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Subspace Correction Method for Computing Magnetic Shields in Large Power Transformers

Weiying Zheng[1], *Member, IEEE*, Xinhong Chen[2]

[1]NCMIS, LSEC, Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing, 100190, CHINA
[2]Department of Mathematics, Zhongyuan University of Technology, Henan, 450007, CHINA

In a large power transformer, magnetic shields of the oil tank are made of grain-oriented (GO) silicon steel laminations. The thickness of a lamination is 0.3mm and the thickness of its coating film is only 4μm. Accurate solution of nonlinear eddy current problem in such a multiscale structure is very challenging. This paper proposes a subspace correction method (SCM) to solve the nonlinear eddy current problem in the lamination system. The method can compute three-dimensional eddy currents in the steel laminations and is very efficient for large-scale simulations. Numerical experiments on the TEAM benchmark model P21^c-M1 show good agreements between the calculated and the measured data and demonstrate the competitive behavior of the SCM.

Index Terms—**Eddy current problem, finite element method, subspace correction method, GO silicon steel lamination.**

I. Introduction

In a large power transformer, iron cores and magnetic shields of the oil tank are made of grain-oriented (GO) silicon steel laminations which have multi-scale geometric sizes [1], [2]. The complex structure consists of many laminations (0.3mm thick) and very thin coating films (4μm thick) over them. The ratio of the largest scale to the smallest scale can amount to 10^6. Full three-dimensional (3D) finite element modeling is extremely difficult due to extensive unknowns from meshing both laminations and coating films. There are very few works on the computation of 3D eddy currents in the literature. Simulating magnetic shields plays an important role in avoiding overheating the oil tank locally. The purpose of this paper is to propose an efficient subspace correction method (SCM) to compute 3D eddy current distribution in GO silicon steel laminations.

In recent years, there are many papers devoted to developing efficient numerical methods for nonlinear eddy current problems in steel laminations. In electrical engineering, the most popular approach is the homogenization method that uses effective permeability and conductivity to replace the physical ones in the lamination stack (cf. e.g. [3]–[10]). It provides an efficient way to compute the electromagnetic field in steel laminations. The effective conductivity has zero value in the normal direction to the lamination plane and thus leads to two-dimensional (2D) eddy currents.

When the leakage magnetic flux is very strong and enters the lamination plane perpendicularly, the eddy current loss induced there must be taken into account in electromagnetic design. In [11], Cheng et al divide the lamination stack into a 2D eddy current region and a 3D eddy current region. Effective permeability and conductivity are used in the 2D eddy current region while laminations and coating films are partitioned into anisotropic grids in the 3D eddy current region. They investigate the effects of the eddy currents, induced by the normal magnetic field, on the total iron loss and the distortion of local magnetic flux in laminations. Since the coating film is only 4μm thick, meshing coating films usually leads to very anisotropic meshes and large number of elements, and as a result, the discrete problem will be very difficult to solve. To avoid this, Zheng and Cheng proposed an inner-constrained separation technique to compute 3D eddy current density in GO silicon steel laminations based on the magnetic vector potential [12]. Their approach omits the coating film over each lamination but still insures that eddy currents do not flow through the interfaces between neighboring laminations.

The objective of this paper is to propose an SCM for computing 3D eddy current density in magnetic shields of large power transformers. The method is based on a Helmholtz-type decomposition of the magnetic field and splits the original eddy current problem into a system of easy-to-solve problems. Coating films do not appear in these problems and are thus not meshed in practical computations. In each lamination, eddy current density is computed individually by solving one local eddy current problem, and thus do not flow through the lamination interfaces. The magnetic field necessitates to solve an elliptic equation in the whole domain. The discrete problem is solved by successive subspace corrections back and forth in nodal element space and edge element spaces. The SCM converges optimally in the sense that the convergence rate is independent of the number of elements and the number of laminations.

The proposed method is implemented on the parallel finite element package PHG [13] and demonstrated by computing the TEAM Benchmark Problem P21^c–M1 on a mesh with 1.5×10^8 tetrahedra. The numerical results show good agreements with the experimental data. The uniform convergence of the SCM is presented with respect to the number of elements. Computational time is also provided for different meshes in the last section.

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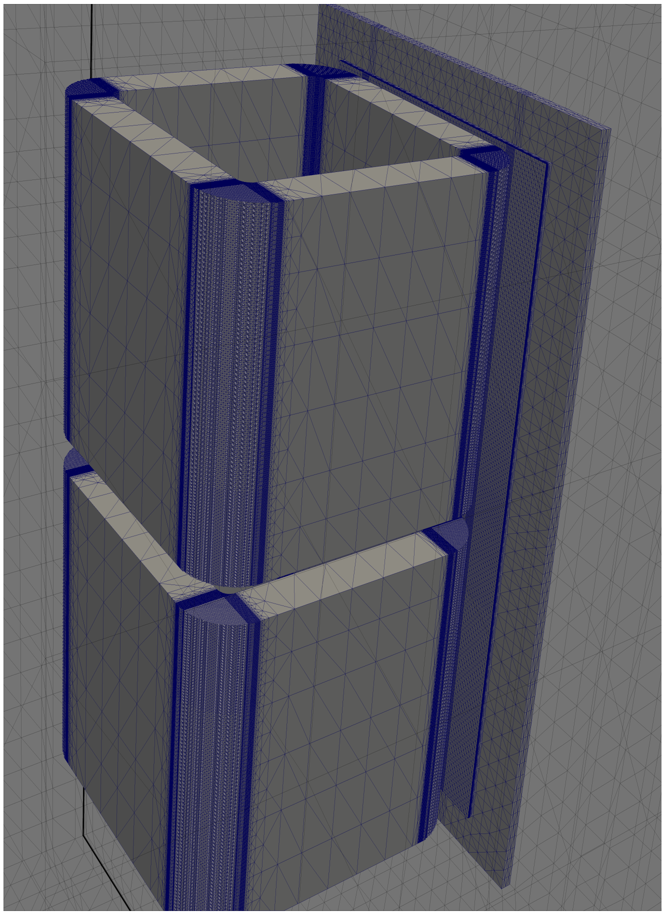

Fig. 6: Tetrahedral mesh of the coils and conductors.

developed a parallel finite element code to solve the nonlinear eddy current problem in silicon steel laminations.

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