Efficient calculation of harmonic distortion measurements involving closed magnetic circuit

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A hybrid spatial/spectral formalism is proposed for the efficient numerical simulation of harmonic distortion measurements in setups involving closed magnetic circuits. The magnetic circuit and the specimen are treated separately, with the two calculations been coupled by means of an equivalent source at the specimen interface. Dissociating the yoke geometry from the specimen calculation, allows us to apply Fourier transform in the normal to the yoke plane, and treat the resulting modes independently.

Keywords: magnetic circuit, harmonic distortion, non-linear formulation, semi-analytical modelling, hybrid modelling.

1. Introduction

Magnetic circuits in form of yokes is one of the most popular setups used in non-destructive magnetic characterization applications as they exploit the special magnetic characteristics of yokes, in specific the high magnetic permeability. In particular, they are met in standard commercial devices such as the single strip tester or the 3MA system [1, 2].

From the point of view of numerical modelling, mesh-based approaches, such as the finite element method (FEM), encounter certain computational difficulties due to the extremely fine meshing required around the yoke and the huge number of degrees of freedom (DoF) caused by the model configuration owing to the geometry of the core and its high magnetic permeability. This difficulty can be partly overcome by splitting the problem into two sub-problems, where core and specimen are treated separately. This idea has been successfully applied for the linear case of a non-magnetic specimen with promising results [3]. Once the yoke geometry has been dissociated from the specimen, one can make a step further and try to simplify the solution for the specimen itself, since its geometry is symmetric in both tangential directions. The combination of spatial discretization with modal approaches in configurations with one axis of invariance can result in a further reduction of the solution time since modes are treated separately from each other, thus enabling an efficient parallelization [4]. In this contribution, the strategies presented in [3] and [4] will be combined in a hybrid non-linear formulation (HnLF) to efficiently address the harmonic distortion problem in 3MA-like configurations.

2. Results and discussion

We consider a standard yoke configuration located above an infinite ferromagnetic plate. Let the yoke be parallel to the *xz*-plane. The yoke is excited by a couple of coils wound around its legs connected in series with a sinusoidal current source of radial frequency ω_0. We apply a 2D orthogonal mesh in the *xz*-plate cross-section and a Fourier decomposition in the *y*-direction. The resulting equation for the *n*th Fourier term (mode) at the *k*th harmonic reads [4]:

$$\left(\mathbf{C}_n + i\alpha_n \mathbf{C}'_n + \alpha_n^2 \mathbf{C}''_n + im\omega_0 \mathbf{M}_{\sigma;n}\right)\mathbf{A}_{mn} = \mathbf{m}_{mn}(\mathbf{A}_{kn}) + \mathbf{b}_n$$

where $\mathbf{C}_n, \mathbf{C}'_n, \mathbf{C}''_n$ and $\mathbf{M}_{\sigma;n}$ are the projections of the curl-curl and conductivity matrices, respectively, onto the development basis associated with the discretisation mesh, α_n is the spatial frequency corresponding to the *n*th mode, $\mathbf{A}_{mn}$ is the state vector (vector magnetic potential) $\mathbf{m}_{mn}(\mathbf{A}_n)$ the corresponding magnetisation, and $\mathbf{b}_n$ represents the equivalent magnetic charge source on the plate interface stemming from the yoke flux. The latter will be obtained by the solution of the yoke in the air (the retroaction of the plate to the yoke magnetisation is considered negligible). The accuracy of the yoke approximation via an equivalent magnetic charge distribution is shown (for a linear plate) in Fig. 1.

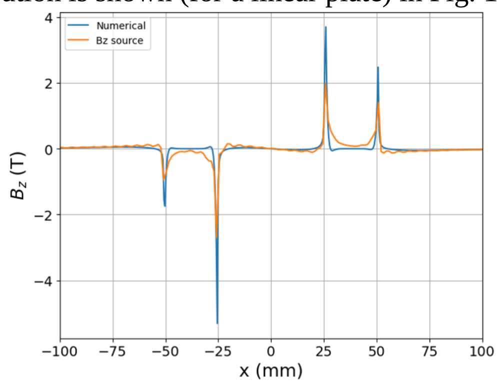

Figure 1: Hybrid solution result vs. FEM reference solution for the magnetic field of a 2D yoke above a linear ferromagnetic plate.

In the non-linear case, the plate magnetisation depends on the (unknown) magnetic potential value in the plate. The state equation becomes thus an implicit relation, which will be solved using the fixed-point approach. In the full paper, a detailed description of the formalism will be provided, and the results for the harmonic distortion from a ferromagnetic plate will be compared with the FEM solution as well as laboratory measurements.

References

[1] S. Tumanski, Handbook of Magnetic Measurements; CRC Press, 2011.
[2] G. Dobmann, In *Proceedings of the 10th European Conference on Non-Destructive Testing*, 2010.
[3] Kyrgiazoglou, A., Skarlatos, A., Theodoulidis, T., NDT&E Int. **154** (2025), 103379.
[4] A. Skarlatos, IEEE Trans. Magn. **56** (2020), 9137712.