presented at the 9th Weimar Optimization and Stochastic Days 2012
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Understanding the Acoustic Behavior of Electrical Drives

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1 Engineering the Sound

Operating noise is an important parameter of technical devices operating near humans. Many regulations define maximum values for operating devices. This is especially true for permanent working systems. Furthermore, reducing noise emission is often a key goal in order to achieve higher quality standards and thus new markets.

1.1 The Sound Propagation Path

Here one can categorize noise sources in two distinct groups [1]

1. The first type of noise excitation originates from time varying forces acting on solids. These forces provoke mechanic vibrations (structure bound sound) within the solid parts which propagate until the outer surface of the bodies. At this outer boundary the vibrations are partly transferred to the adjacent fluid as a result of a fluid-structure-interaction (FSI).
2. The second type of noise excitation provokes fluid bound vibrations directly. This can be observed in fans, ventilation exhaustions and fast moving parts. Here the vibrations are generated due to the turbulent flow of the fluid directly.

The process of noise formation and transfer can be described in the frequency domain very conveniently [2]. A particular excitation spectrum F(jω) is multiplied with a frequency dependent transfer function T(jω) which represents the propagation of noise. For the second type of noise T(jω) represents solely the propagation through the fluid while for the first type the transfer function represents solid-state-wave-propagation, FSI and finally the fluid bound propagation.

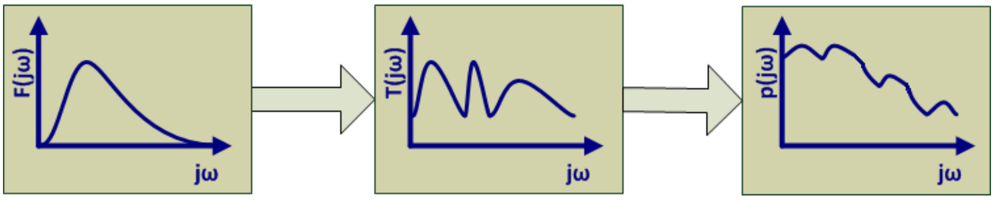

Fig. 1: Block diagram of noise propagation

1.2 Electrical Drives as Noise Source

In general following sources of noise can be identified in an operating electric motor:

1. Cooling fan (if applicable)
2. Bearings and mechanical connections
3. Vibration of the actuator and housing

From this list number 2 and 3 starts as structure bound sound while 1 generates fluid vibrations directly. While 1 and 2 result of the movement of parts mechanically coupled to the motor 3 has it's origin in the motor's principle of operation itself.
Considering this the Maxwell forces on ferromagnetic parts of the drive are of major interest. These forces are typically maximized to provide the operational torque.
The acoustic design for stator's vibration causes by Maxwell forces cannot be separated from the design process of the motor itself (which is possible when designing quieter fans and bearings). This piece of work will focus on this third source of operating noise. Furthermore only structural vibration will be simulated since they correlate with the operating noise in amplitude and frequencies.

2 Modal Extraction

To predict how the structure will react to the periodic forces a structural mode superposition analysis can be done. This linear approach is valid since the deformations caused by the structure bound noise are small. A mode superposition analysis is much more resource effective than a fully coupled

magnetic-structural analysis. By performing a modal analysis the normal modes and resonant frequencies of the structure can be determined.
The results of the modal analysis should be used to determine which normal modes are of interest. The operating noise of an electric drive is mainly determined by the modes which lead to an vibration of the outer housing as a hole. Internal oscillations of the stator's teeth for example have a little contribution to the operating noise.

In Fig. 2 one can see two exemplary normal modes of the outer parts of an electric drive (stator and housing).
The left mode leads to significant deformations at the outer boundary of the motor. The right one depicts mainly a bending of the stator's teeth.

This evaluation of the normal modes and their corresponding frequencies should be used to define the simulation time step in the upcoming analysis to determine the force loads.

