Modeling of Anisotropic Laminated Magnetic Cores using Homogenization Approaches

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Outline

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2. Homogenization Procedures
3. Transient Electromagnetic Inductor Model
4. Measurement and Simulation Results
5. Conclusions
1 Introduction

Laminated magnetic cores
- Used to reduce eddy currents
- Sheet thickness $d \ll$ Core thickness

\[ d < 2\delta = \frac{1}{\sqrt{\pi f \sigma \mu}} \]

Zipernowsky, Déri, Bláthy, 1885
[F. Uppenborn: History of the transformer 1889]
2 Homogenization Procedures

**Principle**

- Replacing the laminated structure (a) by a single domain of an electrically orthotropic material (b) which exhibits the same macroscopic behavior
- Computational effort can be significantly reduced
2 Homogenization Procedures

- Several approaches published, e.g. [1 - 5]
- Orthotropic electrical and magnetic material characteristics assumed

\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\end{bmatrix}
= \begin{bmatrix}
\sigma_b \\
\frac{\sigma_b}{n^2} \\
\sigma_b \\
\end{bmatrix}
\quad \begin{bmatrix}
\mu_x \\
\mu_y \\
\mu_z \\
\end{bmatrix}
= \begin{bmatrix}
\mu_b \\
\mu_b \\
\frac{1}{\mu_0} \\
\end{bmatrix}
\]

\text{KiWitt} [2]
\[
\sigma_x = \sigma_y = \frac{1}{n^2} \sigma_b \\
\sigma_z = \sigma_b \\
\mu_x = \mu_y = F \mu_b
\]

\text{WANG} [3]
\[
\sigma_x = \sigma_y = \sigma_b \\
\sigma_z = \left(\frac{d}{b}\right)^2 \sigma_b \\
\mu_x = \mu_y = F \mu_b \\
\mu_z = \frac{1}{\frac{\mu_b}{\mu_0} + \frac{1-F}{\mu_0}}
\]

\(\sigma_b\): isotropic conductivity of the bulk material,
\(n\): number of stacked sheets

3 Transient Electromagnetic Inductor Model

Investigated Transformer Cores

- Permalloy tape wound core
- Core sheet thickness 250 µm, 5 sheets (helically wound)
- Core width 6 mm, mean length of the flux path 284 mm
- Secondary coil is closely wound directly on the core (65 windings)
- Primary coil is equally distributed over the ring (9 / 74 windings)
3 Transient Electromagnetic Inductor Model

**Finite Element Model**
- Parametric 3D geometry, advantage of \( \frac{1}{2} \cdot \frac{1}{32} \) symmetry
- Core as sheets with insulating layers between or as solid
- \( mf \) mode used for the transformer model, time-dependent study
- Current on a circular edge around the core, sinusoidal excitation current
4 Measurement and Simulation Results

**Dynamic hysteresis loops**

- Magnetic flux density and lamination plane in parallel
- Measured data vs. simulation results from models with explicitly modeled core structure vs. models with homogenized core
4 Measurement and Simulation Results

Dynamic hysteresis loops

- Coercivity
- Dynamic hysteresis losses

![Graphs showing relative coercivity and relative hysteresis losses vs frequency for different models and measurements.](image)
4 Measurement and Simulation Results

Dynamic hysteresis loops

- Influence of width-to-thickness ratio of the sheets
- Simulated for linear magnetic core material
- Explicitly modeled core structure vs. homogenized core

![Graph 1: Relative Coercivity vs. Sheet Dimension Aspect Ratio](image1)

![Graph 2: Relative Eddy Current Losses vs. Sheet Dimension Aspect Ratio](image2)
5 Measurement and Simulation Results

Dynamic hysteresis loops

- Magnetic flux density and lamination plane inclined

![Graphs showing hysteresis loops](image)

\[ \mu_r = 1.500 \]
\[ d = 0.5 \text{ mm} \]
\[ \phi = 15^\circ \]
5 Conclusions

- Homogenization approaches for laminated magnetic cores are easy to use
- Significant reduction of DoF compared to models with explicit core structure
- Simulation results were compared both to those found on explicitly modeled laminations and to experimental results
- The KIWIT homogenization approach
  - fits best the results from models with laminated cores provided that the magnetic flux is in parallel to the sheets
  - reliable within large ranges of frequency and width-to-thickness ratio
  - underestimates dynamic hysteresis effect for inclination angles between flux and lamination plane
- The WANG model
  - underestimates slightly both the coercivity and the dynamic losses
  - is applicable for sheets with an width-to-thickness ratio > 4
  - is robust against inclinations between flux and lamination plane
- Other models show larger deviations
Thank you very much for your attention.