Strong Coupling Method between Magnetic Field Equations and Hysteresis Model for Accurate Prediction of Core Loss in Inductive Components

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A new method for combining the magnetic field equations and hysteresis model is studied. We implemented a simulator according to discretization procedure of the finite element method (FEM) to incorporate hysteresis model that we have developed recently: a grain magnetics (GM) model. In our method, the magnetic field equations and the equations of the GM model are calculated alternatively until the magnetic flux density and the magnetization converge simultaneously. An inductor under DC bias was used to verify our simulation method. In the calculations, especially core losses of the models ware reproduced with high accuracy. Here we show a method of combining the magnetic field equations and the GM model.

***Index Terms*— hysteresis model, micromagnetics, finite element method, core loss, inductor, magnetic simulation, LLG equation**

I. Introduction

AN ACCURATE prediction of core loss in inductive components, such as inductors in DC/DC converters, is required for computer-aided device design. To compute the core losses in time-dependent finite element analysis, the magnetic flux density and the frequency are used by multiplying loss coefficients pre-calculated for the material properties [1]-[2]. It is, however, still quite difficult to predict the core loss using only the loss coefficients, because the characteristics of the hysteresis widely change according to material properties and drive conditions.

The magnetic hysteresis model for numerical simulation was developed based mainly on the mathematical formulas [3]-[5]. We studied the grain magnetics (GM) model which is based on the Stoner-Wohlfarth (SW) model [6]-[7]. The GM model can express B-H curves accurately with a few parameters, therefore we can identify the model parameter from a major and a few minor loops [8].

We showed that the finite element analysis (FEA) with the GM model provides a simulation result data close to the experimental data of the inductor [9]. In this paper, we propose a method of combining the magnetic field equations and the GM model based on discretization procedure of the finite element method (FEM).

II. Hysteresis Modeling

GM model deals with a magnetic material as the aggregate of the single-domain particle, and defines a magnetization vector M as the averaged magnetization:

$$\boldsymbol{M} = \frac{M_s}{N}\sum_{i=1}^{N}\boldsymbol{m}_i, \tag{1}$$

where M_s is the saturated magnetization and m_i is a normalized magnetization vector of the i-th single-domain particle. The effective field in the i-th single-domain particle is as follows:

$$\boldsymbol{H}^i_{eff}(\boldsymbol{m}_i) = \boldsymbol{H} + \boldsymbol{H}^i_{ani}(\boldsymbol{m}_i) + \boldsymbol{H}^i_{\lambda\sigma}(\boldsymbol{m}_i) + \boldsymbol{H}^i_{exc}(\boldsymbol{m}_i), \tag{2}$$

where $\boldsymbol{H}$, $\boldsymbol{H}^i{}_{ani}$, $\boldsymbol{H}^i{}_{\lambda\sigma}$ and $\boldsymbol{H}^i{}_{exc}$ are the external field, the anisotropy field, the magnetoelastic field and the excess field respectively. $\boldsymbol{H}^i{}_{exc}$ is due to eddy current caused by magnetic domain wall motion and c_β is a material constant.

$$\boldsymbol{H}_{exc} = c_\beta \frac{\partial \boldsymbol{M}}{\partial t} \tag{3}$$

To find the local minimum state of the single-domain, we use the Landau–Lifshitz–Gilbert (LLG) equation which is as follows:

$$\frac{d\boldsymbol{m}_i}{dt} = -\frac{\gamma_g}{1+\alpha^2}\boldsymbol{m}_i \times \boldsymbol{H}_{eff} - \frac{\alpha\gamma_g}{1+\alpha^2}\boldsymbol{m}_i \times \left(\boldsymbol{m}_i \times \boldsymbol{H}_{eff}\right),\ i = 1,\ldots, N, \tag{4}$$

where, γ_g and α are the gyromagnetic ratio and Gilbert damping parameter.

III. Method of FEA with GM Model

The governing equation of the magnetic field is formulated with the vector potential $\boldsymbol{A}$,

$$\nabla \times \left(\frac{1}{\mu_0}\nabla \times \boldsymbol{A}\right) + \sigma\left(\frac{\partial \boldsymbol{A}}{\partial t} + \nabla\varphi\right) = \frac{1}{\mu_0}\nabla \times \boldsymbol{M} + \boldsymbol{J}_0, \tag{5}$$

where $\boldsymbol{M}$ is the magnetization vector and $\boldsymbol{J}_0$ is exciting current density vector. And the equation for preserving the eddy current derived from the scaler potential φ is given as:

$$\nabla \cdot \sigma\left(\frac{\partial \boldsymbol{A}}{\partial t} + \nabla\varphi\right) = 0. \tag{6}$$

Where μ_0 is the vacuum permeability and σ is the conductivity. The magnetic field $\boldsymbol{H}$ related to the magnetic flux density vector $\boldsymbol{B}$ $(=\nabla \times \boldsymbol{A})$ is calculated as follows:

$$\boldsymbol{H} = -\frac{1}{\mu_0}\boldsymbol{M} + \frac{1}{\mu_0}\boldsymbol{B}. \tag{7}$$

$\boldsymbol{H}$ corresponds to the external field of the GM model, therefore the effective field $\boldsymbol{H}^i_{eff}$ of the i-th single-domain particle is as follows:

$$\boldsymbol{H}^i_{eff} = -\frac{\boldsymbol{M}}{\mu_0} + \frac{\boldsymbol{B}}{\mu_0} + \boldsymbol{H}^i_{ani} + \boldsymbol{H}^i_{\lambda\sigma} + \boldsymbol{H}^i_{exc}. \quad (8)$$

The term of magnetization $-\boldsymbol{M}/\mu_0$ acts to prevent itself from magnetizing.

