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A holistic vibration analysis of an electric engine including mechanical and electrodynamic interactions

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In this paper, a method for vibration analysis of electric engines and associated structure is presented. For this purpose, a multi-body simulation (MBS) is extended in such a way that electromagnetic loads can be considered using the finite element method (FEM). Subsequently, the determined loads lead to an excitation of the structural vibrations and a sound radiation of the engine, which is analyzed at selected operating points. A test rig will be used to validate the implemented method. Finally, different design variations of the engine are evaluated with respect to their acoustic behavior. The developed method is not limited to the presented application, but it can be applied to any system with electric drives.

1 Introduction

Due to the lower local emissions, electromobility has become increasingly important in recent years. This trend is expected to continue, which moves new research fields into the focus of the automotive industry. In this work, a simulation method is presented that allows a determination of the drive train vibration behavior, which influences for example the operational life, comfort and acoustics. Therefore, the feedback including coupling of structural vibrations, large rotations and displacements as well as electrodynamic forces and moments induced by the electric field of the engine have to be taken into account.

2 Coupling of multi body systems and electrodynamics

MBS is suitable for describing the dynamic behavior of bodies under the influence of dynamical loads. The behavior of the overall system is characterized by the interaction of the individual bodies. The equation of motion for elastic bodies with large rotations and translations but small deformations can be derived using a mechanical principle (e.g. Hamilton's principle) for elastic bodies [1]

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

Therefore, the kinematic quantities position $\underline{x}$, orientation $\underline{\varphi}$ and elastic deformations $\underline{q}$ and their time derivatives, the mass matrix $\underline{\underline{M}}_{\text{MBS}}$ and 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 vector of elastic forces $\underline{h}_{\text{el}}$, and the acting forces $\underline{h}_0$ are considered. The solution of this system of equations can be realized with stadardized solvers. In contrast to the mechanical system, the electromagnetic forces in the engine are determined, as a function of the kinematic quantities at each time step using the FEM formulation of the electromagnetic phenomena, which is described in detail in literature [2] and leads to the following system of equations

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

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

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

As a last step the electromagnetic forces $d\underline{h}_{\text{o,elec}}$ finally can be determined using the Maxwell stress tensor by integration along the edges Γ and the magnetic permeability μ_0

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

and passed to the MBS.

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3 Influence of electromagnetic excitations on the vibration behavior

Figure 1 (middle) shows the engine under investigation on a test rig on which, among others, the torque was measured with strain gauges and the sound emission using a microphone. The spectrogram shows speed-dependent amplitudes for both the torque (left) and the sound radiation (right). Prominent amplitudes correspond for example to the speed of the engine times the number of poles (28) or the number of pole pairs times three, which is the number of the phases of the current. It can be seen that both torque and sound radiation are strongly influenced by the electromagnetic field.

The application example is a small, compact engine, whose sound radiation is to be reduced for selected operating points. The workflow in Figure 2 illustrates the procedure. First, the stiffnesses of the bearings are determined, which connect the rotor and stator of the engine and thus have an important influence on the vibration behavior of the system, especially since relative movements between the rotor and stator lead to large electromagnetic forces [3]. Elastic structures can be considered with modal reduced FE-models before the coupled rotor dynamic simulation. In this work all bodies are assumed to be rigid, so this step is not necessary. The MBS simulation, which has been extended by the consideration of electromagnetic forces, is performed in the time domain. The electric field is determined as a function of the actual current, the displacement and the velocity, as well as the angle of rotation and the rotational speed. The resulting forces, which are calculated in every time step, also can be used in the frequency domain as excitation for a harmonic analysis to determine the vibrations of the engine as well.

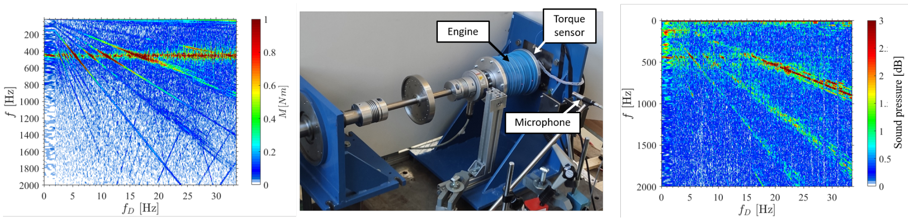

Fig. 1: left: spectrogram of the torque, middle: experimental setup for the measurement of torque and sound radiation, right: spectrogram diagram of the sound pressure

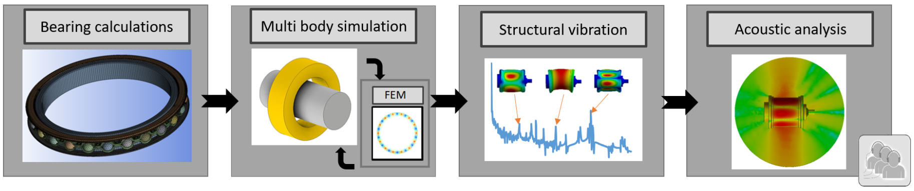

Fig. 2: Workflow for the determination of the sound radiation of an electric engine under consideration of the electromagnetic excitations

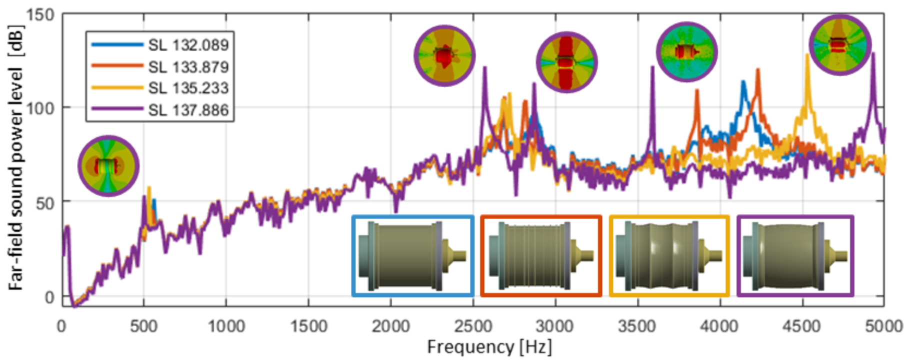

Fig. 3: Determined vibration behavior of different engine designs under consideration of electromagnetic loads at a speed of 1000 rpm

The structural vibrations are subsequently used as excitation of the surrounding air, whereby the sound emission of the investigated structure can be determined. As an example, figure 3 compares the sound radiation of the engine for four different cylinder designs. These can be compared, for example, using third-octave-bands, sum levels (SL) or psychoacoustic analyses.

4 Summary

A method for considering electromagnetic loads within a vibration analysis was presented and an application example was shown. The influence of electrical loads on the overall system vibrations as well as the sound emission was demonstrated on a test rig.

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References

[1] A. Shabana, Dynamics of multibody systems (Cambridge university press, 2014), doi:10.1017/CBO9781107337213.
[2] J. P. Bastos, Electromagnetic modeling by finite element methods (CRC press, 2003).
[3] M. Wallin, M. Ranlof, and U. Lundin, IEEE transactions on magnetics **47**, 4827-4833 (2011), doi:10.1109/TMAG.2011.2160727.

