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Modeling of Anisotropic Laminated Magnetic Cores using Homogenization Approaches

Johannes Ziske[1] , Holger Neubert[1*], Rolf Disselnkötter[2]

1 - TU Dresden, Institute of Electromechanical and Electronic Design, Dresden, Germany
2 – ABB AG, Corporate Research Center Germany, Ladenburg, Germany

*** Corresponding author: TU Dresden, IFTE, 01062 Dresden, Germany, holger.neubert@tu-dresden.de**

1 INTRODUCTION

A specific issue in transformer modeling using the finite element method is the consideration of electric sheets or other laminated core materials which are used to reduce eddy currents (**Figure 1.a**). Instead of explicitly modeling the geometry of every single core sheet material homogenization procedures can be applied [1-5]. They substitute the laminated core structure for a virtual bulk material which has the same outer dimensions and nearly the same electromagnetic behavior. (**Figure 1.b**). In our study, we have implemented a selection of them in an inductor model. Simulation results thereby obtained are compared to those from models with explicitly modeled lamination and also to experimental test results.

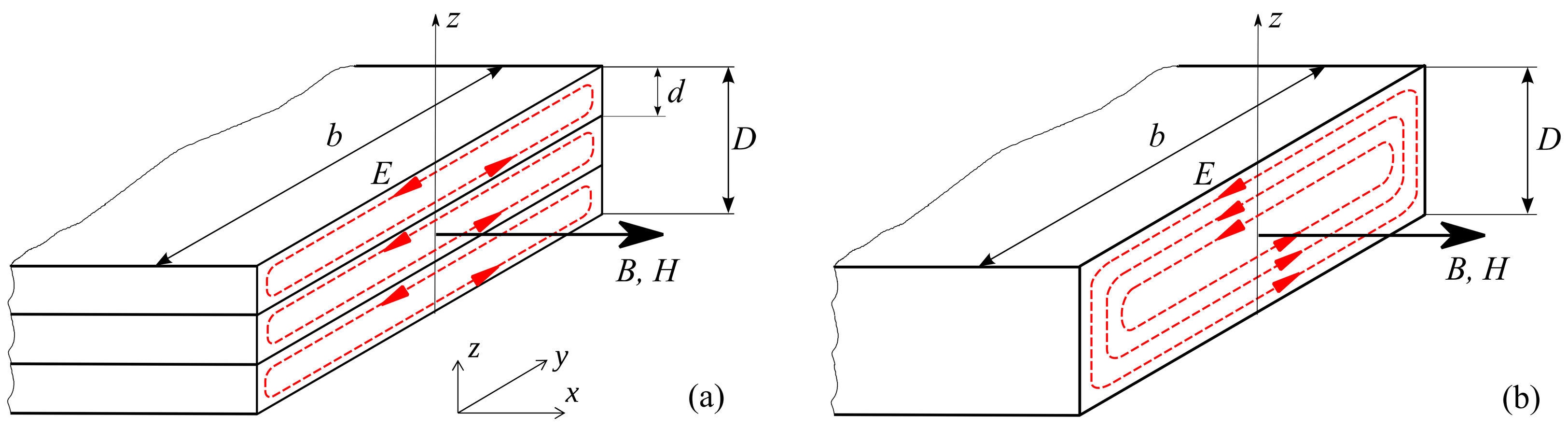

Figure 1: Eddy currents in a laminated magnetic core (a) and in an equivalent homogenized core (b); B, H – magnetic field, E – electric field

2 TRANSIENT INDUCTOR MODEL

Figure 2 depicts the core sample which was both experimentally investigated and simulated. The tape-wound core wears a closely wound secondary coil and a primary coil equally distributed over the ring core.

