FEM2measurement transfer functions - definition of acoustic transfer functions of electrical drives

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Introduction

The influence of geometrical parameters of stator and rotor on the acoustic performance on a electrical drive is investigated in [1], design-of-experiment methodology is employed to keep the number of necessary numerical simulations low. In contrast to this paper, the vibrational and acoustic behavior is assessed individually by means of a vibrational measurement (modal analyses) and an analytical radiation model. Vivier et al. use an analytical model for the magnetic circuit parameters and do not account for complicated magnet geometry.

The idea of FEM-to-measurement transfer function can also be found in [2]. In his thesis, Roivainen analyses the vibro-acoustic behavior of direct-torque-controlled (DTC) induction machines. Therefore, a structural dynamic analysis using unit-forces is performed. For verification purposes, the surface acceleration of the machine is measured and the unit-force transfer function is defined as the ratio of measured acceleration to simulated forces. Sound pressure measurement are not used for the measurement-to-FEM transfer functions.

Compared to the approaches presented in the literature, in this paper the novel aspect of using microphone measurements for FEM-to-measurement transfer functions for the acoustic optimization of permanent-magnet excited synchronous machines (PMSM). It may not be as accurate as measuring solely the mechanical transfer function as e.g. in [2], but may be sufficient for optimization starting from an existing prototype, which may have poor acoustic performance, and it is easy in terms of measurement. Furthermore, no sufficient acoustic model, structural and radiation, model is required. In addition to [3] a generalization of the FEM-to-measurement transfer function and a verification of this approach by an experimental modal analysis is presented.

FEM-to-measurement transfer functions

Electromagnetically excited audible noise from electrical machines is typically analyzed in three simulation steps: 1) Electromagnetic field and forces, 2) Mechanical oscillating deformation, and 3) acoustic radiation and perception [4]. Each step can be either investigated by analytical calculation, by numerical simulation or by measurement. In this sense, there is a signal (and energy) flow from current/PM excitation, via flux density and reluctance forces, through surface velocity to sound pressure and particle velocity. For each of the three parts a transfer function can be defined, where the transfer function of the latter two typically can be considered being linear. For example, the mechanical transfer function can be determined by means of numerical modal analysis (using

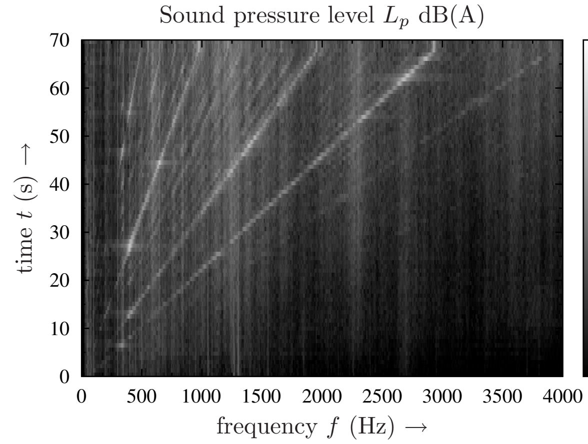

Abbildung 1: Spectrogram of the PMSM run-up.

FEM) or by means of experimental modal analyses (using shaker, accelerometer and dual-spectrum analyzer), for a point excitation.

Alternatively to defining the transfer function purely from measurement, or purely from simulation, it is possible to define a mixed form, if it can be assured that the operating conditions are approximately equal, in the sense

$$H = \frac{B_{\text{meas}}}{A_{\text{simu}}}\,, \tag{1}$$

where B_{meas} is the measured output of the transfer function, and A_{simul} is the simulated input. Using magnetic forces as A_{simu} is a good choice for two reasons: First they can be simulated comparatively accurate using 2D-FEM and they are very difficult to measure. In [2], B_{meas} is chosen to be the surface acceleration and A_{simu} is indeed the magnetic force. In this paper, the transfer function of 2) and 3) is considered at once, thus the sound pressure is used as B_{meas}. The idea of formulation of the transfer function has been deduced from the well known operational modal analysis, and is therefore considered to be a valid approximation.

The starting point for the determination of transfer functions is a microphone measurement of sound pressure $p_{\text{meas}}(t)$ and a synchronized speed measurement $n(t)$ during an unloaded run-up of the PMSM with sufficiently slow slew rate. This is mapped to a so called spectrogram given by $p_{\text{meas}}(\omega, 2\pi n)$, which shows dominant lines due to harmonic force excitations, see Fig. 1. Using a peak-picking technique along these lines, allows for the definition of lines of constant order k as $p_{\text{meas}}(\omega, k),\ k = \frac{\omega}{2\pi n}$.

