Multiscale and Harmonic Balance FEM for the Eddy Current Problem in Laminated Iron Cores

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***Abstract*—The multiscale finite element method is an excellent framework to avoid the need of large computer resources to simulate eddy currents in laminated iron cores of electrical devices. On the other hand, harmonic balance finite element method saves mainly computation time in simulations of large devices with harmonic excitation and nonlinear material properties. In this work the attempt will be made to combine the multiscale and the harmonic balance finite element method, respectively, to benefit from the advantages of both methods in the same time.**

***Index Terms*—Eddy currents, harmonic balance finite element method HBFEM, laminated iron cores, multiscale finite element method MSFEM, nonlinear material.**

I. Introduction

The multiscale finite element method (MSFEM) avoids very fine finite element (FE) meshes for laminated iron cores and in turn the necessity to solve extremely large equations systems [1]. The computational effort of MSFEM for a numerical solution is practically independent of the small-scale dimensions. A very moderate increase of the computational costs can be observed when the complexity of the problem grows. Higher order MSFEM copes very well with small penetration depths in eddy current problems (ECPs), [2].

Most of the sources of ECPs alternate harmonically in time and only the solution of the steady state has to be calculated. However, in case of nonlinear materials the solution is not harmonic any more, but still periodic. Thus, the solution can be represented as a Fourier series. This can be exploited advantageously by the harmonic balance method [3] or as also called the multi-harmonic ansatz [4], i.e., a truncated Fourier series expansion at a finite number. Only a few harmonics are required for a sufficiently accurate approximation. That's why the harmonic balance method is superior to the time stepping method particularly in case of a transient that takes a long time. A rigorous estimate for the total error due to the use of truncated Fourier series is presented in [4].

The successful use of the harmonic balance finite element method (HBFEM) in simulations of electromagnetic devices in the frequency domain can be found in [5] or in [6].

Applying Fourier block diagonalization to the equation system obtained by time stepping of one period yields N_T decoupled equations of the system, where N_T is the number of time steps of one period and the number of unknowns in each linear system is just the number of degrees of freedom at a time instant. Exploiting the fixed-point method for nonlinear materials a nonlinear term appears on the right-hand side only and Fourier block diagonalization can be applied again [7]. Thus, the periodic nonlinear problem can be solved very efficiently too.

A 2D FEM considering the main magnetic flux with a 1D diffusion equation across the lamination and using a multi-harmonic ansatz of the magnetic vector potential including hysteresis is shown in [8].

The aim of the present work is to exploit the advantages of both the MSFEM and the HBFEM.

II. Multiscale finite element method MSFEM and harmonic balance finite element method HBFEM

The multiscale approach [2]

$$\tilde{\mathbf{A}} = \mathbf{A_0} + \phi_1 \begin{pmatrix} 0 \\ A_1 \end{pmatrix} + \nabla(\phi_1 w_1) \tag{1}$$

in $2D$ for the magnetic vector potential $\mathbf{A}$ is considered. Each quantity $\{\mathbf{A_0}, A_1, w_1\}$ in approach (1) is written in terms of a truncated Fourier expansion

$$u(x,t) = u_0(x,t) + \sum_i^N u_i^c(x)\cos(i\omega t) + u_i^s(x)\sin(i\omega t), \tag{2}$$

where $u(x,t)$ can be scalar or vector valued.

Numerical simulations will be presented in the full paper. A feasible truncation of the Fourier expansion, i.e. a proper choice of N in (2) in the context of MSFEM, the selection of even and odd terms and the savings in computational costs of the different methods will be discussed.

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