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Accuracy Improvement of Magnetic Hysteresis Calculated by LLG Equation

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Abstract. Quantitative estimation of iron loss including magnetic hysteresis behavior is essential to the development of high-efficient electrical machines. A simplified micromagnetic model using Landau-Lifshitz-Gilbert (LLG) equation is one of the useful models for calculating the hysteresis behavior. However, further improvement of the calculation accuracy under magnetic saturation is required. This paper presents the accuracy improvement of the magnetic hysteresis calculated by the LLG equation.

1. Introduction

Quantitative analysis of iron loss including magnetic hysteresis behavior is necessary to the development of high-efficient electrical machines. A lot of methods for calculating the hysteresis behavior have been proposed. Among them, a simplified micromagnetic model using Landau-Lifshitz-Gilbert (LLG) equation [1] is one of the useful models for calculating the hysteresis behavior. In a previous paper [2], the magnetic circuit model combined with the above-mentioned LLG equation was proposed, in which dc hysteresis is expressed by the above-mentioned LLG equation, while classical and anomalous eddy current losses are calculated by magnetic circuit elements. The proposed model can calculate the hysteresis loops of various materials under various exciting voltage waveforms. However, further improvement of the calculation accuracy under magnetic saturation is required.

To calculate the hysteresis loops with high accuracy, first, the equation expressing the magnetoelastic energy in [1] is improved to express the strong magnetic nonlinearity. Second, the equation for the magnetic anisotropy field in [1] is also improved to express the shape of the hysteresis loop with high accuracy.

2. Accuracy improvement of magnetic hysteresis calculated by LLG equation

The motion of the magnetizations in a magnetic substance can be represented by the following LLG equation:

$$\frac{d\boldsymbol{m}_i}{dt} = -\frac{|\gamma|}{1+\alpha^2}\{(\boldsymbol{m}_i \times \boldsymbol{H}_{eff}) + \alpha(\boldsymbol{m}_i \times (\boldsymbol{m}_i \times \boldsymbol{H}_{eff}))\} \quad , \tag{1}$$

where the magnetization vector is $\boldsymbol{M}_i = M_s\boldsymbol{m}_i$, the spontaneous magnetization is M_s, the normalized magnetization vector is $\boldsymbol{m}_i$, the gyromagnetic ratio of electron is γ, the damping constant is α, and the effective field is $\boldsymbol{H}_{eff}$, respectively.

In the reference [1], the effective field $\boldsymbol{H}_{eff}$ in equation (1) is given by

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$$\boldsymbol{H}_{eff} = \boldsymbol{H}_{app} + \boldsymbol{H}_{ela} + \boldsymbol{H}_{ani}\,, \tag{2}$$

$$\boldsymbol{H}_{ela} = -\frac{1}{M_s}\frac{\partial E_{ela}}{\partial \boldsymbol{m}_i},\quad E_{ela} = b_2\overline{m}^2 + b_4\overline{m}^4 + b_6\overline{m}^6\,, \tag{3}$$

$$\boldsymbol{H}_{ani} = -\frac{1}{M_s}\frac{\partial E_{ani}}{\partial \boldsymbol{m}_i},\; E_{ani} = \frac{h_{ani}M_s}{2}(a_1{}^2a_2{}^2 + a_2{}^2a_3{}^2 + a_3{}^2a_1{}^2)\,, \tag{4}$$

where the applied field is $\boldsymbol{H}_{app}$, the field generated by magnetoelastic energy is $\boldsymbol{H}_{ela}$, the anisotropy field is $\boldsymbol{H}_{ani}$, the magnetoelastic energy is E_{ela}, the parameters of Taylor expansion are b_2, b_4, and b_6, the magnetic anisotropy energy is E_{ani}, the coefficient of magnetic anisotropy is h_{ani}, and the direction cosines of magnetization vectors with respect to x, y, and z axes (easy axes) of each grains are a_1, a_2, and a_3, respectively. In the simplified micromagnetic model [1], all the parameters above mentioned are determined by fitting the measured dc hysteresis loops. In addition, although the LLG equation is generally used for expressing the dynamic hysteresis behavior, only steady-state value of the LLG equation is used for expressing dc hysteresis.

Figure 1 shows the measured and calculated dc hysteresis loops. It is found that the previous model [1] cannot simulate the strong nonlinearity. To calculate the hysteresis loops under the strong nonlinearity, the order of equation (3) is increased as follows:

$$E_{ela} = \sum_{j=1}^{10} b_{2j}\overline{m}^{2j}\,. \tag{5}$$

Figure 2 shows the measured and calculated hysteresis loops using equation (5). Figure 3 is an enlarged view of figure 2. It is clear that the strong nonlinearity can be expressed by using equation (5). However, the shape of the hysteresis loops is still different from the measured loops, especially under magnetic saturation.

To express the shape of the hysteresis loop with high accuracy, the magnetic anisotropy field in [1] is also improved as the following equation:

$$\boldsymbol{H}_{ani} = -k_{ani}\frac{1}{M_s}\frac{\partial E_{ani}}{\partial \boldsymbol{m}_i}\,, \tag{6}$$

$$k_{ani} = 1 + k_1 \min(1, \exp(k_2(|\overline{\boldsymbol{m}}\cdot\boldsymbol{m}_i| - k_3)))\,, \tag{7}$$

where the k_{ani} is the newly defined coefficient. To restrict the maximum value of k_{ani}, “min” is used in equation (7). Figure 4 shows the coefficient k_{ani} in equation (7) at $k_1 = 2$, $k_2 = 5$, and $k_3 = 0.7$ which are determined by fitting the measured dc hysteresis loops.