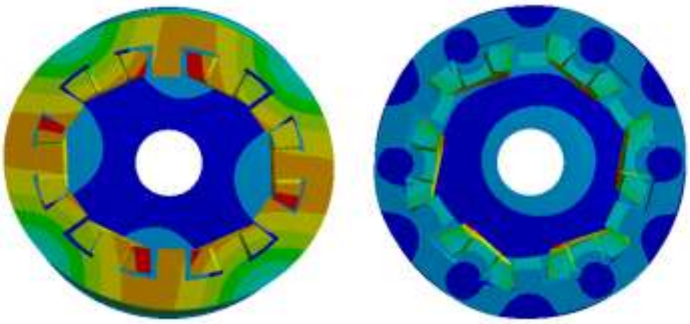

Fig. 2: Normal modes of outer parts of a motor

3 Electromagnetic Excitation

When applying a current excitation to the stator's windings the produced magnetic field interacts with the permanent magnets leading to a tangential force on the rotor and thus a rotational movement. This interaction results in an equal reaction force on the stator. Furthermore there are also radial forces and torques acting on the stator's teeth.
The first step in order to calculate the time dependent forces on the stator's teeth is to simulate the transient magnetic field in the motor. The force is computed by evaluating the Maxwell's stress tensor and integrating it along a path [3]. The stress tensor can be written as:

$$T_M = \begin{pmatrix} B_X H_X - \frac{1}{2}|B||H| & B_x H_y & B_x H_z \\ B_y H_x & B_y H_y - \frac{1}{2}|B||H| & B_y H_z \\ B_z H_x & B_z H_y & B_z H_z - \frac{1}{2}|B||H| \end{pmatrix} \quad (1)$$

The precise mathematical formulation of (1) allows its usage only to obtain forces integrating it along closed loops/surfaces. However in most of the motors the magnetic co-energy (and therefore the terms inside the tensor) is much larger inside the air gap than in the other areas. Fig. 3 shows a contour plot of the magnetic co-energy at the air gap, stator and windings.

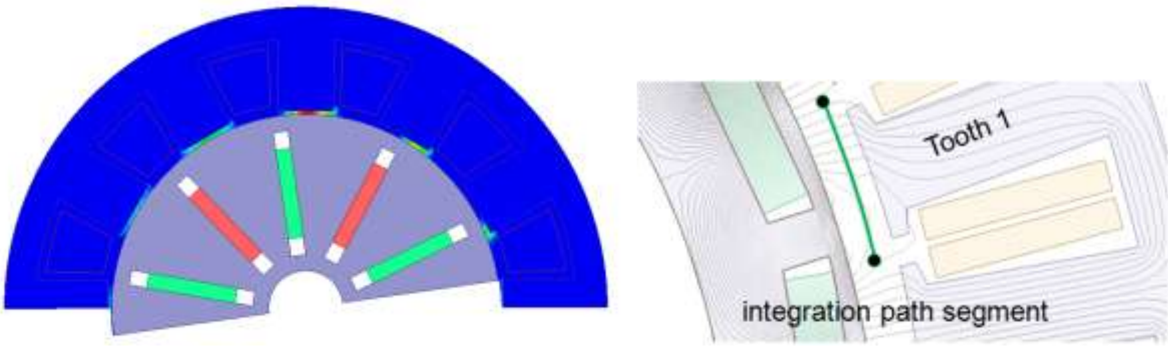

Fig. 3: Co-energy distribution inside the air gap and stator of a synchronous machine with permanent magnets and reduced force integration path

The integrated force evaluated along the arc in the air gap is used as force load on the corresponding tooth. This engineering approach neglects the particular distribution of the force density along the inner side of the tooth. The distribution is, however, of minor interest while evaluating the vibrations which will be transmitted to the air at the outer side of the machine.

4 Harmonic Response Analysis

After determining time dependent forces for each tooth these quantities are Fourier transformed and used as complex loads in a harmonic response analysis using modal superposition. With this approach one can determine how the normal modes of the structure will react to the determined magnetic forces.