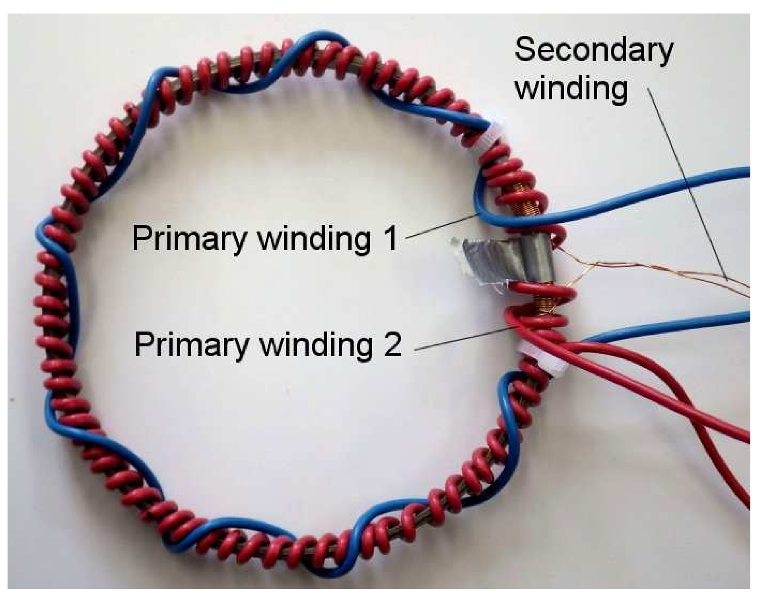

Figure 2: Permalloy tape-wound core for experimental investigations

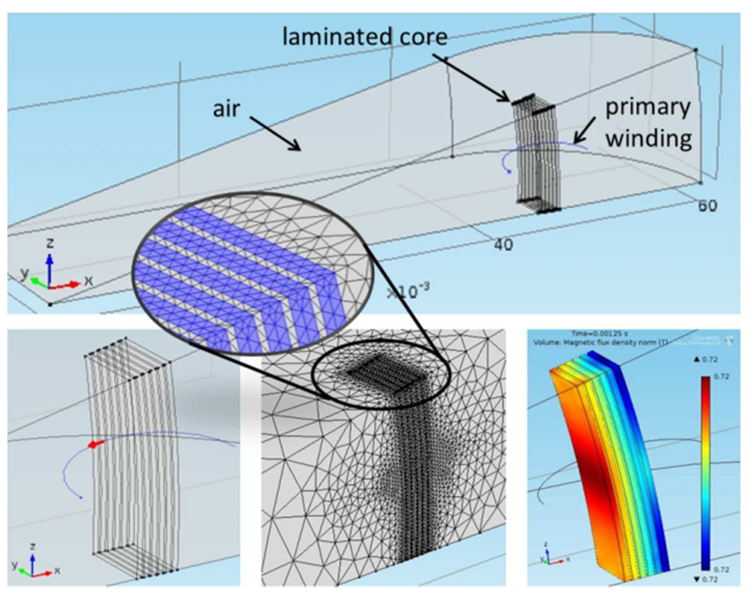

Figure 3: 3D finite element inductor model

3 HOMOGENIZATION APPROACHES

In each of the approaches listed in **Table 1**, orthogonal electrical conductivity $\sigma = [\sigma_x\, \sigma_y\, \sigma_z]$ and permeability $\mu = [\mu_x\, \mu_y\, \mu_z]$ are proposed to adapt the behavior as desired. The magnetic material behavior is considered in $H(|B|)$ form by piecewise cubic interpolation of the measured static commutation curve.

Table 1: Homogenization approaches for laminated magnetic cores; σ_b isotropic conductivity of the bulk material, n number of stacked sheets

KIWITT [3]	$\sigma_x = \sigma_y = \frac{1}{n^2}\sigma_b,\quad \sigma_z = \sigma_b$	$\mu_x = \mu_y = F\mu_b$
WANG [5]	$\sigma_x = \sigma_y = \sigma_b$ $\sigma_z = \left(\frac{d}{b}\right)^2 \sigma_b$	$\mu_x = \mu_y = F\mu_b$ $\mu_z = \dfrac{1}{\dfrac{F}{\mu_b} + \dfrac{1-F}{\mu_0}}$

