

Modelling of Magnetic Characteristics of Soft Magnetic Composite Using Magnetic Field Analysis

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Soft magnetic composite (SMC) is composed of ferromagnetic powder particles surrounded by electrical insulation. SMC has advantages such as three-dimensional (3D) isotropic magnetic characteristics, low eddy current loss, and easy manufacture of complex shape compared with laminated core stacked with electrical steel sheets. In this paper, to establish the homogenization technique for the magnetic field analysis of an electrical machine using SMC, the method of determining the effective permeability taking account of nonlinear magnetic characteristics and eddy currents is proposed by using a cell model composed of one particle of SMC. The effects of the particle size and frequency on not only the effective permeability but also the iron loss are demonstrated. It is shown that proper results are obtained using the proposed method.

Index Terms—Eddy current, Homogenization, Magnetic field analysis, Soft magnetic composite.

I. INTRODUCTION

A CORE composed of soft magnetic composites (SMCs), which are ferromagnetic powder particles surrounded by electrical insulation has advantages such as three-dimensional (3D) isotropic magnetic characteristics, low eddy current loss, and easy manufacture of complex shape [1] compared with ordinary laminated core stacked with electrical steel plates. But it is difficult to model the ferromagnetic powder particles of huge number in the design process of an electrical machine made of SMCs using magnetic field analysis. Therefore, several homogenization techniques of SMCs have already been proposed. In magnetostatic analyses, the homogenization technique using the effective permeabilities based on the energy conservation has been proposed [2]. However, eddy current effect cannot be considered using this technique. To consider the eddy current effect, the technique using effective permeabilities determined by using an analytical solution of a particle of simple shape has been proposed [3]. However, this technique cannot be applied to SMCs of random shape distorted by pressure.

In this paper, the method of modelling SMCs by using FEM is proposed to establish a practical homogenization technique, which can take account of the eddy currents, nonlinear magnetic characteristics, and distorted shape of powder particle. Then, the effects of frequency and particle size on the effective permeability and iron loss are illustrated.

II. ANALYSIS MODEL

First, the 3D nonlinear eddy current analysis of a cubic magnetic particle surrounded by insulation of 1/8 region is carried out under the assumption that the particles are regularly and infinitely formed as shown in Fig. 1. A uniform flux density B_{oz} is applied in the z -direction by using the boundary condition and it is sinusoidal in time (peak value $B_{om} = 0.5T$, frequency $f = 10$ kHz and 30 kHz). The particle size D

is changed from 25 μm to 200 μm keeping the thickness of insulator 0.1 μm . The initial BH curve and the conductivity $\sigma = 1.9 \times 10^6$ S/m of the isotropic electric steel plate (JIS C 2552-2014: 35A300) are applied for the particle in the nonlinear and eddy current analysis.

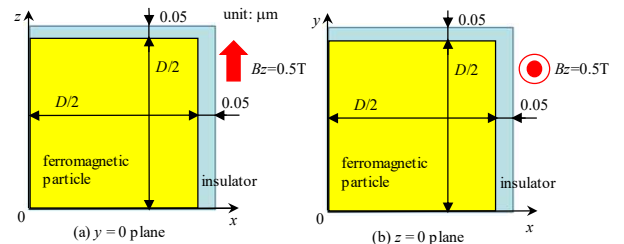


Fig. 1 Cell model of soft magnetic composite (1/8 region).

III. METHOD OF ANALYSIS

A. Magnetic Field Analysis

The flux and eddy current distributions of steady state are calculated by using the A - ϕ method (A : magnetic vector potential, ϕ : electrical scalar potential) with the first order brick edge finite element method. The time interval Δt is equal to $1/16 T$ (T : one period time) for the step-by-step method.

B. Effective Complex Permeability

The effective complex permeabilities μ_s' and μ_s'' are used to demonstrate the magnetic characteristics of the homogenization magnetic body simply in this paper. First, the applied magnetic field H_{oz} is calculated at each time step by using the following equation [4]:

$$H_{oz} = \sum_{ie=1}^{N_{air}} \frac{B_z^{(ie)}}{\mu_0} \cdot l_z^{(ie)} \bigg/ \sum_{ie=1}^{N_{air}} l_z^{(ie)} \quad (1)$$

where N_{air} is the mesh number of elements in the insulation in the x -direction. B_z is the z -component of flux density and l_z is the element length in the z -direction. Then, complex effective permeabilities are calculated by using the following equations:

$$\mu_s' = B_{oz}' / H_{oz,\max} \quad (2)$$

$$\mu_s'' = B_{oz}'' / H_{oz,\max} \quad (3)$$

where $H_{oz,\max}$ is the maximum H_{oz} in time. B_{oz}' and B_{oz}'' are the applied flux density at the instant when H_{oz} is the maximum and 1/4 period delay, respectively.

C. Iron Losses

In the iron loss calculation in this paper, the eddy current loss in the particle is directly calculated by using the eddy current distribution. The hysteresis loss is calculated by using the distribution of the maximum flux density B_m and the hysteresis loss curve obtained from catalogue data.

IV. RESULTS AND DISCUSSION

A. Flux and Eddy Current Distributions

Fig. 2 shows the flux and eddy current distributions with particle size $D = 100 \mu\text{m}$ and frequency $f = 10 \text{ kHz}$ and 30 kHz . The skin effect due to eddy current cannot be observed at $f = 10 \text{ kHz}$, whereas it is observed at $f = 30 \text{ kHz}$.