As a second step, it is essential to trace back each order line to a specific harmonic. This can either be done using standard table works [4], or more sophisticated even tracing back to individual field harmonics, the latter detailed approach is not necessary for the method proposed in this paper, it however may reveal more insight and may help trouble shooting the computer routines. For the unloaded run-up, the space vector diagrams are flat, i.e. there is no imaginary component of the force waves, due to the absence of stator currents. The Fourier decomposition of the reluctance-force-density waves reads

$$\sigma(x,t) = \sum_{k=1}^{K} \sum_{r=-R}^{R} \hat{\sigma}_{rk} \cos(rx + k \cdot 2\pi n \cdot t + \varphi) \,. \quad (2)$$

Now the assumption is made, that one harmonic force wave given by frequency harmonic number k' and by wave number r is dominant and solely accounted for at one line of constant order. Then, the FEM-to-measurement transfer function is defined as

$$H_r(\omega) = \left.\frac{p_{\text{meas}}(\omega, k)}{\hat{\sigma}_{rk}}\right|_{k=k'} , \quad (3)$$

where $\hat{\sigma}_{rk}$ is determined from a FEM simulation of the very geometry as the prototype delivering sound pressure measurements $p_{\text{meas}}(\omega, k)$.

The SPL for a given force excitation $\tilde{\sigma}_{rk}$ can be calculated by means of superposition:

$$L_p(\omega, n) = 20 \log_{10} \left(\sum_{k=\frac{\omega}{2\pi n}}^{K} \sum_{r=-R}^{R} \frac{\tilde{\sigma}_{rk} \cdot H_r(\omega)}{p_{\text{ref}}} \right) - \Delta_A(\omega) \,, \quad (4)$$

where $p_{\text{ref}} = 20\mu\text{Pa}$.

Generalization of the FEM-to-measurement transfer functions

A possible extension of the proposed transfer function approach to evaluating more than one force order per frequency order line can obtained from the following considerations. If there are for example two relevant frequency order lines crossing at a specific frequency ω with different force orders r, then it is possible to not only obtain the transfer function by one value of the force density σ_{rk}, but include the other force order as well, which is of minor importance. In this case, the pressure at the crossing speed $n = n_1$ with order line 1 can be regenerated by

$$p(\omega, n_1) = \sigma_{r_1 k_1} H_{r_1}(\omega) + \sigma_{r_2 k_1} H_{r_2}(\omega) \quad \text{with} \quad k_1 = \frac{\omega}{2\pi n_1} \,. \quad (5)$$

The same holds true, of course, for the second crossing speed $n = n_2$. Writing this in matrix form gives

$$\begin{pmatrix} p(\omega, n_1) \\ p(\omega, n_2) \end{pmatrix} = \begin{pmatrix} \sigma_{r_1 k_1} & \sigma_{r_2 k_1} \\ \sigma_{r_1 k_2} & \sigma_{r_2 k_2} \end{pmatrix} \cdot \begin{pmatrix} H_{r_1}(\omega) \\ H_{r_2}(\omega) \end{pmatrix} , \quad (6)$$

or short

$$\mathbf{p}(\omega) = \boldsymbol{\sigma} \cdot \mathbf{h}(\omega) \,, \quad (7)$$

which can be used to determine the transfer function $\mathbf{h}$ including the influence of more than one force wave per order line by inverting the sigma matrix $\boldsymbol{\sigma}$

$$\mathbf{h}(\omega) = \boldsymbol{\sigma}^{-1} \cdot \mathbf{p}(\omega) \,. \quad (8)$$

Since sigma only depends on the frequency order k and not on the actual frequency ω, it is sufficient to invert σ only once per frequency range. The boundaries between frequency ranges occur, if the constitution of force orders changes, this is the case if the measurement limits are reached, i.e. at maximum speed or maximum frequency. The benefits drawn from this approach depends on the condition number of σ, which is large if a column of σ only contains very small force densities entries. This means that there has to be a significant force density value from the electromagnetic FE simulation at least for one order line for the algorithm to give good results.

Conclusions

In this paper an approach to determine the mechanical transfer functions of electrical drives is presented. The proposed transfer function is required for the acoustic characterization of electrical machines. Often, noise, vibration and harshness of electrical drives are investigated after having built a prototype. Fast and reliable approaches for the determination of the mechanical transfer functions are than required for the optimization of the electromagnetic excited noise. In contrast to the proposed approach, these transfer functions are usually determined by means of time-consuming numerical simulations or experimental modal analysis. The presented approach relies on numerical simulated excitation forces, which are usually calculated before building a prototype, and a run-up measurement of the air-borne or structure-borne noise of the prototype in no-load condition. With the proposed approach it is possible to optimize the electromagnetic circuit of a given motor without numerical simulations of the structure and ca thereby help to find a quick optimization of the electromagnetic excited noise.

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