3D Anisotropic Model for the Numerical Computation of Nonlinear Magnetostriction

A. Volk*, M. Kaltenbacher†, A. Sutor*, M. Ertl‡, R. Lerch*
*Chair of Sensor Technology, University of Erlangen-Nuremberg, Paul-Gordan-Straße 3/5, 91052 Erlangen, Germany
†Institute of Mechanics and Mechatronics, Vienna University of Technology, Wiedner Hauptstr. 8, 1040 Wien, Austria
‡Siemens Energy Sector, Katzwanger Str. 150, 90461 Nuremberg, Germany
E-mail: adrian.volk@fau.de

***Abstract*—In this work we present a simulation approach to compute the vibration behavior of transformer cores due to magnetostriction. Thereby, the magnetic and mechanical material properties of electrical sheets are characterized by a built up measurement setup, including the hysteretic as well as anisotropic material behavior. These results are used within the numerical computation, which is done by applying the Finite Element Method (FEM), while the hysteresis behavior is simplified to a nonlinear one. Finally, the numerical computation is demonstrated with a simplified model of a transformer core joint region, which also shows the importance to properly incorporate the nonlinear as well as anisotropic material behavior.**

***Index Terms*—Magnetostriction, Electromagnetic measurements, Finite element methods, Magnetic anisotropy, Nonlinear magnetics**

I. Introduction

Magnetostrictive materials are widely used for actuator and sensor applications. Often the magnetostrictive behavior of these alloys is an undesirable effect, as e.g. in electric machines and power transformers, where it is one of the main sources for noise generation. Unfortunately, these materials exhibit nonlinear behavior for the magnetic properties as well as the mechanical characteristics leading to the well-known hysteretic magnetization and magnetostriction loops, respectively. Accounting for the anisotropy concerning magnetic and mechanical material behavior is a very important aspect which is especially true for electrical sheets as used in transformers.

Well-known measurement methods to capture magnetostrictive effects are based on different layout and type of strain gauges, accelerometers or capacitive dilatometers [1], [2] with the disadvantages of electromagnetic cross sensitivity, influence of mechanical contact and less accuracy compared to laser optical techniques. Therefore, we present an enhanced setup based on a Single Sheet Tester (SST) to allow for measurements of the magnetostrictive strain as well.

There are a lot of different numerical methods available to model magnetostrictive effects which can be classified in three main approaches, which are all restricted to isotropic or uniaxial behavior. Either a magnetostrictive strain tensor is introduced whose entries are depending on the magnetic flux density (e.g. [3]), or a free energy as a tensor function is used depending on the magnetic induction and the mechanical strain [4]. Furthermore, thermodynamic consistent models decompose the magnetic induction and the mechanical strain into a reversible and an irreversible part to separate its computation [5]. The latter approach is also used within [6] which is enhanced by the presented model to properly account also for the z-direction. Thereby, the irreversible parts are described on the basis of prior measurements, to account for the complex material behavior, including three-dimensional anisotropy and nonlinearity.

II. Determination of Material Parameters

In order to correctly model the real material behavior within the simulation, it is necessary to properly characterize the material properties by measurements at first. Therefore, we built up an enhanced setup based on a SST [7], which is extended by laser vibrometer measurements, to be able to record the magnetostrictive strain as well. The SST is a measurement setup permitting the investigation of magnetic material parameters of electrical steel, at which the magnetic field intensity and magnetic polarization are determined [7]. Measuring the nonlinear material behavior of sample sheets leads to the well-known hysteretic magnetization loops. The setup is extended by a lifting mechanism (see Fig. 1) to unload the sample sheet to ensure its stressless vibration, while the vibration is measured by a laser vibrometer. The