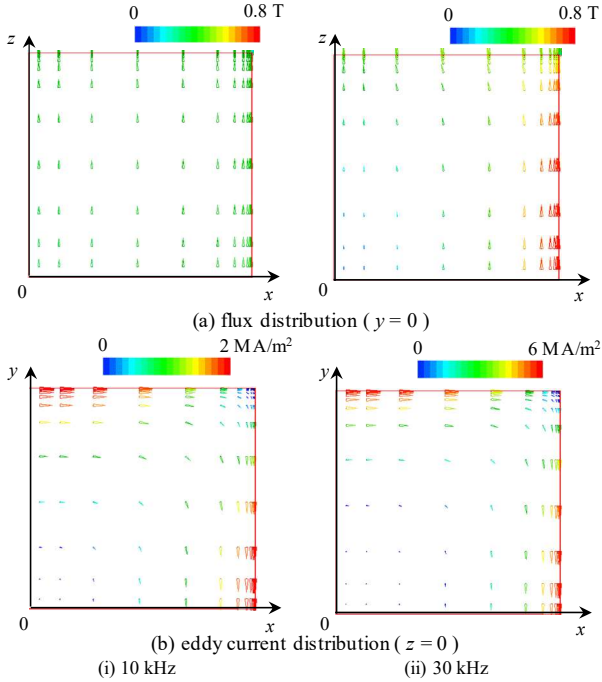


Fig. 2 Flux and eddy current distributions.

B. Complex Effective Permeability

Fig. 3 shows the effect of the particle size D and the frequency f on the relative effective permeabilities μ_s' and μ_s'' . μ_s' is decreasing when f is increasing due to eddy current. μ_s' is larger when D is larger because the effect of the magnetic resistance due to insulation is larger than that due to the eddy current effect. μ_s'' is larger when f is larger due to eddy current.

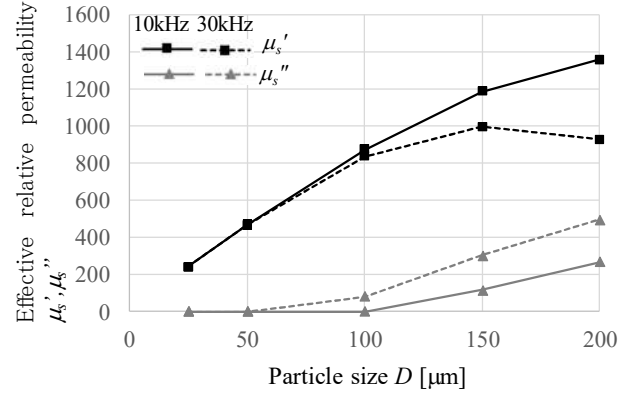


Fig. 3 Effects of particle size and frequency on effective permeability.

C. Iron Losses

Fig. 4 shows the effect of the particle size D and the frequency f on the eddy current loss W_e and hysteresis losses W_h . W_h is dominant when D is small, whereas W_e becomes dominant when D is large. W_h is larger at $f = 30 \text{ kHz}$ than that at 10 kHz due to the skin effect.

It can be concluded that the tendencies of the obtained complex effective permeability and losses are correct theoretically. In the full paper, results of validation using actual magnetic characteristics of SMCs will be demonstrated.

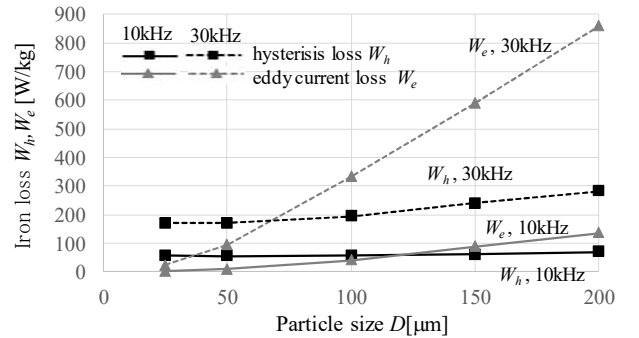


Fig. 4 Effects of particle size and frequency on iron losses.

REFERENCES

- [1] Y. G. Guo, J. G. Zhu, Z. W. Lin, and J. J. Zhong, "Measurement and modeling of core losses of soft magnetic composites under 3-D magnetic excitations in rotating motors," *IEEE Trans. Magn.*, vol. 41, no. 10, pp. 3925–3927, 2005.
- [2] H. Waki, H. Igarashi, and T. Honma, "Estimation of effective permeability of magnetic composite materials," *IEEE Trans. Magn.*, vol. 41, no. 5, pp. 1520–1523, 2005.
- [3] A. Bordianu, O. Barriere, O. Bottauscio, M. Chiampi, and A. Manzin, "A multiscale approach to predict classical losses in soft magnetic composites," *IEEE Trans. Magn.*, vol. 48, no. 4, pp. 1537–1540, 2012.
- [4] K. Muramatsu, T. Okitsu, H. Fujitsu, and F. Shimanoe, "Method of non-linear magnetic field analysis taking into account eddy current in laminated core," *IEEE Trans. Magn.*, vol. 40, no. 2, pp. 896–899, 2004.