Figure 2 shows the frequency spectrum of one FE node on the surface of the air gap (a) of the stator and (b) of the rotor. The blue curves show the model with rigid bearings so that the rotor is centered in the stator and the red curves with elastic bearings. For this purpose, the forces determined by the Maxwell stress tensor during the time integration were converted into the frequency domain using the Fast Fourier transformation (FFT). In both curves of Fig. 2(a) a frequency of 200 Hz, which is the product of the poles and the rotational speed, is clearly visible. Moreover, a frequency of 400 Hz, which is two times 200 Hz, is conspicuous. Higher multiples such as 600 Hz and 800 Hz are also included in the spectrum, but are not shown here. Using elastic bearings with a stiffness of 600 kN/m, further frequencies become visible. Neglecting the electromagnetic forces the rotor behaves like a single mass oscillator, the natural frequency is 157 Hz with an assumed mass of the shaft of 0.62 kg. Taking electromagnetic forces into account, this frequency is shifted for the rotor as well for the stator to 138 Hz, see the gray dashed lines. This can be explained with the UMP, which has a similar effect like a spring with a negative stiffness, which results in a reduced overall stiffness. In addition, distortion frequencies appear. In Fig. 2(a) they are the sum and difference between 200 Hz and 138 Hz respectively 400 Hz and 138 Hz and in Fig. 2(b) the sum and difference of the current frequency of 100 Hz and 138 Hz. Also the rotational speed of 50 Hz can be clearly seen in Fig. 2(b) for both models. Consequently, the vibration behavior of the structure has changed due to the coupling to the electromagnetic circuit. In this minimal example, only the elasticity of the bearings was taken into account. Nevertheless, significant influences on the excitation behavior of the system were determined. These excitations influence the vibration behavior of the structure and thus, for example, the sound radiation.

4 Results and outlook

In this contribution, a method for coupling structural vibrations and electrodynamic forces was presented. This was applied to a simple engine. Due to the interaction of the two systems, one natural frequency was shifted and two new frequencies were created. This effect cannot be reproduced without coupling the systems, which allows this method to better predict the real behavior of an electric machine. An increase in the level of detail and a validation on a real engine are carried out next.

Acknowledgements The presented work is part of the research project KeM (Kompetenzzentrum eMobility) and financially supported by the European Union through the European Funds for Regional Development (EFRE) as well as the German State of Saxony-Anhalt.
Open access funding enabled and organized by Projekt DEAL.

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