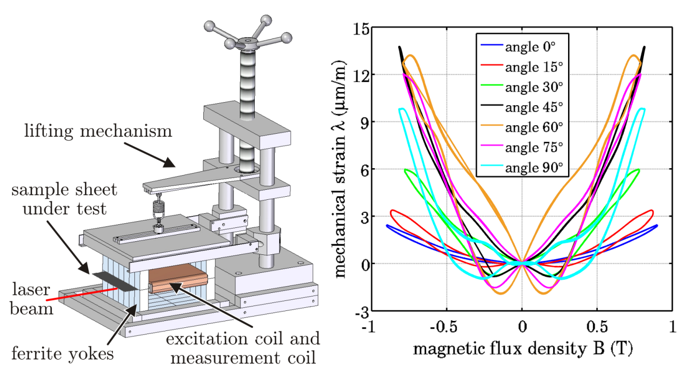

Figure 1: Engineering drawing of the accomplished SST (left) and angle-dependent butterfly curves of a sample sheet (right), while rolling direction corresponds to angle 0°.

measurement of the nonlinear mechanical strain as a function of the exciting magnetic field results in the magnetostrictive hysteresis loop (so-called butterfly curve). Since the material parameters show a high-grade anisotropic behavior [2], a series of measurement is performed with different sample sheets which have been cut out of the transformer sheet with varying cutting angles. As total result we obtain angle-dependent magnetization curves as well as butterfly curves, including its nonlinear and hysteretic behavior. The latter one are also shown in Fig. 1 to demonstrate the achieved results.

III. Physical Modeling and FE Simulation

The physical model is based on the obtained measurement data to incorporate the nonlinear and anisotropic material behavior within the simulation process. Therefore, the angle-dependent magnetization and butterfly curves are used to compute the corresponding commutation curve, so that the hysteretic behavior is simplified to a nonlinear one. Interpolating these curves to z-direction on the basis of an empirical model leads to a three-dimensional set of measurement data describing the material behavior used within the simulation.

Furthermore, the computation of the magnetostrictive vibration is decomposed into the separate calculation of the magnetic and the mechanical field in order to gain optimal solving conditions and to reduce complexity. Because of this decomposition the change of magnetic properties due to the mechanical field is not considered. Since a working point can be determined by pre-stressing the measurement samples of the SST, only the variation of mechanical field is neglected.

Starting with the magnetic field computation, the quasistatic eddy current case of magnetics is modeled with the classical vector potential formulation (see e.g. [8]). Referring to [6], the magnetic behavior is modeled by its vector relation between the magnetic induction $\boldsymbol{B}$ and field intensity $\boldsymbol{H}$

$$\boldsymbol{B} = \boldsymbol{B}(\boldsymbol{H}) = B_{\varphi\theta}(H)\boldsymbol{e}_B\,; \quad \boldsymbol{e}_B = \frac{\boldsymbol{B}}{B}\,. \tag{1}$$

Here, we compute the unit vector $\boldsymbol{e}_B$ and evaluate the nonlinear and angle-dependent magnetic commutation curve $B_{\varphi\theta}$, while $B_{\varphi\theta}$ is calculated by bilinear interpolation of the best fitting orientations of spherical coordinates φ, θ w.r.t. $\boldsymbol{e}_B$. An important enhancement comparing the presented formulation in [6] is that here also the z-direction is taken into account by polar angle θ which is in particular very important for the correct simulation of transformer cores and its stacked grain-oriented electrical sheets. Furthermore, an interpolation of the underlying measurement curves is added to ensure the ideal application during simulation. Finally, the magnetic field equation is discretized by applying edge finite elements while the arising algebraic system of equations is solved by an efficient Newton scheme utilizing a two level solver.

Subsequently, the magnetostrictive induced strain tensor $\boldsymbol{S}^{\mathrm{m}}$ is calculated by

$$\boldsymbol{S}^{\mathrm{m}} = \frac{3}{2}\left(\boldsymbol{e}_B \otimes \boldsymbol{e}_B - \frac{1}{3}\boldsymbol{I}\right) S^{\mathrm{m}}_{\varphi\theta}(B)\,, \tag{2}$$

where $\boldsymbol{I}$ denotes the unit tensor and $S^{\mathrm{m}}_{\varphi\theta}(B)$ the evaluated magnetostrictive commutation curve, which analogously gets computed of the best fitting curves w.r.t. $\boldsymbol{e}_B$. Finally, nodal finite elements are applied to calculate the magnetostrictive vibration due to the magnetic excitation field B.