4 SIMULATION RESULTS AND MEASUREMENTS

Measurements and simulations utilized a Permalloy core with a narrow static hysteresis loop. Therefore, dynamic effects are dominant. The models used the measured non-linear commutation curve in form of a $\mu_r(B)$ lookup table. **Figure 4** shows measured and simulated dynamic hysteresis loops (laminated model). **Figures 5** and **6** compare the extracted coercivity and eddy current losses from measurements and simulations with respect to simulation results from models with explicitly modeled core laminations. **Figure 7** shows the performance of the different homogenization approaches dependent on the width-to-thickness ratio of the core sheets.

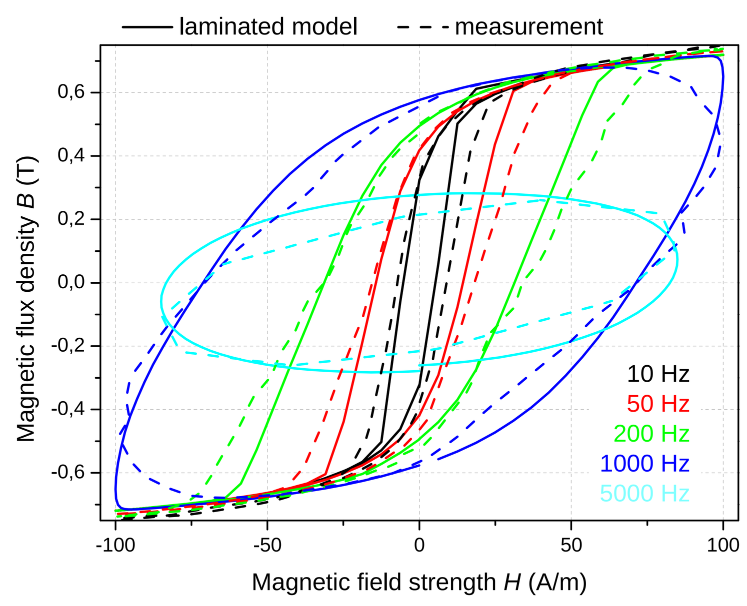

Figure 4: Dynamic hysteresis loops with explicitly modeled lamination compared to measurements