Figure 5 indicates the measured and calculated dc hysteresis loops using the proposed method. Figure 6 is an enlarged view of figure 5. It is understood that the shape of calculated hysteresis loops is improved by using equation (6).

Figure 7 illustrates the magnetic circuit model combined with the improved LLG equation. Using the improved model, current waveforms are calculated when the sinusoidal voltage waveform corresponding to the maximum flux density B_m = 1.8 T is applied. Figure 8 and 9 denote the current waveforms calculated by the previous [2] and improved models. It is clear that the calculation accuracy is remarkably improved.

3. Summary

This paper presented the accuracy improvement of the magnetic hysteresis calculated by the LLG equation. First, the equation expressing the magnetoelastic energy in [1] was improved to simulate the strong magnetic nonlinearity. Second, the equation for the magnetic anisotropy field in [1] was also improved to express the shape of the hysteresis loop with high accuracy. It was demonstrated that the proposed method can improve the accuracy of the magnetic nonlinearity and hysteresis behavior.

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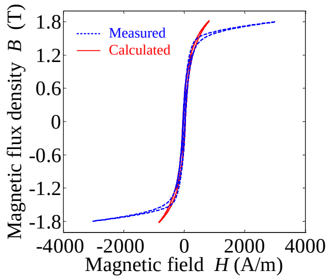

Figure 1. Measured and calculated dc hysteresis of non-oriented Si steel.

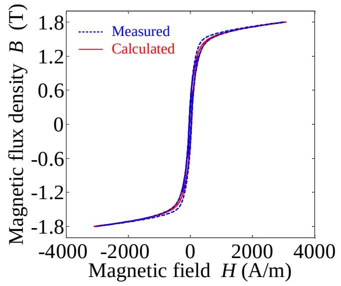

Figure 2. The dc hysteresis of non-oriented Si steel calculated by using equation (5).

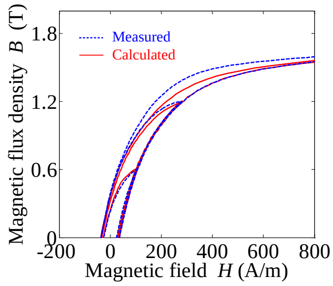

Figure 3. Enlarged view of figure 2.

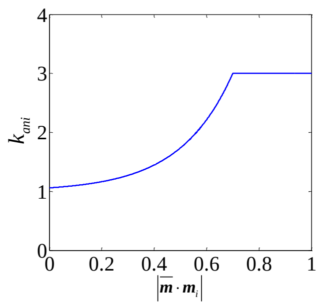

Figure 4. Relation between k_{ani} and the absolute value of an interior product of a normalized magnetization vector $\boldsymbol{m}_i$ and an average of the normalized magnetization vectors $\overline{\boldsymbol{m}}$.

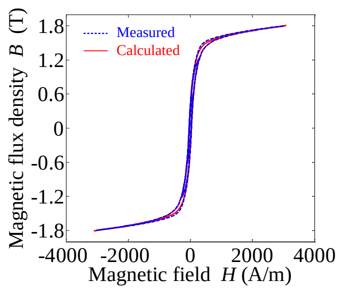

Figure 5. The dc hysteresis of the non-oriented Si steel calculated by the proposed method.

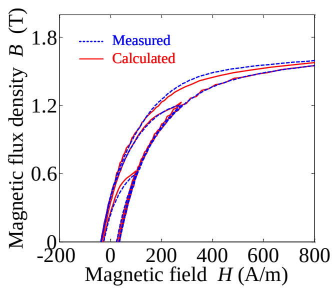

Figure 6. Enlarged view of figure 5.

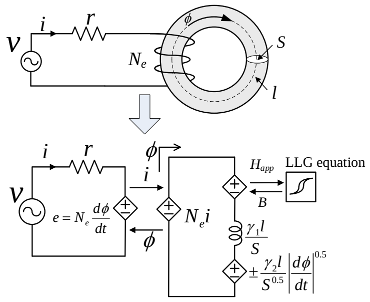

Figure 7. Magnetic circuit model combined with LLG equation.

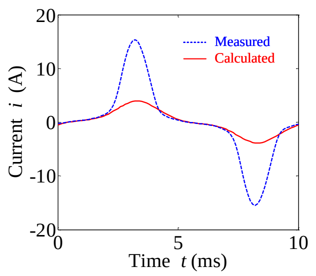

Figure 8. Current waveform calculated by the previous model.

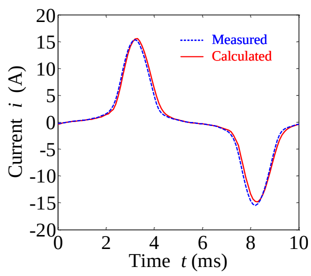

Figure 9. Current waveform calculated by the proposed model.

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