IV. Numerical Results

First numerical results have been achieved by applying the presented approach to a simplified quarter model of an Epstein frame, consisting of six stacked layers at the joint with a 90 degree overlap and two current driven excitation coils along each yoke. The resulting magnetostrictive deformation due to the exciting magnetic field generated by the coils is displayed in Fig. 2, showing the main source of vibration at the joint region of yokes. Since the results indicate the main part of vibration pointing in thickness direction, a spectrum of the mechanical displacement at an observation point is also displayed, showing higher harmonics and the characteristical vibration behavior known from measurements at real transformers.

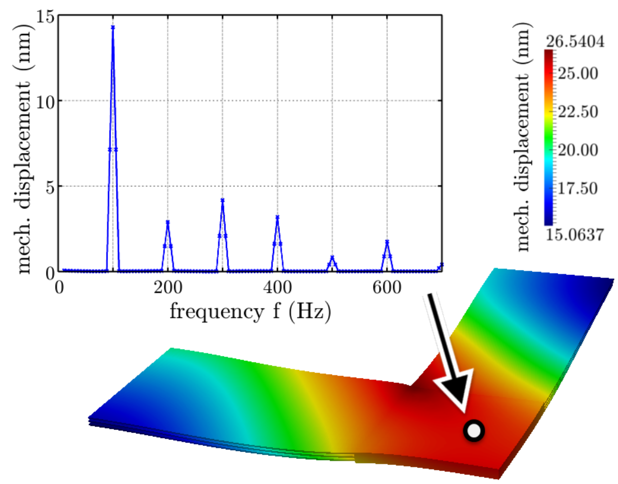

Figure 2: Magnetostrictive deformation of Epstein frame due to magnetic excitation (coils not displayed) for a characteristical time step and spectrum of the mechanical displacement in thickness direction at an observation point at joint region.

References

[1] Y. Kai, Y. Tsuchida, T. Todaka et al., "Measurement of the two-dimensional magnetostriction and the vector magnetic property for a non-oriented electrical steel sheet under stress", Journal of Applied Physics, 111 (7), 2012.

[2] S. Somkun, A. J. Moses, P. I. Anderson et al., "Magnetostriction anisotropy and rotational magnetostriction of a nonoriented electrical steel", IEEE Trans. on Magnetics, vol. 46, no. 2, pp. 302-305, 2010.

[3] K. Delaerea and W. Heylena and K. Hameyer and R. Belmans, "Local Magnetostriction Forces for Finite Element Analysis", IEEE Transactions on Magnetics, vol. 36, no. 5, pp. 31153118, 2000.

[4] K. Fonteyn, A. Belahcen, R. Kouhia et al., "FEM for Directly Coupled Magneto-Mechanical Phenomena in Electrical Machines", IEEE Transactions on Magnetics, vol. 46, no. 8, 2010.

[5] K.Linnemann, S. Klinkel and W. Wagner, "A constitutive model for magnetostrictive and piezoelectric materials", International Journal of Solids and Structures 46, 2009.

[6] M. Kaltenbacher, A. Volk and M. Ertl, "Anisotropic Model for the Numerical Computation of Magnetostriction in Steel Sheets", 15th International IGTE Symposium, pp. 181-185, Graz, Austria, 2012.

[7] Magnetic materials - Part 3: Methods of measurement of the magnetic properties of electrical steel strip and sheet by means of a single sheet tester, IEC 60404-3:1992 + A1:2002 + A2:2009, 2010

[8] M. Kaltenbacher, "Numerical Simulation of Mechatronic Sensors and Actuators", Springer, 2nd ed., 2007.