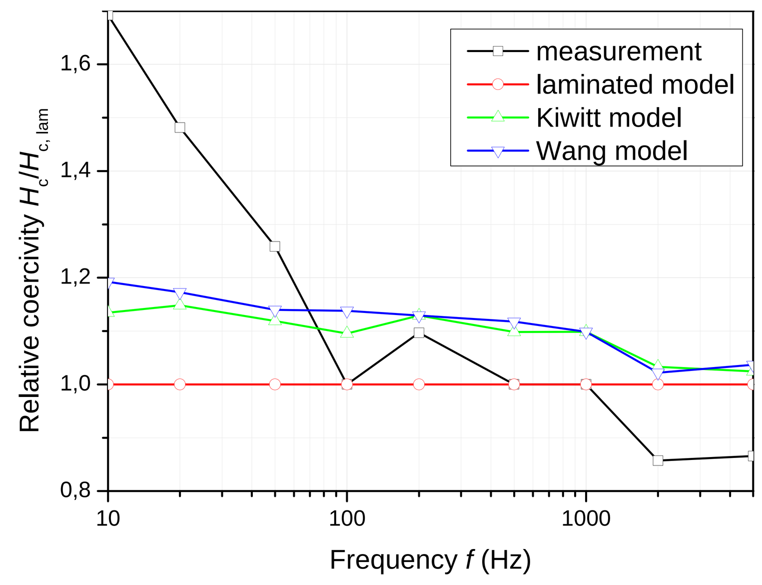

Figure 5: Relative coercivity from measurements and simulations

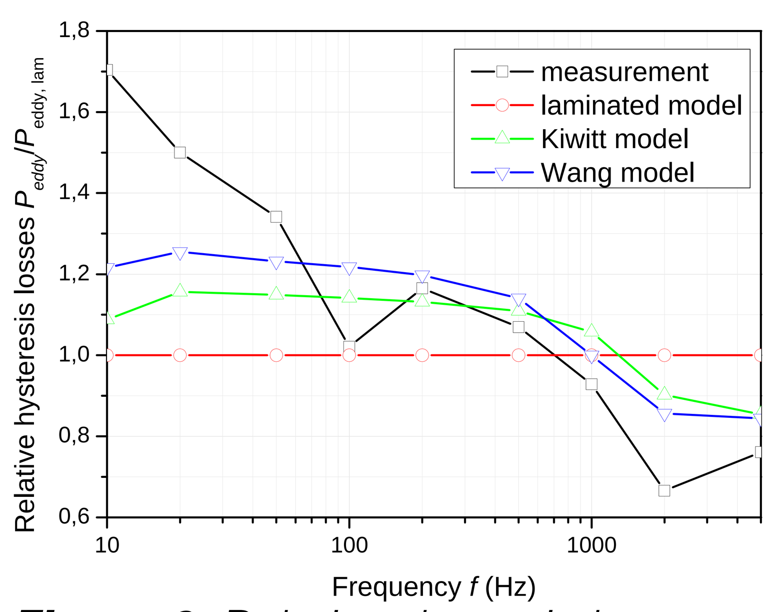

Figure 6: Relative dynamic hysteresis losses from measurements and simulations

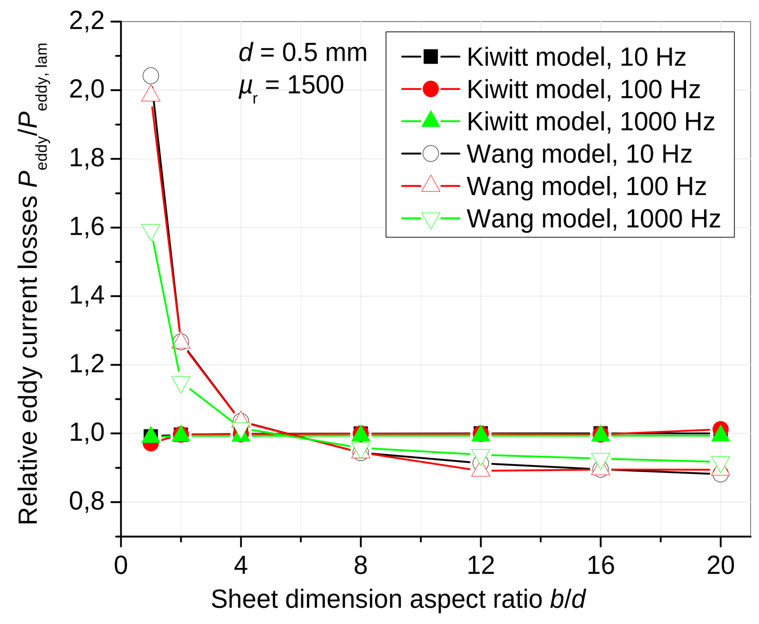

Figure 7: Relative dynamic losses from homogenized core models depending on the sheet aspect ratio

5 CONCLUSIONS

The KIWITT approach simulates best the coercivity and dynamic losses of laminated cores, provided that the magnetic flux is in parallel to the lamination plane. In this case, the KIWITT approach is reliable within large ranges of frequency and aspect ratio of the sheet geometry. The WANG model underestimates slightly but systematically both the coercivity and dynamic losses. It can be applied only for sheets with an width-to-thickness ratio of larger than 4. However, in contrast to the KIWITT approach, the WANG model is robust against inclinations between flux density and the lamination plane (see the paper).

If the known restrictions are taken into account, the number of the finite elements in the simulation models can be significantly reduced, which results in faster computation.

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Technische Universität Dresden
Institute of Electromechanical and Electronic Design
D-01062 Dresden
Germany
www.ifte.de

ABB AG
Corporate Research Center Germany
Wallstadter Straße 59
D-68526 Ladenburg
Germany

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