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Calculation of energy loss due to macroscopic eddy currents in ferromagnetic materials considering hysteresis loop

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Abstract. The paper presents an algorithm for calculating the energy loss due to macroscopic eddy currents considering the non-linearity of magnetization characteristics and magnetic hysteresis. It was found that for non-oriented steel sheet with a silicon content of 6.5% and thickness 0.1 mm the consideration of non-linearity and magnetization characteristics has a little effect on the energy loss, at least up to 400 Hz. In the application of the algorithm, there are some limitations resulting from the assumption of the average value of the induction flux in the sample cross-section, numerical problems and hysteresis loop shapes.

1 Introduction

Energy loss is one of the fundamental parameters of magnetic materials. It is described via empirical and theoretical formulas [1-5]. According to the classical approach, energy loss in magnetic materials is related to eddy currents and change in magnetization (hysteresis loss). The classic equation determining the energy loss due to macroscopic eddy currents was derived by adopting a series of simplifications, i.e. neglecting not only magnetic hysteresis, but also the non-linearity of magnetic material. The authors of the study decided to check how the non-linearity and hysteresis loop affect the classical energy loss due to eddy currents. The algorithm is an original extension of that given in [7].

2 Algorithm of energy loss calculation

The theoretical description of macroscopic eddy current loss is presented in several works, e.g. [3, 8]. For a cuboidal sample of thickness g, height $a \gg g$ and length $l \gg g$, as in Fig. 1, after several simplifications the formula for the energy loss per unit time and volume of the sample becomes as follows:

$$P_{\mathrm{cl}} = \frac{\pi f B_{\mathrm{m}}^2 \gamma}{2\mu}\left(\frac{\sinh\gamma - \sin\gamma}{\cosh\gamma - \cos\gamma}\right). \qquad (1)$$

where f - frequency, B_{m} - magnetic flux density, μ - magnetic permeability, $\gamma = g/$, δ – skin depth.

The Maxwell equations for the sample are as follows:

$$\frac{\partial J_x(y,t)}{\partial y} = \sigma \frac{\partial B_z(y,t)}{\partial t}, \qquad (2)$$

$$\frac{\partial H_z(y,t)}{\partial y} = J_x(y,t), \qquad (3)$$

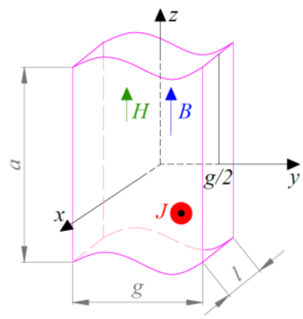

Fig. 1. The geometry of the analyzed sample.

where: J_x – x component of current density vector, B_z – z component of magnetic flux density vector, σ – sample conductivity, H_z – z component of magnetic field intensity vector. Magnetic properties of the sample are detected via measurement and are denoted as follows:

$$B_z = f_{\mathrm{HB}}(H_z), \quad H_z = f_{\mathrm{BH}}(B_z), \qquad (4)$$

where f_{HB} and f_{BH} are mutually inverse relationships between B_z and H_z (they can be vertex characteristics or hysteresis loop family). Equations (2)-(4) are solved iteratively, maintaining sinusoidal the total magnetic flux. Then the energy loss is calculated as follows:

$$P_{\mathrm{eddy}} = \frac{4f}{\sigma g}\int_{t=0}^{1/2f}\int_{y=0}^{1/2g} J_x^2(y,t)\,\mathrm{d}y\,\mathrm{d}t. \qquad (5)$$

The algorithm for solving field equations is presented in Fig. 2. In the first step, a certain spatial and temporal distribution of magnetic flux density is assumed. Based on the distribution of the flux density, the density of eddy currents and the magnetic field intensity are determined – Eqs. (2) and (3). Then B field is found via

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Eq. (4). This field is adjusted so that the total magnetic flux remains sinusoidal. If the difference between the induction of the current step obtained and the previous step is larger than a presumed value, the iterations are repeated, otherwise the procedure is finished and energy loss is calculated using Eq. (5). Other condition for finishing the iterative process is reaching a maximum number of iterations.

