

Identification of B -dependent Coefficient for Excess Eddy-current Field

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An accurate excess eddy-current loss modeling is vital for the evaluation of iron loss in core materials. Bertotti's excess eddy-current loss model has good accuracy for silicon steel sheets, which gives the excess eddy-current field as $g_{\text{ex}}(dB/dt)^{1/2}$. In previous research, the coefficient g_{ex} is often treated as independent of magnetic flux density, which is not always true for real materials. In this research, we developed a method for identifying the magnetic flux density dependence of the coefficient using measured excess eddy-current loss. The proposed method improves the iron loss evaluation for the silicon steel sheet under compressive stress.

Index Terms—Cauer circuit, eddy-current loss, excess loss, magnetic core, mechanical stress

I. Introduction

Silicon steel sheets are widely used as magnetic core material. The iron loss of a silicon steel sheet depends on the eddy-current inside the sheet. According to the classical eddy-current theory, at low frequencies, the AC magnetic field in a sheet material can be decomposed into the static magnetic field H_{dc} and the eddy-current field $(\sigma d^2/12)(dB/dt)$, where σ and d are the conductivity and the thickness of the sheet. The eddy-current loss evaluated by the model above is generally lower than the measured eddy-current loss, because of the excess eddy-current loss [1]. Accordingly, the conductivity is often multiplied by an anomaly factor k for including the excess eddy-current loss. Then the AC magnetic field can be represented as:

$$H_{\text{ac}} = H_{\text{dc}} + \frac{k\sigma d^2}{12} \frac{dB}{dt} = H_{\text{dc}} + g \frac{dB}{dt} \quad (1)$$

where $k\sigma$ is called effective conductivity. The coefficient of eddy-current loss $g = k\sigma d^2/12$ is usually assumed as a constant. Actually, g depends on the magnetic flux density B . In previous research, we replaced g with a function of flux density $g(B)$, which improved iron loss evaluation [2]. However, this model often overestimates the eddy-current loss, when the frequency of the magnetic field is hundreds Hertz.

Bertotti [1] decomposed the eddy-current field into two parts as:

$$H_{\text{ac}} = H_{\text{dc}} + \frac{\sigma d^2}{12} \frac{dB}{dt} + g_{\text{ex}} \left(\frac{dB}{dt} \right)^{\frac{1}{2}}. \quad (2)$$

where g_{ex} is the coefficient of excess eddy-current field. The coefficient g_{ex} is often assumed to be constant, which is a possible reason for the deviation between the computed and the measured losses, because g_{ex} also has B dependence in fact. Previous studies [5], [6] represented the B dependence by parameter fitting to assumed functions of B for some specific materials. However, the suitable function may depend on the type of core material and external factors such as the applied mechanical stress, because the excess loss is affected by the magnetization

process. In this research, we derive an integral equation for g_{ex} and solve it analytically to identify g_{ex} from the measured excess loss, without assuming a specific function. Next, we incorporate the B dependence coefficient into the Cauer circuit model [Fig. 1], a homogenization method for evaluating iron loss of any arbitrary input flux waveform.

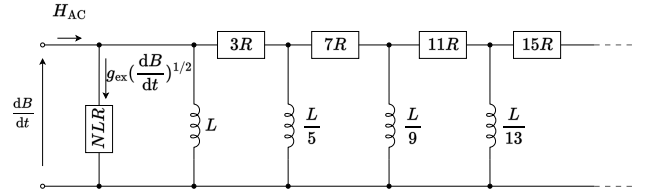


Fig. 1: Cauer circuit with a nonlinear resistance

II. Identification of excess eddy-current loss coefficient

The iron loss per period of a sheet material under a sinusoidal B -field ($B = B_a \sin \phi$) at low frequency is given as:

$$\begin{aligned} W &= \int_0^T H \frac{dB}{dt} dt \\ &= \int_{-\pi}^{\pi} H_{\text{dc}} B_a \cos \phi d\phi + \omega \int_{-\pi}^{\pi} \frac{\sigma d^2}{12} B_a^2 \cos^2 \phi d\phi \\ &\quad + \omega^{\frac{1}{2}} \int_{-\pi}^{\pi} g_{\text{ex}}(B_a \sin \phi) B_a^{\frac{3}{2}} \cos^{\frac{3}{2}} \phi d\phi \\ &= W_{\text{dc}} + W_c f + W_{\text{ex}} f^{\frac{1}{2}} \end{aligned} \quad (3)$$

where W_{dc} is the static hysteresis loss, $W_c f$ is the classical eddy-current loss and $W_{\text{ex}} f^{1/2}$ is the excess eddy-current loss; ϕ is the phase angle of the sinusoidal B -field. From (3), the integral equation for $g_{\text{ex}}(B)$ can be written as follows:

$$\int_{-\pi}^{\pi} g_{\text{ex}}(B) \cos^{\frac{3}{2}} \phi d\phi = \frac{W_{\text{ex}}(B_a)}{(2\pi B_a^3)^{\frac{1}{2}}} = F(B_a) \quad (4)$$

where $F(B_a) = W_{\text{ex}}(B_a)/(2\pi B_a^3)^{1/2}$. In this research, we have derived the analytical solution of (4) as below:

$$g_{\text{ex}}(B) = \frac{2}{\pi} [p(0) + \int_0^{\frac{\pi}{2}} B p'(B \sin \alpha) d\alpha] \quad (5)$$

$$p(b) = \frac{\sqrt{2}}{12} A \int_0^{\frac{\pi}{2}} \tan^{\frac{1}{2}} \theta [\frac{3}{2} F(b \sin \theta) + b \sin \theta F'(b \sin \theta)] d\theta \quad (6)$$

$$p'(b) = \frac{\sqrt{2}}{12} A \int_0^{\frac{\pi}{2}} \tan^{\frac{1}{2}} \theta [\frac{5}{2} \sin \theta F'(b \sin \theta) + b \sin^2 \theta F''(b \sin \theta)] d\theta. \quad (7)$$

where $A = \int_0^{\frac{\pi}{2}} \cos^{3/2} \theta d\theta \approx 0.874$. The derivation will be presented in the full paper.

III. Experimental result

A. $F(B_a)$ curve

The iron loss of silicon steel sheet JIS:35A300 along the rolling direction (RD) and transverse direction (TD) were measured using a single sheet tester. A compressive stress of 0 or 100 MPa is applied along the longitudinal direction of the strip sheet sample. The excess eddy-current loss was separated from the measured iron loss to identify $g_{\text{ex}}(B)$. Since (5) includes the first and second derivatives $F'(B_a)$ and $F''(B_a)$, the measured $F(B_a)$ is required to be smoothed before identification. For confirmation, the identified $g_{\text{ex}}(B)$ was substituted to (4) to reconstruct $F(B_a)$ curve. As shown in Fig.2, the reconstructed $F(B_a)$ is consistent with the measured result, and the F exhibits flux-dependence under compressive stress of 0 and 100 MPa.

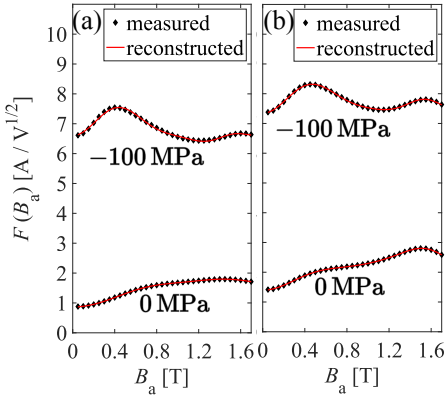


Fig. 2: Measured and reconstructed $F(B_a)$ with 100 MPa compressive stress and no stress: (a) RD; (b) TD

B. Iron loss simulation

The iron loss of silicon steel sheets was evaluated under AC magnetic field at 200 Hz. To evaluate AC loss in silicon steel sheets over a few hundred Hertz, the skin effect should be considered. A Cauer circuit is often used to evaluate the AC loss of silicon steel sheets, considering skin effect. In this research, AC magnetic properties are represented using

a four-stage Cauer circuit. The first inductor gives the hysteretic magnetostatic field H_{dc} , which is represented by the play model [3]. For representing the excess eddy-current field, a nonlinear resistance (NLR) is connected in parallel with the R - L ladder [Fig.1]. The nonlinear resistance has the current-voltage relationship $i = g_{\text{ex}}(B)v^{1/2}$ [4], where $v = dB/dt$.

The iron loss evaluated using the $g(B)$ model and the $g_{\text{ex}}(B)$ model, given by (1) and (2) respectively, are compared with the measured loss in Fig. 3. Under the compressive stress, the loss using $g(B)$ model is overestimated. On the other hand, $g_{\text{ex}}(B)$ model shows better agreement with the measured result.

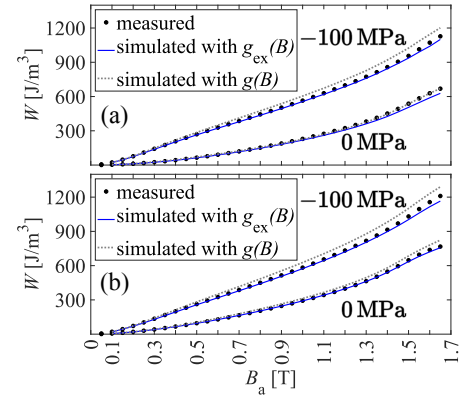


Fig. 3: Iron loss evaluated using the $g(B)$ model and $g_{\text{ex}}(B)$ model, under 100 MPa compressive stress and no stress: (a) RD; (b) TD

IV. Acknowledgement

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