미소자성체를 이용한 자기히스테리시스 모델 연구

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Basic study on hysteresis modeling using micromagnetics for magnetic field analysis

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Abstract - In magnetic field analysis of electrical machines, hysteresis phenomena of B-H curves should be taken into account in order to obtain more accurate results. In this paper, the hysteresis modeling using the micromagnetics for the magnetic field analysis is investigated. In the micromagnetics, usually, it takes much CPU times. Therefore, the method for representing hysteresis phenomena by minimum modeling is investigated in order to applying it to the magnetic field analysis. First, the micromagnetics is described. Then, the method of minimum modeling is shown. Finally, the hysteresis curve obtained by the minimum modeling is demonstrated. The effect of parameters of micromagnetics on the shape of hysteresis curve is investigated.

Keyword: hysteresis, micromagnetics, magnetic characteristics, magnetic field analysis

1. introduction

As the method of considering the magnetic properties of core materials in magnetic field analysis of electrical machines, a virgin curve is generally used. And the analysis methods that take into account hysteresis phenomena are introduced in magnetic field analysis to obtain more accurate results for example mathematical modeling methods, such as the Preisach modeling, physical modeling methods, such as Jiles-Atherton modeling and the interpolation of hysteresis curve from actual measurements. But these have defects that cannot consider physical phenomena like rotation energy of magnetization or are required parameters from actual measurements. Therefore it is required the introduction of new physical modeling in magnetic field analysis. In the field of magnetic record, a physical modeling method, the micromagnetics is usually used. Micromagnetics can represent physical phenomena. But micromagnetics hasn't been used for the method of magnetic field analysis because of its long calculation time.

So in this paper, with the purpose to apply the micromagnetics to a magnetic field analysis of electrical machines, the method to describe a hysteresis curve in a few elements and effects of micromagnetics parameters to the shape of hysteresis curve are investigated. Detailed physical phenomena such as magnetic domain walls are ignored to reduce the calculation time.

2. Micromagnetics

A. The energy of a ferromagnetic material

The free energy of a ferromagnetic specimen can be written as a sum of several energy contributions where $E_{ext}$is the energy due to the interaction between an applied field and magnetic moments, E_d is the demagnetizing energy arising from the interactions of magnetic moments, E_{ani} is the energy due to the crystalline anisotropy and E_{exch} is the energy due to quantum-mechanical exchange effect nearest neighbors. Other energy terms may be included such as the magnetostrictive energy, but they are not considered here.The individual energy terms are expressed.

$$E_{ext} = -\boldsymbol{M} \cdot \boldsymbol{H}_{ext} \quad (1)$$

$$E_d = -\frac{1}{2}\boldsymbol{M} \cdot \boldsymbol{H}_d \quad (2)$$

$$E_{ani} = -K(\boldsymbol{M} \cdot \boldsymbol{n} / M)^2 \quad (3)$$

$$E_{exch} = \frac{A}{M^2}\left\{\|\nabla M_x\|^2 + \|\nabla M_y\|^2 + \|\nabla M_x\|^2\right\} \quad (4)$$

M is the vector magnetization. M_x,M_y,M_z are the x,y,z components of $\boldsymbol{M}$. $\boldsymbol{H}_{ext}$ is the externally applied field, $\boldsymbol{H}_d$ is the demagnetizing field, K is the anisotropy constant, $\boldsymbol{n}$ is the unit vector of an uniaxial anisotropy, A is the exchange stiffness constant, "∇" represents the gradient, "‖ ‖" represents the norm.

So total energy is

$$E_t = E_{ext} + E_d + E_{ani} + E_{exch} \quad (5)$$

B. The effective field

The effective field is defined via the variational derivative of E_t with respect to $\boldsymbol{M}$.

$$\boldsymbol{H}_{eff} = -\frac{\partial E_t}{\partial \boldsymbol{M}} = \boldsymbol{H}_{ext} + \boldsymbol{H}_d + \boldsymbol{H}_{ani} + \boldsymbol{H}_{exch} \quad (6)$$

Where $\boldsymbol{H}_{ext}$, $\boldsymbol{H}_d$, $\boldsymbol{H}_{ani}$, $\boldsymbol{H}_{exch}$ are external field, demagnetizing field, anisotropy field and exchange field. The external field is known generally and $\boldsymbol{H}_{ani}$ and $\boldsymbol{H}_{exch}$ can be evaluated using the Eq.6.

$$\boldsymbol{H}_{ani} = -\frac{\partial E_{ani}}{\partial \boldsymbol{M}} = \frac{2K}{M}(\boldsymbol{M} \cdot \boldsymbol{n})\boldsymbol{n} \quad (7)$$

$$\boldsymbol{H}_{exch} = -\frac{\partial E_{exch}}{\partial \boldsymbol{M}} = \frac{2A}{M^2}\nabla^2 \boldsymbol{M} \quad (8)$$

Et with respect to M.

