Implementation and verification of a dynamic vector-hysteresis model

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Abstract

This paper presents the application and verification of a dynamic vector-hysteresis model for non-grainoriented ferromagnetic materials. The hysteresis model is based on the fundamental principles of thermodynamics. Since the model is completely consistent with a genuine energy interpretation it can be considered from this point of view as a mechanical analog. To validate the model, the response of the model is compared to measured material characteristics of an isotropic electrical steel grade.

Energy-based hysteresis modeling

The first law of thermodynamics (1) states that every system has an internal energy that can only be changed by the transport of work and/or heat beyond the boundaries of the system:

$$\dot{\rho}^{\Psi} = \dot{\rho}^{W} + \dot{\rho}^{Q}. \tag{1}$$

Thermal effects are neglected since entropy ($\dot{s} = 0$) is assumed to be constant. The internal energy corresponds to a reversible magnetic field strength $\vec{h}_r$ and the dissipated work within the system to an irreversible magnetic field strength $\vec{h}_{irr} = \vec{h}_i + \vec{h}_j$. Deriving the energy dissipation functional with respect to $\dot{\vec{M}}$ makes it possible to represent the energy balance as a function of the magnetic field strength $\vec{h} = \vec{h}_r + \vec{h}_{irr}$.
At the macroscopic level the microscopic distribution of the pinning points, hindering the domain wall motion, cannot be modeled explicitly. The pinning force can be modeled as an analog by a dry friction force κ as in the J-A model. This force counteracts any change in magnetization and the corresponding energy density is converted into heat. Considering the dynamics of the magnetization process, the attenuation by microscopic eddy currents can be represented as an mechanical analog by a movement with viscous friction with the global friction constant λ:

$$\vec{h}_{irr} = \frac{\partial}{\partial \dot{\vec{M}}}\left(\kappa \cdot \left|\dot{\vec{M}}\right|\right) + \frac{1}{2}\frac{\partial}{\partial \dot{\vec{M}}}\left(\lambda \cdot \dot{\vec{M}}^2\right). \tag{2}$$

Since the energy dissipation functional is not differentiable, it models the memory effect. This makes it possible to specify the macroscopic magnetization with consideration of hysteresis:

$$\vec{B}(\vec{h}) = \vec{M}(\vec{h}_r) + \mu_0 \cdot \vec{h}. \tag{3}$$

To represent the statistical distribution of the pinning point strength (local coercive forces) it is reasonable to assume that the magnetization is a multi-scale function, depending on the global value $\left|\vec{h}_r\right|$, which is composed of local values $\vec{h}_r^k$ with the weighting w: $\left|\vec{h}_r\right| = \left|\sum_k w^k \cdot \vec{h}_r^k\right|$. This can be accounted for in the model by combining several elementary parts and defining for each part a time-independent pinning force κ^k. Therewith the global scale can be treated independently from the local scale. Each cell can be initiated independently and assigned to a local coercive force (i.e. local friction force).
The viscous friction force acts on all cells similarly. The equilibrium equation can be written as a sum of independent cell-based magnetic fields:

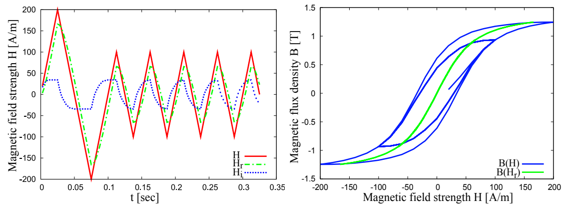
$$\vec{h} = \sum_k w^k \cdot \left(\vec{h}_r^k + \vec{h}_j^k\right) + \sum_k w^k \cdot \vec{h}_i^k. \tag{4}$$

Identification of the free parameters

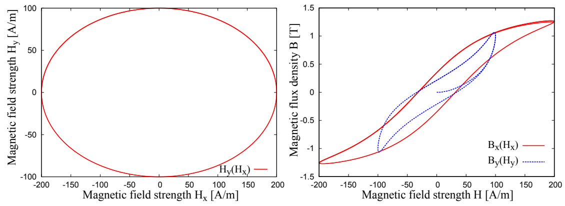
- Measured material characteristics on a standard Epstein frame (or single sheet tester) serve for the parameter identification.
- Magnetization $\vec{M}(\vec{h}_r)$ is described by a parametric saturation curve, least-square fitted to the measured anhysteretic magnetization curve . Two Langevin functions are chosen to describe the anhysteretic magnetization curve. The first Langevin function represents the motion of Bloch walls, the second one the rotation of the magnetic moments relative to the preferred axis (coherent rotation).
- Identification of the local pinning forces κ^k and their weightings w^k is done by interpolating the coercive curve $H_c(H)$ by a staircase function, which describes the abrupt, discontinuous magnetization process. Coercivity explicitly represents the lag of the reversible magnetic field $\vec{h}_r$ behind the externally applied field $\vec{h}$. In the future, a microstructural analysis of the distribution function of the pinning points will serve for the determination and identification of the weighting of individual cells.
- The global viscous friction constant describing dynamic magnetization effects is currently identified by a try&error fitting with measured hysteresis loops and losses at higher frequencies.

Analysis of the hysteresis model

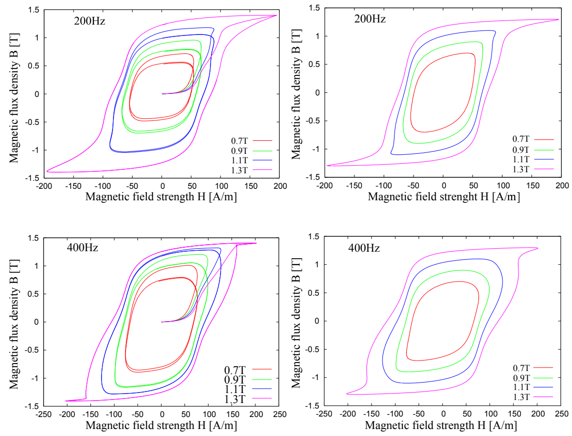
To study the stability of the hysteresis model the applied magnetic field oscillates at first between the main hysteresis loop and then around an internal loop. The vector-hysteresis model provides a stable loop within the main loop and the turning point rule is adhered. Additionally a stable minor loop is obtained if the applied magnetic field alternates between two positive values as long as the turning point values stay unchanged.



The magnetic field strength vector is described in the 2D case by $H_x(t) = H_x \cdot sin(\omega t)$ and $H_y(t) = H_y \cdot cos(\omega t)$ with the angular velocity ω. Although the parameters of the vector-hysteresis model are identified using standard uniaxial measurements the model is able to reproduce the material behavior of isotropic materials under generally rotating or elliptical fields.



To validate the identified parameters, the response of the hysteresis model $B_{mod}(H_{meas})$ is compared with measured material characteristics $B_{meas}(H_{meas})$. Deviations mainly occur in the medium magnetic flux density region. The model reacts sensitive to the description of the reversible magnetization and the representation of the pinning point distribution. The hysteresis model describes the bulging of the hysteresis loops using a single global constant parameter λ.



Conclusion

The vector-hysteresis model describes the metrological characteristics of non-grainoriented electrical steel accurately. Further work is required regarding the physical justification of the parameter identification and the modeling of the anhysteretic curve to enable a more accurate modeling of hysteresis curves at various frequencies and magnetic flux density levels. Anisotropy can be considered by adding a weighting function of the angle of each individual magnetic moment with respect to the field.

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