5 Sensitivity Analysis and Optimization

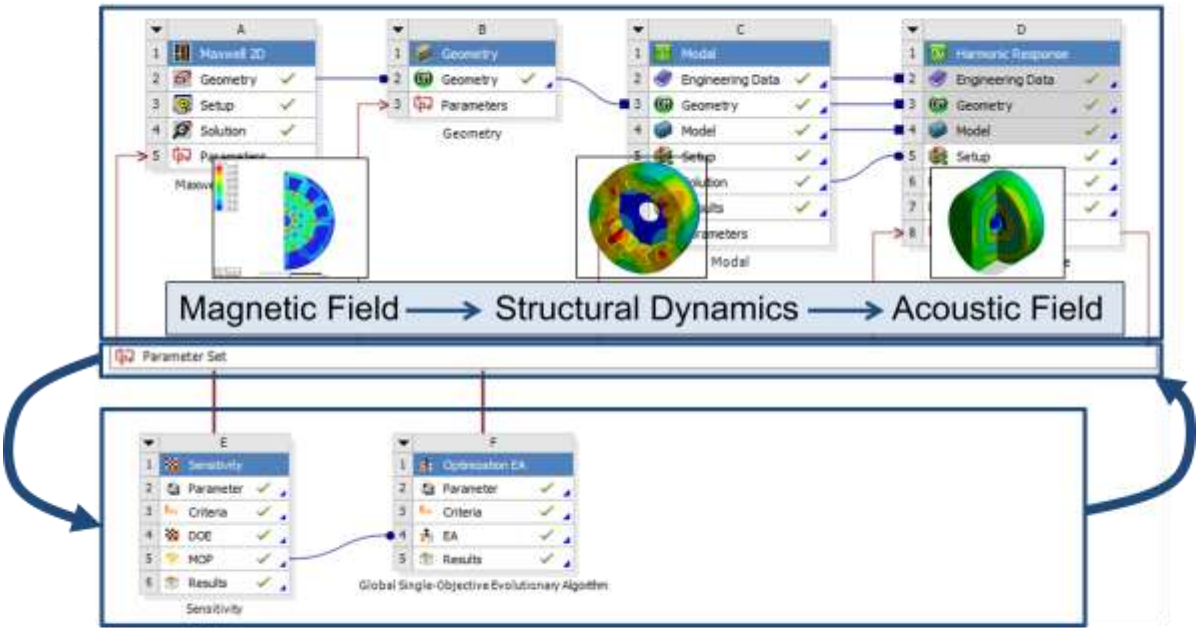

Fig. 4: Full parameterized optimization environment in ANSYS Workbench

Having parameterized the whole workflow, the next step is to couple it to optiSLang inside Workbench for doing a sensitivity study with a subsequently optimization.
Several parameters are set in the geometry and also the rotations per second could be varied. The output parameter is the amplitude for the frequency of 600Hz.
The sensitivity analysis shows CoPs from 96%-98% and clearly filters out the important input parameters. This allows doing a quick optimization using the Metamodel of optimal Prognosis.
As a result this procedure creates a modified model that vibrates with 30% less amplitude than the original model.

6 Conclusion and Wrap up

By performing a simulation of the magnetic fields inside a motor one can calculate the magnetic forces which lead to operating noise evaluating Maxwell's stress tensor. These forces can be Fourier transformed and applied as excitations to structural mode superposition analysis. This workflow leads to a time and computational resource effective simulation of the vibrations of the motor caused by periodic magnetic forces. This effective workflow can be used as part of the standard motor design process to optimize drives on their operating noise.
A seamless workflow can be achieved using ANSYS tools Maxwell and Mechanical and combining them in the Workbench environment. With optiSLang inside Workbench, a sensitivity study and an optimization can be done in an easy-to-use environment.

With this one can characterize (locate) sound sources that can be e.g. magnetic forces that excite stator structure to radiate sound or distributed and time varying eddy currents that cause acoustic relevant radial forces.
The workflow also enables one to develop new designs based on an interdisciplinary optimization workflow in order to meet acoustic regulation and customer comfort criteria.

7 References

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