(6) Eq.6 Hexch , "∇" represents the gradient, "‖ ‖" represents the norm. B. The effective field

The effective field is defined via the variational derivative of Et with respect to M. (6)

Where Hext, Hd, Hani, Hexch are external field, demagnetizing field, anisotropy field and exchange field. The external field Hext is known generally and Hani and Hexch can be evaluated using the Eq.6.(7)

(8) B. The effective field The effective field is defined via the variational derivative of Et with respect to M. (6) Et with

respect to M. (6)

$\boldsymbol{H_d}$ is the sum of the demagnetizing field contributions at the center of cell (i,j,k) from all other cells. $\boldsymbol{H_p}$ is demagnetizing field at point $p(x_p,y_p,z_p)$ shown in Eq.9 when $\boldsymbol{M}$ is distributed in a hexahedron L_1,L_2,L_3 on a side shown in Fig.1. Only H_{px}, x component of $\boldsymbol{H_p}$ is represented in Eq.9.

$$H_{px} = -\frac{1}{4\pi\mu_0}\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2}(-1)^{i+j+k}\left\{\left[-\tan^{-1}\frac{(y_p-y_j)(z_p-z_k)}{(x_p-x_i)r_{ijkp}}\right]M_x + \ln\left[r_{ijkp}+(z_p-z_k)\right]M_y + \ln\left[r_{ijkp}+(y_p-y_j)\right]M_z\right\}$$

(9)

r_{ijkp} is a distance between point p and vertex (x_i,y_j,z_k) of a hexahedron. Other components y, z are same.

C. The Landau-Lifshitz-Gilbert Equation

The direction of $\boldsymbol{M}$ gets toward the direction of $\boldsymbol{H_{eff}}$ with precession shown in Fig.2. LLG Eq represents the motion of $\boldsymbol{M}$.

$$\frac{\partial \boldsymbol{M}}{\partial t} = \frac{-\gamma}{(1+\alpha^2)}\left(\boldsymbol{M}\times\boldsymbol{H}_{eff}\right) - \frac{\gamma\alpha}{M(1+\alpha^2)}\left(\boldsymbol{M}\times(\boldsymbol{M}\times\boldsymbol{H}_{eff})\right)$$

(10)

α is the damping parameter, γ is the gyromagnetic ratio.

Ⅲ. Proposed numerical model

The calculation time is the most important problem in magnetic field analysis of electrical machines. It'll be taken long time when Micromagnetics is used as the hysteresis modeling for the magnetic field analysis because of its properties. Therefore in this paper, the method is investigated to reduce the calculation time as much as possible without detailed physical phenomena such as magnetic domain walls.

Firstly in order to reduce the number of elements, only the minimum elements of ferromagnetic materials are taken. It's assumed that magnetizations of the minimum elements distribute cyclically on whole magnetic materials. Divided 2*2*2 model of a cube element is used shown in Fig .3.a. Fig.3.b shows the assumed distribution of magnetizations.

And the summating of the demagnetizing field contributions from all other cells takes very long time so we assumed that the demagnetizing fields by faraway cells from cell (i,j,k) can be ignored. Only near surrounding elements are used shown in Fig.4.

Ⅳ. Micromagnetics simulation

To investigate the feasibility of the proposed method, hysteresis curve is drawn and the effects of parameters are investigated.

Calculated model for the investigation is the minimum elements divided 2*2*2 shown in Fig 3.(a). The geometry of the element is a regular hexahedron 0.01㎛ on a side. Directions of the uniaxial anisotropy face to vertexes of a regular hexahedron from the center of each element.

The uniaxial anisotropy constant K are $7\times10^2, 3\times10^4, 4\times10^7 J/m^3$, exchange stiffness constant A are $9\times10^{-14}, 5\times10^{-12}, 2\times10^{-11} J/m$. The magnitude of spontaneous magnetization is 1T. The direction of an applied field is 30deg from x-axis and 30deg from z-axis. The magnitude of an applied field has maximum value +4000kA/m, minimum value -4000kA/m. Δt of LLG equation is 0.01ps.