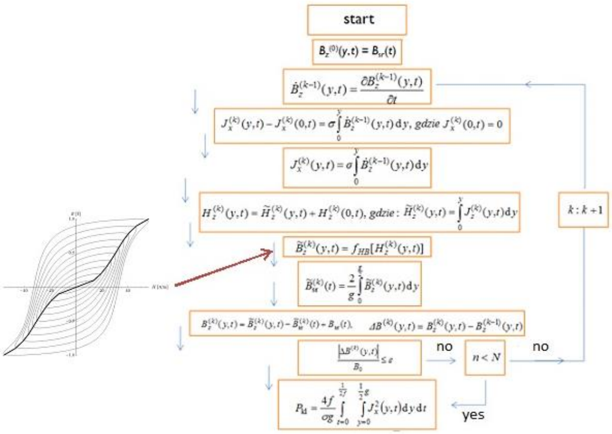

Fig. 2. Block diagram of the algorithm.

3 Results and discussion

The algorithm was used for non-oriented 6.5% Si-Fe steel in the form of a sheet of dimensions 500 mm × 500 mm, with thickness g = 0.1 mm and conductivity $\sigma = 1.22 \times 10^6$ S/m, for frequencies in the range 10-400 Hz, and magnetic flux density B_{m} within 0.1-1.2 T. The measurements were carried out using an MAG-RJJ-2.0 computerized measurement system. The resulting energy loss was compared with that determined via Eq. (1) by calculating the percentage relative difference:

$$\delta_P = \frac{P_{\text{eddy}} - P_{\text{cl}}}{P_{\text{cl}}} \times 100\%. \tag{6}$$

The results of calculations are presented in Figures 3-5. They indicate the nonlinearity as well as the hysteresis have a relatively small effect on the macroscopic eddy current loss for the considered material.

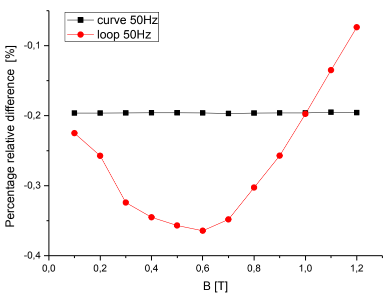

Fig. 3. Percentage relative difference of eddy current energy loss for 6.5% Si-Fe, g = 0.1 mm, f = 50 Hz.

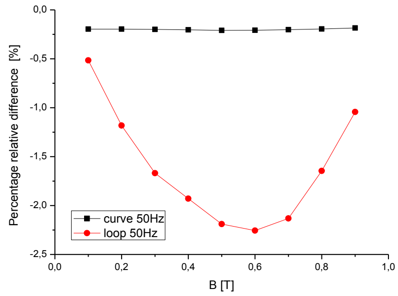

Fig. 4. Percentage relative difference of eddy current energy loss for 6.5% Si-Fe, g = 0.1 mm, f = 400 Hz.

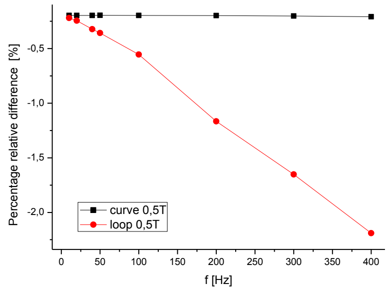

Fig. 5. Percentage relative difference of eddy current energy loss for 6.5% Si-Fe, g = 0.1 mm, B_{m} = 0.5 T.

The relative difference between losses calculated according to the algorithm and those calculated in accordance with the classical formula did not exceed 0.2% and 2.4% when taking into account the nonlinearity and the hysteresis, respectively. This a rather small influence can be attributed probably to a very weak skin effect (small thickness, small frequencies). It can be expected that stronger skin effect affects the results much more. To check this, it is required to improve the algorithm, because the it is not free of restrictions; in particular the conversion between B and H field should be improved. This is the subject of further considerations.

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