Semi-analytical calculation of excess hysteresis losses in ferromagnetic laminates

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The harmonic balance method is combined with a modal solver for the treatment of the hysteresis loss problem. To properly address the excess losses contribution, an supplementary term involving a fractional derivative operator is introduced in the classical formalism. The theoretical results will be compared with experimental data obtained for a nano-crystalline material.

Keywords: hysteresis losses, eddy-current losses, partial derivative, non-linear formulation, semi-analytical modelling.

1. Introduction

The accurate calculation of magnetic losses in ferromagnetic laminates plays an important role to the design of electromagnetic devices. According to Bertotti's statistical theory of losses (STL) the total losses in a ferromagnetic specimen comprise three different mechanisms each one having a different frequency dependence: the frequency independent static hysteresis losses, linked to the wall pinning, the macroscopic eddy-current losses with a linear frequency dependence, and the excess losses, which stem from the correlation between the different walls [1]. The frequency dependence of this latter term is best fitted by an exponential law, where the exponent is a fractional number. The general expression reads:

$$\mathrm{W} = a + bf + cf^p$$

where f is the excitation frequency.

Most electromagnetic solvers do not take the last term into account, which becomes non-negligible at high frequencies. Recent studies have shown that the excess losses term can be described with good accuracy by a fractional derivative operator $\mathrm{W}_e \sim \rho d^p B / dt^p$, with the dissipation coefficient ρ and the fractional derivative order p being parameters being determined by a suitable identification procedure [2].

In the present paper, a fractional excess losses term is integrated into a 2D modal solver to address the magnetic loss problem in ferromagnetic laminates with rectangular cross-section. The problem is treated in the frequency domain, where the time fractional derivatives become exponential relations of the frequency, using the harmonic balance method. Beside the practical interest of the problem itself, the proposed solution is seen as a first step towards the solution of more complicated problems involving infinite plates or tubes. To avoid the complexity stemming from the hysteresis, this study will be focused on nano-crystalline materials presenting a very narrow hysteresis loop. A typcial example of a nano-crystalline material hysteresis loop at different frequencies is shown in Fig. 1. The theoretical results will be validated using experimental data for different excitation frequencies.

2. Mathematical formulation

Assume an infinite along the z direction laminate with a rectangular cross-section. The laminate is excited by an infinitely-long coil, tightly wound around it. The state equation for the nth harmonic of the magnetic induction along the strip axis reads:

$$\frac{\partial^2 B_n}{\partial z^2} - \mu \frac{i\omega\mu\sigma}{1+\mu(i\omega)^p\rho} B_n = \frac{1}{1+\mu(i\omega)^p\rho} \frac{\partial^2 I_n}{\partial z^2}$$

where μ, σ are the electrical conductivity and the magnetic permeability of the strip, respectively, and I is the magnetic polarisation associated with the static hysteresis curve of the material

$$I(B) = B - \mu_0 H^{(s)}(B).$$

$H^{(s)}(B)$ stands for the material curve obtained by quasi-static measurement. Upon projection onto the suitable modal basis, one obtains a relation for the modal coefficients, which is solved iteratively for all harmonics with the polarisation function been updated at the end of each iteration [3]. The advantage of the modal basis with respect to mesh-based approaches consists in the diagonalization of the system matrix, resulting in the reduction of the computational time per iteration.

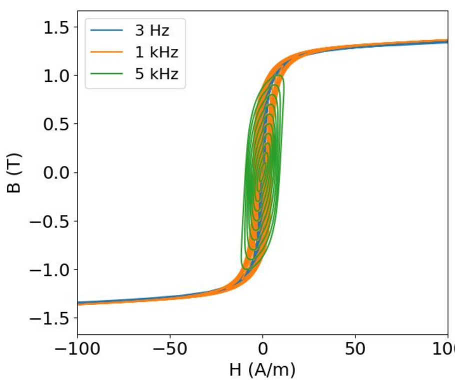

Figure 1: Hysteresis loops of a nano-crystaline material at different frequencies. One recognises the effect of the excess losses, which result in an opening of the static-curve with increasing frequency.

References

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