Fig.5 shows hysteresis curves according to the variety of anisotropy and exchange constants. We can know that smooth hysteresis curves could be drawn in case of the minimum element model with the adjusted demagnetizing field region. And shape variations are different according to the constant' changes. So it's possible to obtain wish hysteresis curves if we choose suitable constants.

Ⅴ. Conclusion

In order to investigate the micromagnetics's possibility as the hysteresis modeling method in magnetic field analysis of electrical machines, we tried to draw the hysteresis curve in model divided 2×2×2 and adjusted calculation region of demagnetizing field. As the results, by the above proposed method, smooth hysteresis curve can be drawn and since shape variations are different according to the constant' changes, it's possible to obtain wish hysteresis curves if we choose suitable constants.

The proposed method is different with real ferromagnetic material because of the ignoring of magnetic domain walls, and so on. In the next study, an establishment of parameters for an appearance of real hysteresis curve will be investigated.

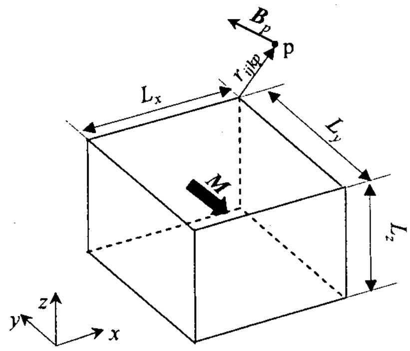


Fig. 1 Method of calculation for demagnetizing field.

Considered Region

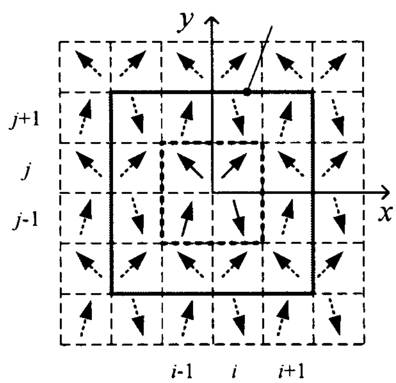


Fig. 2 Region considered for calculation of demagnetizing field.

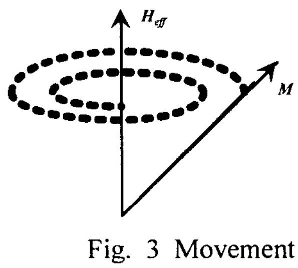
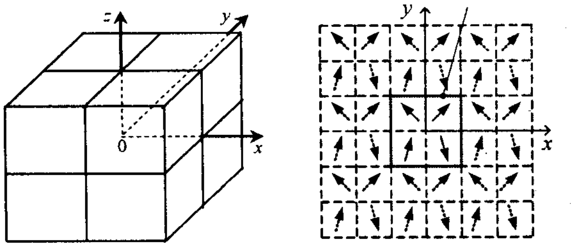
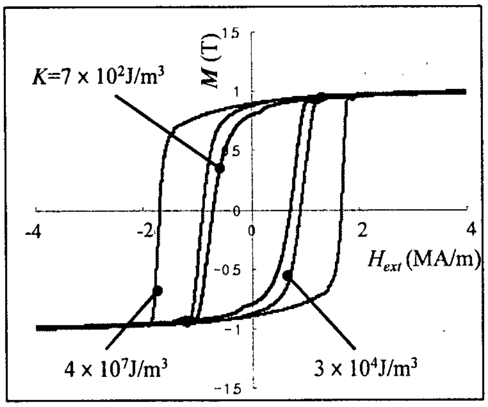


Fig. 3 Movement of magnetization.

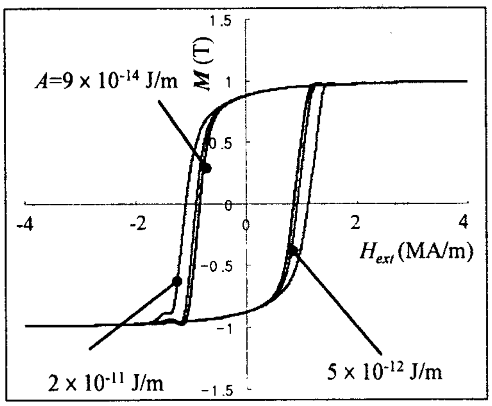


(a) Calculated model (b) distribution of ***M***

Fig.3 Calculated model



(a) Effect of anisotoropy constant K (A=5 × 10^{12} J/m)



(b) Effect of exchange stiffness constant A (K=3 × 10^4 J/m^3)

Fig. 5 Hysteresis curve.

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