Fig. 1 shows a conceptual diagram of the coupling method between the magnetic field equations and the GM model at each time step of the simulation. We computed these equations by exchanging the flux density vector $\boldsymbol{B}$ and the magnetization vector $\boldsymbol{M}$ repeatedly until $dM<\varepsilon$. The dM is maximum norm of the deviation of the magnetization vector $\boldsymbol{M}$ of all elements in one iteration, and ε is a sufficiently small value such as 10^{-6}.

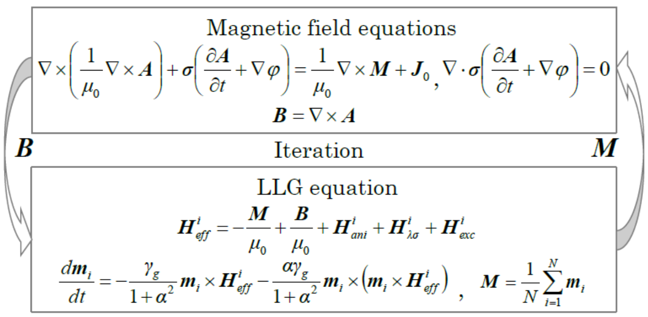

Fig. 1. Conceptual diagram of the strong coupling method.

IV. RESULTS

For fitting parameters of GM model, we used a toroidal core to measure the intrinsic magnetic properties of Ni–Zn ferrite core. Fig. 2 shows the B-H major loops of experimental results and simulation results of the GM model.

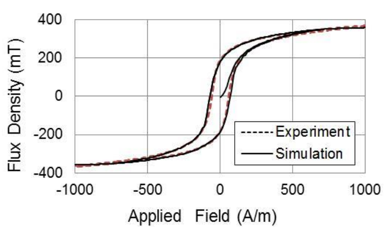

Fig. 2 Experimental (dashed lines) and simulation (solid lines) results of the B-H major loops.

Similarly, Fig. 3 shows the B-H minor loops with and without DC bias at 400 kHz. The shapes of lower B-H minor loops without DC bias are round and symmetric. On the other hand, the shapes of upper BH minor loops with DC bias are sharp and asymmetric. These characteristic features are well reproduced by the GM model.

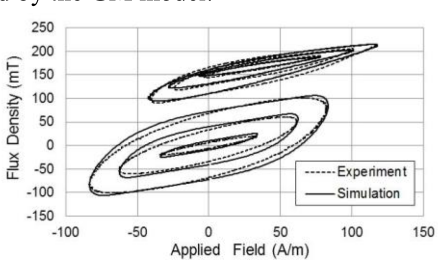

Fig. 3 Experimental (dashed lines) and simulation (solid lines) results of the B-H minor loops with and without DC bias at 400 kHz.

Fig. 4 shows a mesh of the inductor used by the FEA with the GM model, current density and magnetic flux density of the simulation result. Since Ni - Zn ferrite is high resistance, the conductivity σ is set to zero in this simulation.

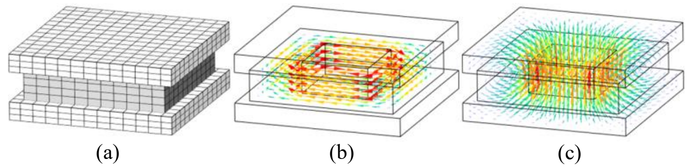

Fig. 4 (a) A mesh for simulation, (b) current density and (c) magnetic flux density of the result.

The results of the core loss of the inductor under DC bias are shown in Fig. 5. The hysteresis loops shrink vertically with increasing of the Idc, then the core loss decreases. The FEA with the GM model reproduced the core loss values close to the experimental data. Since the GM model is able to describe the intrinsic properties of the magnetic material, the FEA with the GM model can accurately predict the characteristics of the inductor with accounting for geometric effects.

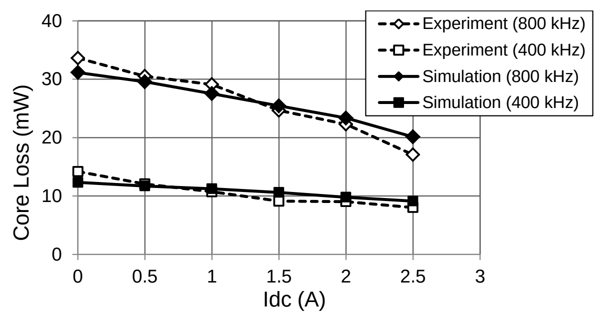

Fig. 5 Experimental (dashed lines) and Simulation (solid lines) results of the core loss under DC bias current Idc.

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